NEW ZEALAND
Society on Large Dams

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NEW ZEALAND DAM SAFETY GUIDELINES

Contents

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OBJECTIVES AND PRINCIPLES

Preface

The New Zealand Society on Large Dams (NZSOLD) is a technical society of Engineering New Zealand .

NZSOLD represents New Zealand at the International Commission on Large Dams (ICOLD). An important activity of ICOLD is the development and publication of technical bulletins that provide international recommended practice which member countries can apply to their own situations.

These NZSOLD Dam Safety Guidelines (Guidelines) have been prepared from the technical bulletins published by ICOLD and other internationally recognised references on dam engineering.

These Guidelines outline recommended practices that should be considered during the investigation, design, construction, commissioning, assessment, rehabilitation, and operation of large dams in New Zealand. In these Guidelines a dam is defined as 'a barrier that is constructed or modified to divert, store or hold back water or other fluids'. A large dam is defined as 'a dam 4m or more in height and impounds 20,000 or more cubic metres volume, of water or other fluid'. All of the principles and many of the recommended practices are however, also applicable to dams that do not meet the large dam threshold.

The use of practices and criteria other than those indicated by these Guidelines may be appropriate to accommodate conditions arising at some projects. All of the principles and recommended practices in these Guidelines are applicable to dams where the consequences of dam failure are expected to be unacceptable to the public.

Advances in knowledge and improved techniques continue world-wide and these Guidelines should be interpreted and applied accordingly.

In all cases, the determination of what material included in these Guidelines is relevant to a particular project should be established by the dam Owner in consultation with his/her Technical Adviser.

The Guidelines are not intended for use in the investigation, design, construction, commissioning, assessment, rehabilitation and operation of road and rail embankments not intended for water detention or storage, holes excavated below the surrounding natural ground surface, concrete tanks and pressure vessels (including penstocks and pipelines).

These Guidelines are also not intended as design specifications or an all-inclusive instruction manual. Specialists experienced in the design, construction and operation of dams are best qualified to judge the suitability of a guideline for a particular purpose. It is incumbent on dam Owners to seek such specialist experience as appropriate.

In publishing these Guidelines, NZSOLD intends to facilitate the transfer of information among professional engineers and others involved in maintaining and administering dam safety. The responsibility for interpreting and applying these Guidelines lies with those engaged in dam safety work, whether they are Owners, Designers, Contractors or Regulators.

These Guidelines have been issued with an awareness of the current New Zealand legislation relating to dam design, construction and operation, such as the Building Act (2004) (Act (2004)) and the Building (Dam Safety) Regulations (2022) (Regulations (2022)) which provide minimum levels of acceptance for these activities, whereas these Guidelines reflect recommended industry practice.

In addition to the legislation, regulations and this Guideline, the Ministry of Business, Innovation & Employment (MBIE) published "Guide to complying with the Dam Safety Regulations" (MBIE (2023)) in November 2023 to "… support the understanding of the Building (Dam Safety) Regulations 2022 (the regulations) for dam owners, technical practitioners and Regional Authorities, and to provide guidance to assist preparing for and fulfilling the requirements of the regulations". MBIE (2023) should be the first reference for any interpretation of the Act (2004) and Regulations (2022). Note – this was previously titled "Dam Safety Guidance, Guidance for dam owners, technical practitioners and Regional Authorities" (Guidance Document) and first published in May 2022.

From time to time, portions of these Guidelines will be amended or revised to reflect changes in industry knowledge and practice, or changes in the regulations, and the user is responsible for ensuring that the most up-to-date issue of the Guidelines is used. The most up-to-date issue of the Guidelines can be downloaded free from **NZSOLD's website**. The Guidelines include this parent document, which covers overarching dam safety objectives and principles, and the following supporting modules:

- **Module 1: Legal requirements**
- **Module 2: Consequence assessment and dam potential impact classification**
- **Module 3: Investigation, design and analysis**
- **Module 4: Construction and commissioning**
- **Module 5: Dam safety management**
- **Module 6: Emergency preparedness**
- **Module 7: Lifecycle management**

The formatting of these Guidelines into a parent document and a series of supporting modules is intended to enable non-technical persons to access the overarching dam safety objectives and principles, and provide technical guidance, via the supporting modules, to those involved in the investigation, design, construction and operation of dams.

NZSOLD recognises that the value of these Guidelines will benefit from the experience and knowledge of others and, as such, welcomes contributions from its users.

Acknowledgements

These Guidelines have been prepared by representatives of dam owner and dam safety practitioner organisations in New Zealand. The completion of the Guidelines incorporated a review process which included checks that references to New Zealand Law were accurate at the time of publishing, a review from an internationally recognised dam safety engineer to ensure the Guidelines reflected international dam safety practice, and a review by the general membership of the New Zealand Society on Large Dams.

These Guidelines would not have been possible without the support and encouragement of the corporate and individual members of NZSOLD who have provided their time, knowledge and facilities towards the completion of these Guidelines. NZSOLD acknowledges the time and effort that have been provided by all contributors and reviewers.

Legal notice

The Institution of Professional Engineers New Zealand Incorporated, trading as Engineering New Zealand, is the non-aligned professional body for engineering and technology professionals in New Zealand.

Practice Notes and other technical publications offer guidance to practicing engineers by exploring issues of importance to the profession and setting out good-practice methodologies. They are written by practitioners and subject to peer review by Engineering New Zealand members. While every care is taken in their preparation, these documents are not offered as formal advice and practitioners must exercise their own professional skill and judgement in applying them. Engineering New Zealand accepts no liability from their use.

Document history

Release	Date	Released with
Original	May 2015	Parent and all modules
2023	December 2023	Updates to Parent and Modules 1, 2 and 5

1. How to use these Guidelines

These Guidelines comprise:

- A parent document (this document) that defines dam safety objectives and principles applicable to the investigation, design, construction, commissioning, assessment, rehabilitation and operation of dams in New Zealand.
- A series of separate supporting document (modules) prepared to outline recommended processes and criteria for the management of dam safety in accordance with the principles included in the parent document.

A schematic showing the structure of these Guidelines into a parent document and seven separate supporting modules is provided in Figure 1.1.

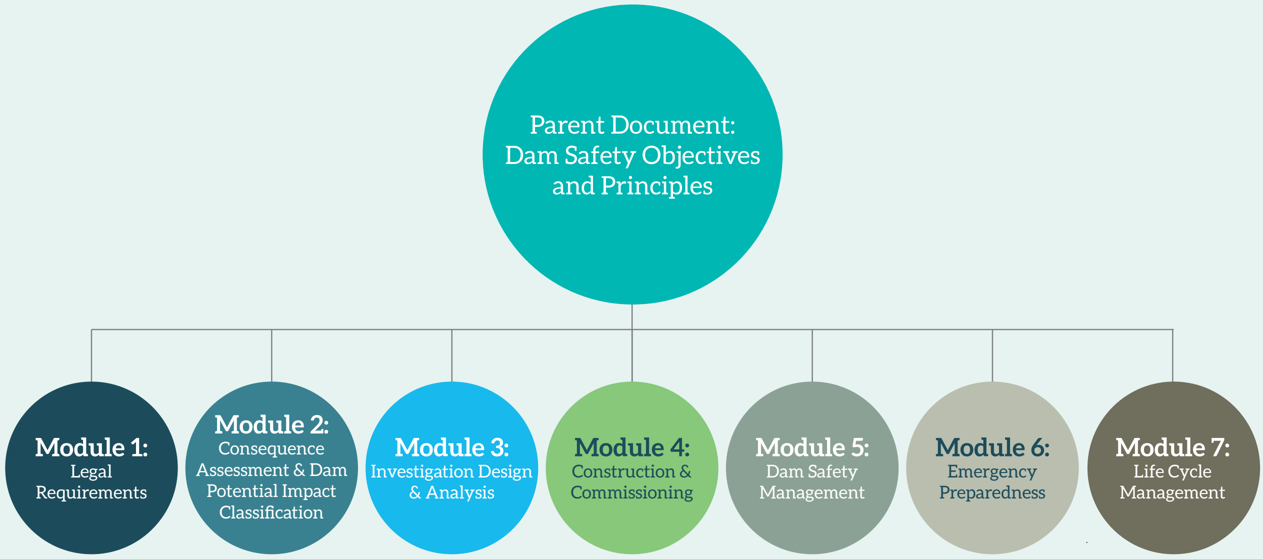

Figure 1.1: Structure of Guidelines

The module format has been adopted to assist readers in accessing the material most relevant to their particular needs. An outline of the content included within the parent document and each supporting module is as follows:

Parent document
Outlines the scope of the Guidelines, and defines dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, assessment, rehabilitation and operation of dams in New Zealand. A glossary of terms relevant to dam safety, and terms defined in the Act (2204) and the Regulations (2022), is included.

Module 1: Legal requirements
Outlines New Zealand's current legislative framework for the development and operation of dams, and has been prepared to assist Owners, Designers and Contractors in meeting the requirements of the legislation.

Module 2: Consequence Assessment and Dam Potential Impact Classification
Provides guidelines for the completion of consequence assessments and determining the potential impact classification of a dam.

Module 3: Investigation, Design and Analysis
Provides guidelines for the investigation and design of new dams, the assessment of existing dams, and the design of rehabilitation works for existing dams. The module includes an outline of dam types, hazards, personnel and quality assurance requirements, the scope of investigation and design activities, and the scope of design documentation.

Module 4: Construction and Commissioning
Provides guidelines for the construction and commissioning of new dams and rehabilitation works for existing dams. The module includes an outline of personnel responsibilities, quality control measures, construction issues and commissioning issues.

Module 5: Dam Safety Management
Provides guidelines for establishing and implementing a Dam Safety Management System. The module includes an outline of surveillance, operation, maintenance and testing activities that are relevant to dam safety.

Module 6: Emergency Preparedness
Outlines emergency preparedness planning processes and provides guidelines for emergency action plans, and review and training requirements to ensure emergency action plans remain effective.

Module 7: Life Cycle Management
Provides guidelines for dam safety issue and deficiency management, risk informed decision making, the rehabilitation of dams, the decommissioning of dams, and change of use. While the focus of the module is primarily related to issues and activities that can directly affect dam safety, the module also provides guidance on the management of public safety around dams.

2. Introduction

2.1 Objective of the Guidelines

These Guidelines are intended for use in New Zealand and must be read together with appropriate legislation, regulations and standards that are in place.

- Legislation is law passed by the New Zealand Parliament.
- Regulations are rules issued by a government agency that provide details on how legislation will be implemented and may set specific minimum requirements for the public to meet if they are to be considered in compliance with the legislation and the regulations that implement it.
- Standards typically refer to product performance or how to do a job. While standards may not be written by a government body, they may be adopted into regulations making them legal requirements.
- Guidelines consist of recommended, non-mandatory controls that help support standards or serve as a reference when no applicable standard is in place. Guidelines should be viewed as strongly recommended practices but are not usually requirements.

These Guidelines represent the recommended practice for dam safety in New Zealand. The reader may refer to Guidelines or Standards from other countries, but must recognise that those documents are written for that jurisdiction and legal system.

These Guidelines are relevant to Technical Advisers, Owners, Contractors, Regulators and others who have a responsibility and a duty of care for dam safety. All parties share responsibilities for achieving safe dams, but the Owner is ultimately responsible for the management of dam safety throughout the complete life cycle of the dam.

There is a wealth of technical literature available from ICOLD and other internationally recognised agencies that provide guidelines for the design, construction, commissioning, assessment, rehabilitation and operation of dams. These Guidelines are well aligned to similar documents from comparable jurisdictions and have been developed to fulfil the following objectives:

- To provide guidelines for the design, construction and commissioning of new dams, the evaluation, performance management and rehabilitation of existing dams, and the maintenance and operation of dams in New Zealand.
- To provide a framework for the management of dam safety, and guidelines for the development and implementation of appropriate dam safety practices throughout New Zealand.
- To assist Owners in understanding the requirements of the Resource Management Act 1991 (RMA), the Act (2004), Regulations (2022) and other legislation relevant to the design, construction and operation of dams in New Zealand.

2.2 Dams and Dam System Components

2.2.1 Overview

In these Guidelines a dam is defined as a barrier that is constructed or modified to divert, store or hold back water or other fluids. Flood control facilities, tailings dams, canals in fill, storage reservoirs and natural features modified to store water or other fluids fit this description. The purpose of dam safety assurance is to minimise the potential for an uncontrolled escape of the stored contents.

Dams are somewhat different from other engineered works that are built of customised, purpose built manufactured materials and do not store large volumes of fluids. Unlike buildings for example, dams pose a potential hazard to communities, the environment and property often well beyond their locations. Furthermore, dams typically have expected life spans well in excess of other engineered works and, as such, need to demonstrate resilience over time.

Dams are often built from a combination of natural and engineered materials, usually store large volumes of fluids, and are very dependent on foundations and abutments for support. All dams have unique characteristics that usually include site geology, construction materials and structural form. The variations in geology, building materials, geometry, and flood and earthquake hazards mean that it is not practicable to develop a standard code-type design, or standard analysis or evaluation procedures, for dams.

The physical and non-physical elements to safely contain, convey and control the fluids form the dam system. Each dam system is unique and must be treated individually, taking all relevant factors into account..

2.2.2 Dam system components

The reservoir, dam, foundation, abutments and appurtenant structures are physical components of the total dam system. In many cases the components are sub-systems that in turn have interacting components. The functional requirements of these components, and typical areas where dam safety deficiencies can arise are summarised as follows:

The reservoir – The reservoir will usually have a fluctuating level which rises or falls during normal operation and the passage of flood events. Initial reservoir filling can result in instability along reservoir margins where they are steep and/or have unfavourable geology. Similarly, reservoir drawdown may result in instability along reservoir margins if the drawdown is rapid and the reservoir has been maintained at a high level for an extended period. If the reservoir is full and there is a major landslide into the reservoir, the displaced water or other fluid could overtop the dam and initiate a dam failure. For most dams the reservoir represents the principal hazard, the control of which necessitates dam safety measures.

The dam – The dam creates the barrier which holds back the reservoir or stored fluid. It cannot be treated in isolation from its foundations or abutments with which it acts in an integrated manner. Similarly the design of the dam and appurtenant structures must be integrated to ensure that events such as floods are managed within design expectations without compromising dam safety. The dam, including its foundation and abutments, must also have adequate strength to withstand normal, unusual and extreme loading conditions and adequate facilities for the control and management of any seepage flows.Dam safety deficiencies can arise from the interaction of the dam with its foundation and abutments, the interaction of the dam with its associated appurtenant structures, and the interaction of the dam (and its foundation, abutments and appurtenant structures) with the reservoir. Some dam safety deficiencies can be revealed shortly after commissioning (e.g. excessive leakage, internal erosion, differential settlement and cracking), while others may not become apparent until many years following commissioning (e.g. backward erosion piping, inadequate capacity for the discharge of flood events, inadequate stability during a large earthquake, long-term weathering and chemical degradation of materials).

Foundations and abutments – The area of ground on which the dam is located (sometimes called the dam footprint) and the abutments form part of the total water barrier. If the foundations and abutments do not adequately support the basic dam structure, or are themselves structurally weak, subject to internal erosion, or prone to high seepage flows and forces, then dam safety issues can arise.

Dam safety deficiencies in the foundations and abutments can include weaknesses (e.g. joints, shear zones, faults) that are susceptible to instability, settlement, erosion or liquefaction, and long-term weathering and chemical degradation of materials.

Appurtenant structures – For the purposes of these Guidelines, an appurtenant structure is a structure at the dam site, other than the dam itself, which is designed and is required for the safe containment and control of the reservoir contents and reservoir discharges under all loading conditions. As such, appurtenant structures are required to fulfil functions necessary for the safety of dams and may include, but are not limited to, spillway, intake, outlet and sluice facilities together with their associated gates/valves and control equipment. Spillway facilities enable the management of flood flows and intake, outlet and sluice facilities enable reservoir lowering or dewatering in response to a dam safety emergency. Depending on the specific requirements of a site, other conduits or structures (e.g. tunnels, pipelines, surge chambers, penstocks, power stations) may fit the appurtenant structure definition if they fulfil dam safety functions. For some water storage dams and tailings dams, diversion drains may fit the appurtenant structure definition if they have a dam safety function.

Dam safety deficiencies in appurtenant structures can include structural performance, insufficient spillway capacity, susceptibility to spillway and sluice blockages, erosion and abrasion damage, and scour. Ageing can lead to dam safety deficiencies that are not apparent at commissioning. Inappropriate operation of mechanical and electrical equipment installed in appurtenant structures can also affect dam safety and, as such, operational procedures and personnel training must be in place to ensure the equipment is appropriately operated during normal, unusual and emergency loading conditions.

In addition to physical components, examples of which are provided above, there are also non-physical components of a dam system. These include human and organisational processes, procedures and factors that the dam system depends on for safe function, such as inspections, monitoring, maintenance, operations, testing, emergency response, supervision, management, information flow, control decisions, and documentation.

2.3 Scope of Guidelines

The primary focus of these Guidelines is to provide recommended practices for the investigation, design, construction, commissioning, operation, assessment, rehabilitation and decommissioning of large dams in New Zealand. All of the principles and recommended practices in these Guidelines are applicable to dams where the consequences of dam failure would be unacceptable to the public. In addition, all of the principles and many of the recommended practices are applicable to dams that do not meet the large dam threshold.

In all cases, the determination of what material included in these Guidelines is relevant to a particular project should be established by the dam Owner in consultation with his/her Technical Adviser. The Guidelines are not intended for use in the investigation, design, construction, commissioning, assessment, rehabilitation and operation of; road and rail embankments (unless specifically intended for the purpose of water detention or storage), embankments to support pipeline services (unless specifically intended for the purpose of water detention or storage), holes excavated below the surrounding natural ground surface, or concrete tanks and pressure vessels (including penstocks and pipelines).

The Guidelines do not constitute a design, construction or operations manual and reference must be made to appropriate technical publications, and appropriately qualified and experienced technical personnel during the development or safety evaluation of any dam project. The Guidelines will not cover every conceivable situation, and the Owner and Technical Advisers to the Owner must decide what is appropriate to their particular project.

A glossary of terms relevant to dam safety and used within the Guidelines is provided at the end of this module.

3. Dam safety objective and principles

3.1 Fundamental dam safety objective

The following fundamental dam safety objective is supported by the eight dam safety principles included in section 3.2.

Fundamental Dam Safety Objective – People, property and the environment, present and future, should be protected from the harmful effects of a dam failure or an uncontrolled release of the reservoir contents.

It applies to dams and dam operational activities, and over all lifecycle stages from initial planning, investigation, design, construction, commissioning, assessment, rehabilitation and operation through to dam decommissioning and should be achieved without unduly limiting the benefits created by the operation of dams and reservoirs.

To achieve an appropriate level of safety, measures must be taken to:

- **Control the release of damaging discharges downstream of a dam:** Measures should be taken to prevent dam failure, where a failure would result in unacceptable downstream consequences, and appropriate operational procedures should be in place for the effective control of discharges from a reservoir.
- **Reduce the likelihood of events that might lead to a loss of control over the stored volume and discharges:** There should be a high level of confidence that the likelihood of such events occurring is kept as low as reasonably practicable and is reflected in the design, construction and operational criteria adopted for the dam and its associated appurtenant structures.
- **Mitigate through incident management and emergency planning the potential consequences of such events if they were to occur:** Appropriate procedures should be in place for the management of dam safety incidents or emergencies, and the mitigation of their effects.

3.2 Overarching dam safety principles

The dam safety principles presented below provide an overarching management framework to achieve the Fundamental Dam Safety Objective as described above. The principles have been developed with reference to international practice and with the intention that the minimum levels of acceptance specified in government legislation and regulations (refer Module 1) are met and typically exceeded during the design, construction, commissioning, assessment, rehabilitation and operation of dams, regardless of the downstream consequences of a dam failure. Owners should consider the dam safety principles and satisfy themselves that appropriate systems and procedures are in place for the management of dam safety.

Dam safety requires consideration of the total system surrounding the dam and should not be limited to the dam structure. Dams are usually components of larger systems (e.g. hydropower, water supply or irrigation schemes) and it is important to consider the interaction between parts of the system – not only the technical components, but also the human and organisational aspects. Safe access to and from dams, and reliable escape routes for downstream residents are important, and many dams may require power systems for the operation of equipment that fulfils dam safety functions.

A dam's role in an overall system is also important as the loss of dam operation will affect the facility or infrastructure that it supports. For example, a loss of dam operation could prevent the supply of irrigation water, reduce power generation, destabilise the power transmission system, prevent water supply or prevent mining operations. Dam safety principles should therefore reflect the wider context of the dam system and not be limited to the dam structure.

As part of wider infrastructure systems, dams should incorporate resilient features to safely withstand unusual and unexpected events. These Guidelines recommend the consideration of resilient features and supporting practices in design, construction, operation and dam safety management. Resilience in this context is the capacity of the structure or system to withstand changing conditions caused by sudden shocks, gradual stresses and cumulative change. Resilient features should better enable dams to cope with changing conditions such as previously unrecognised loading conditions and variations in material characteristics.

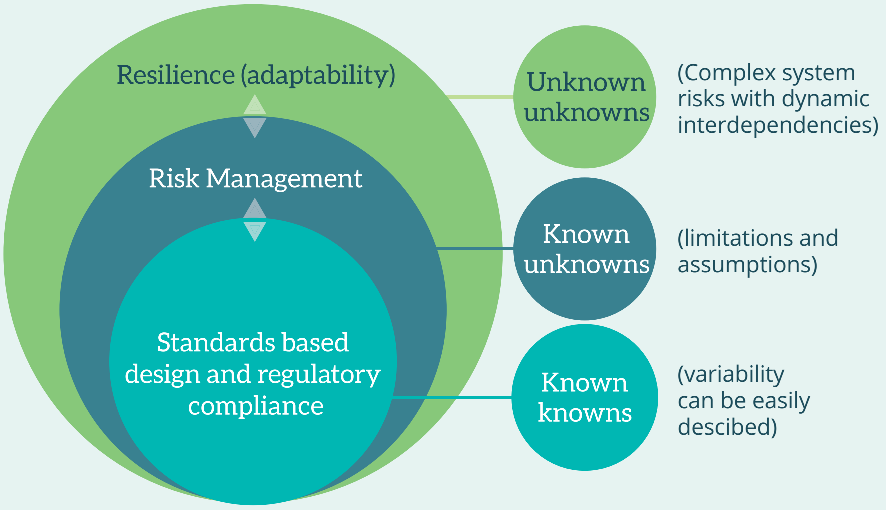

Figure 3.1: Standards Based Design, Risk Management and Resilience.

Note: The boundaries in the diagram are not absolute. For example, standards based design usually incorporates the consideration of risk and resilience.

A high standard of care should be adopted during the design, construction and rehabilitation of any dam and, where appropriate, additional resilient features should be provided to reflect the consequences of dam failure. For example, if the consequences of a dam failure are minimal and are restricted to the downstream river it may be appropriate to incorporate no additional resilient features. However, if the consequences of a dam failure are major and extend well beyond the downstream river, additional risk management procedures (e.g. more frequent inspections, emergency preparedness plans) and resilient features (e.g. defensive design measures, back-up systems) should be included to reduce the likelihood of a dam failure. This is not implying 'gold plating' or 'gross conservatism', but sound and efficient design which provides long term dam safety assurance.

3.2.1 Consequence assessment and Dam Potential Impact Classification

Principle 1 – The consequences of a dam failure should be understood so that appropriate design, construction, and management actions can be applied to protect people, property and the environment.

The potential consequences of dam failure may include loss of life, injury, damage to infrastructure and property, damage to environmental values, and economic and social impacts. To assess the potential consequences of a dam failure, the potential failure modes for the dam should be identified and considered, the resulting discharge characteristics estimated, the affected areas mapped, and the consequences assessed. If a dam failure is related to a natural event, such as an extreme flood, the consequence assessment should identify the incremental consequences of failure (i.e. the consequences above and beyond those that would have occurred had the dam not failed).

Periodic consideration of the need for reassessment of the consequences of dam failure is important (e.g. during the completion of a comprehensive dam safety review). In many cases, community and infrastructure growth downstream of a dam can increase the consequences of failure over the lifetime of a dam. Where an increase in the consequences of failure occurs, upgrading of the dam and appurtenant structures, or enhancement of the existing warning systems or emergency preparedness procedures, may be necessary in order to maintain an appropriate level of risk reduction.

To ensure an appropriate standard of care is exercised and maintained, all dam safety risks, whether they arise during normal operation or extreme events, should be assessed and periodically reassessed throughout the lifetime of a dam. Dam safety risks not 'broadly acceptable' require applying the 'As Low As Reasonably Practicable' (ALARP) principle to determine potential risk mitigation requirements.

A dam classification system that reflects the consequences of a dam failure, together with engineering design and evaluation criteria appropriate to the hazard posed by the dam, provides the framework for establishing an appropriate level of dam safety. It is common in similar international jurisdictions for design and evaluation criteria to provide higher levels of dam safety where the consequences of failure are greater. In simplistic terms, where the consequences of a dam failure are higher, the design and operational processes associated with the dam should be more robust and resilient to reduce the likelihood of dam failure to an acceptable level.

3.2.2 Investigation, design, construction and commissioning

Principle 2 – All natural hazards, human-contributed hazards, loading conditions, potential failure modes and any other threats to the safe design, construction, commissioning, operation and rehabilitation of a dam should be identified.

Hazards that can affect dams and influence dam safety include high rainfall and/or wind events, lightning strikes, flood events, earthquakes, volcanic activity and landslides. The dam Owner cannot preclude the potential occurrence of the hazard or control the size or timing of its occurrence but must ensure that the dam is engineered and managed to keep the risks of dam failure as low as reasonably practicable.

Other factors that can influence dam safety and can usually be controlled by the Owner may arise from errors and omissions in design, construction, operation and maintenance. They can include:

- Inadequate design and construction of the civil works.
- Inadequate design and construction of the mechanical and electrical equipment that fulfils dam safety functions.
- Inappropriate operation, maintenance and testing procedures, surveillance and monitoring procedures, and emergency management procedures.

Vandalism and security breaches can also affect dam safety.

Principle 3 – Dams and appurtenant structures should be designed, constructed, commissioned, operated, and rehabilitated in a manner which ensures they meet appropriate performance criteria.

Design criteria and performance criteria should always be commensurate with the consequences of dam failure. In addition, care should always be taken to ensure that the design is not adversely affected by subsequent construction and commissioning practices. Important tenets that should be applied throughout the dam's lifecycle to achieve an adequate level of dam safety are as follows:

- The competence and experience of the Owner's agents, e.g. Designer, Technical Advisor, Contractor, must reflect the nature of the dam and be commensurate with the consequences of dam failure.
- There must be a co-operative and trusting relationship between the Owner and the Designer, and the Designer must be appropriately involved and consulted in all decisions that affect dam safety.
- The Owner must agree to apply the appropriate level of funding for investigations, design and construction to reduce the chances of critically important issues (particularly related to foundations) being insufficiently assessed or protected.
- The Designer should not compromise safety due to financial or programme accomplishment pressures from the Owner or Contractor. Likewise, the Contractor should not compromise safety due to financial or programme accomplishment pressures from the Owner. Finally, the Owner should not compromise safety by applying such pressures.

- A thorough evaluation of dam safety risks and the measures to control them must be completed as part of the design of a dam and the design of a dam rehabilitation, with a focus on providing affordable and resilient backup features and systems to support primary features and systems.
- Quality assurance procedures commensurate with the consequences of dam failure should be implemented at all stages.
- Continuity of key technical advice should be maintained throughout all stages of the dam's lifecycle to reduce the chances of critical points of design philosophy and intent being misinterpreted .
- Records relating to the investigation, design, construction, commissioning and rehabilitation of the dam should be established and safely retained for the life of the dam.

3.2.3 Dam safety management

Principle 4 – The responsibility for the safety of the dam rests with the dam Owner.

The dam Owner is directly responsible for the safety of a dam. This is both a moral and legal obligation. At a minimum, the responsibility should include:

- Verifying that the design of the dam and appurtenant structures is completed in accordance with current dam safety practice, and that redundancy and resilience are incorporated commensurate with the consequences of dam failure.
- Verifying that the construction of the dam and appurtenant structures is completed in accordance with the design drawings and specifications.
- Ensuring the safe control of the reservoir and outflows.
- Establishing appropriate procedures and arrangements for the maintenance of dam safety under all conditions.
- Establishing and maintaining the necessary competencies for ongoing dam safety management including the training of surveillance and operational personnel.
- Ensuring the completion of periodic dam safety reviews.
- Ensuring that emergency preparedness procedures, commensurate with the consequences of dam failure, are in place and that periodic testing of the procedures is completed.

The New Zealand Government has established a legal and regulatory framework for dam safety management. In New Zealand the dam Owner also has a duty of care in common law to prevent harm befalling others from a release of the contents from their dam (refer Module 1).

Principle 5 – A Dam Safety Management System, commensurate with the consequences of dam failure and incorporating policies, procedures and responsibilities, should be in place for all dams.

Effective dam safety management is primarily achieved through the development and implementation of procedures, commensurate with the consequences of dam failure, which are incorporated within an overall DSMS. The DSMS should reflect the Owner's commitment to dam safety and provide a structured framework for the completion of dam safety activities, reaching appropriate dam safety decisions, and addressing identified dam safety issues and deficiencies.

Dam Safety Management Systems should incorporate:

- A dam safety policy/standard/statement that demonstrates the Owner's commitment to dam safety.
- A description of the elements of the DSMS including the work activities and the resources for completing the work activities.
- Responsibilities for implementing the elements of the DSMS.

- Procedures for implementing the elements of the DSMS including procedures for visual inspection, instrument monitoring, and review and notification if visual or instrument limits are exceeded.
- Procedures for checking and reviewing the performance of the dam and the DSMS.
- Procedures for identifying and addressing any issues and deficiencies in the performance of the dam and DSMS.
- Procedures for regular reporting on the performance of the dam and the adequacy of the DSMS to the Owner and, where appropriate, the Regulator.
- Appropriate supporting systems for management, staff training, communication and information management.
- The DSMS should include procedures for the operation, maintenance and testing of mechanical and electrical equipment that fulfil dam and reservoir safety functions (e.g. power supplies, control and communication systems, spillway gates, low level sluices) which should cover normal, abnormal and emergency operating conditions and include any procedures to lower the reservoir level in response to a dam safety emergency. In some cases it may be appropriate to prepare a separate operations and maintenance manual; however, it is important that the linkage to dam safety is not diluted.

Principle 6 – All reasonable efforts should be made to prevent and mitigate accidental releases, dam safety incidents, and dam failures.

To achieve an adequate level of dam safety, measures should be taken to prevent:

- The occurrence of abnormal conditions or incidents that could lead to an uncontrolled release of part or all of the reservoir.
- The escalation of any such abnormal conditions or incidents to dam safety emergencies.

The primary means of preventing and mitigating the consequences of incidents is resilience, which is achieved through the provision of an appropriate combination of effective management, operational processes and the incorporation of independent engineering features that provide a suitable amalgamation of safety margins, diversity and redundancy.

Resilient engineering maximises the ability of a structure or system to safely manage an abnormal, unexpected or unpredictable condition. Natural hazards are examples of loading conditions which can vary considerably from the idealised product of a hazard identification process. Resilient dam safety practices can mean both smart engineering and redundancy and, when properly implemented, should ensure that no single technical, human or organisational malfunction leads to a dam safety incident and that the combined malfunctions necessary to result in a dam safety incident have an acceptably low probability of occurrence.

3.2.4 Emergency preparedness

Principle 7 – Effective emergency preparedness and response procedures should be in place for dams.

The primary goals of emergency preparedness are:

- To ensure that appropriate arrangements are in place for an effective response at the dam site and, as appropriate, at local, regional and national agencies.
- To ensure that appropriate measures are in place to mitigate the effects of any dam safety emergency or dam failure on people, property and the environment.

Dams should have emergency action plans in place if there is a population at risk or if the implementation of emergency actions could reduce the potential consequences of failure. The level of detail in emergency action plans should reflect the consequences of failure.

The dam Owner is responsible for preparing emergency action plans in consultation with appropriate local and regional agencies, issuing the plans to appropriate personnel and local and regional agencies, maintaining and updating the plans as necessary, and ensuring that all personnel and agencies with emergency preparedness responsibilities are thoroughly familiar with the procedures and their responsibilities.

Emergency action plans should detail the actions to be taken by the dam Owner and Operator, or Contractor if the dam is under construction, and all relevant agencies in response to a dam safety emergency.

3.2.5 Life cycle management

Principle 8 – Due diligence should be exercised during all stages of a dam's life cycle.

Dam safety is important during all stages of a dam's life cycle and includes:

- Appropriate review, approvals and documentation throughout the option assessment and design phases of the initial project and any rehabilitation works.
- The use of risk informed decision making to identify preferred options, design solutions and construction methods.
- Adherence to technical specifications, design approvals for any proposed changes to technical specifications, quality control and documentation during the construction of the dam or during the construction of rehabilitation works.
- Appropriate commissioning and emergency preparedness procedures, and approvals during commissioning.
- Appropriate procedures for surveillance, monitoring, operation, maintenance, testing and emergency response during operation.
- Appropriate procedures for the identification, evaluation and management of dam safety deficiencies.
- The storage and safekeeping of records relating to the investigation, design, construction, commissioning, surveillance and monitoring of the dam and appurtenant structures, and the operation, maintenance and testing of all mechanical and electrical equipment that fulfils dam safety functions.
- The maintenance of appropriate DSMSs throughout the lifetime of the dam that properly reflect lifetime changes such as a change in use or a change in operation.
- Where necessary, appropriate procedures for the decommissioning of dams and the long-term closure of tailings dams.

Glossary

The following terms are relevant to dam safety and these Guidelines. It is important to note that the definitions provided are in the context of these Guidelines.

Abutment
That part of the valley side, excavated to suitable material, against which the dam is constructed. An artificial abutment is sometimes constructed, as a concrete gravity section, to take the thrust of an arch dam where there is no suitable natural abutment.

Acceptable risk
A risk which, for the purposes of life or work, everyone who might be impacted is prepared to accept assuming no changes in risk control mechanisms. Such a risk is regarded as insignificant or adequately controlled. Action to further reduce such risk is usually not required unless reasonably practicable measures are available at low cost in terms of money, time and effort.

Active fault
A fault, reasonably identified and located, known to have produced historical earthquakes or showing evidence of movements in Holocene time (i.e. in the last 11,000 years), large faults which have moved in Latest Pleistocene time (i.e. between 11,000 and 35,000 years ago) and major faults which have moved repeatedly in Quaternary time (1.8 million years). Note – this definition applies to deterministic seismic hazard assessments.

As Low As Reasonably Practicable (ALARP)
A principle established in Common Law that risks should be reduced to the point where the cost of reducing the risk is grossly disproportionate to the improvements gained.

Annual Exceedance Probability (AEP)
The estimated probability that an event of specified magnitude will be equalled or exceeded in any year.

Appurtenant structure
A structure at the dam site, other than the dam itself, which is designed and is required for the safe containment and control of the reservoir contents and reservoir discharges under all loading conditions. Pipelines and penstocks downstream of intake structures should be considered appurtenant structures if there are no gates or valves designed to isolate them from the reservoir contents.

Breach
The uncontrolled release of the contents of a reservoir through failure of a dam or appurtenant structure (see also 'Failure'). The final stage in development of a dam failure, where the preceding stages are initiation, continuation and progression.

Breach outflow hydrograph
A graph of discharge versus time describing the rate that the storage volume is released from an upstream reservoir through a dam breach as the breach forms over time.

Breach parameters
Parameters that describe the nature of dam breach (e.g. shape, width, depth, rate of growth, time to breach).

Canal embankment
An embankment dam that supports a canal as it crosses a valley, or sidles the topographical contour, 'in fill'.

Cascade failure
The 'domino' effect of the failure of an upstream dam causing overtopping and the consequential failure of downstream dams.

Confirmed dam safety deficiency
A situation or condition where dam safety acceptance criteria are not satisfied.

Consequence
The outcome or impact of an event.

Consequences of failure
The downstream and upstream effects that would result from a failure of the dam or its appurtenant structures.

Contractor
The primary construction agency appointed to construct a dam, rehabilitate a dam or decommission a dam.

Controlling Maximum Earthquake (CME)
The maximum earthquake on a seismic source that is capable of inducing the largest seismic demand on a dam.

Crest
The elevation of the uppermost surface of the dam excluding any curbs, parapet walls, railings or other structures that are not part of the water retaining structure.

Criteria
The numerical values or other standards adopted by the dam industry for aspects of dam design and performance.

Dam
A barrier that is constructed or modified to divert, store or hold back water or other fluids.

Dam System
A set of interrelated and interacting components acting collectively to achieve defined containment, conveyance and control functions. Dam system components include the reservoir, dam, foundation, abutments, appurtenant structures, controls, communications, access, and human and organisational factors. In many cases the components are sub-systems that in turn have interacting components. The dam system boundaries can be defined as where the system is impacted by, and impacts on, the external domain.

Damage
The potential adverse effects of a dam failure on people, property and the environment.

Dam-break flood hazard assessment
An assessment of the hazard of a potential dam-break flood to downstream people, property and the environment (e.g. extent of inundation, depth of inundation, velocity, flow, time to peak flow, duration of inundation).

Dam classification
Refer Potential Impact Classification (PIC).

Dam crest flood
The reservoir inflow flood which causes the maximum reservoir level to rise to the dam crest level.

Dam safety deficiency
A situation or condition where dam safety acceptance criteria may not be or are not satisfied. See also Potential Dam Safety Deficiency and Confirmed Dam Safety Deficiency.

Dam safety emergency
Any condition which develops naturally or unexpectedly, endangers the integrity of the dam and downstream property or life, and requires immediate action.

Dam Safety Incident
Any condition which develops naturally or unexpectedly, in which abnormal or adverse behavior is observed or expected and warrants a response, but does not present an immediate danger to the integrity of the dam and downstream property or life. Dam safety incidents can arise through large flood or earthquake events, landslides into reservoirs, sudden uncontrolled releases from reservoirs, excessive controlled releases from reservoirs, failures of plant and equipment that fulfil dam safety functions, and observed departures from expected dam performance.

Dam safety issue
An issue affecting dam safety categorised as a physical infrastructure deficiency, a dam safety deficiency or a dam safety management non-conformance.

Dam Safety Management System (DSMS)
A programme of actions and activities to manage the safety of a dam through its entire life cycle.

Dam safety policy
A dam Owner's acknowledgement of, and articulation of commitment to dam safety responsibilities and implementation of an effective Dam Safety Management System.

Dam safety review
An engineering review of a dam's condition and performance at Intermediate, Comprehensive and Special levels of detail.

Designer
The primary engineering agency appointed to design a dam, to design any rehabilitation works for a dam, or to design any works to decommission a dam.

Emergency
A situation that poses an immediate risk to life, health, property, or the environment and requires a coordinated response.

Emergency Action Plan (EAP)
A document which contains or refers to procedures for dealing with various emergencies, as well as communication directories and inundation maps showing upstream and downstream water levels and times of arrival of floods which would result from the failure of the dam or its appurtenant structures.

Emergency preparedness
In the context of dam safety (protection of people, property and environment) preparedness for dam safety incidents and emergencies through emergency preparedness planning, training, exercises and readiness of appropriate logistics, equipment and materials.

Extreme event
An event which has a very low Annual Exceedance Probability (AEP).

Extreme loads
The rare loadings imposed by extreme events such as earthquakes, floods and landslides.

Factor of safety
In structural and other engineering terms, the ratio of system resistance to the peak design loads, often calculated in accordance with established rules.

Failure
In terms of structural integrity, the uncontrolled release of the contents of a reservoir through failure of a dam or appurtenant structure. In terms of performance to fulfil its intended function, the inability of a dam or appurtenant structure to perform functions such as water supply, prevention of excessive seepage or containment of hazardous substances.

Failure Mode and Effects Analysis (FMEA)
A systematic method for identifying and assessing dam system and component potential failure modes and effects based on a sound appreciation of dam system and component functions, interdependencies, and controls; hazards and threats; human and organisational factors; and dam system and component failures to function.

Flood detention dam
A dam used for the detention of flood flows to protect people, property and the environment. Flood detention dams only impound water during floods.

Flood routing
The propagation of a dam-break flood wave downstream in order to evaluate the extent of flood inundation.

Foundation
The undisturbed material on which the dam structure is placed.

Freeboard
The vertical distance between the still water surface elevation in the reservoir and the lowest elevation of the top of the dam or other containment structure.

Full Supply Level (FSL)
The maximum normal operating water surface level of a reservoir. Also called maximum normal level (MNL) or Maximum Control Level (MCL).

Governance
A commitment to, and oversight and enabling of an Owner's Dam Safety Management System, to ensure appropriate organisational behaviours, delegated authorities, priorities, effective dam safety risk management and continuous improvement.

Hazard
Threat; condition, which may result from either an external cause (e.g. earthquake, flood, or human agency) or an internal vulnerability, with the potential to initiate a failure mode. A source of potential harm or a situation with the potential to cause loss.

Headwater level
The water level immediately upstream of the dam or appurtenant structure; may also be referred to as reservoir level, or lake level.

Incident
An occurrence that requires a response from one or more agencies, but is not an emergency.

Incremental consequences of failure
Incremental losses or damage, which dam failure might inflict on upstream areas, downstream areas, at the dam, or elsewhere, over and above any losses which might have occurred for the same natural event or conditions, had the dam not failed.

Inflow Design Flood (IDF)
The most severe inflow flood (volume, peak, shape, duration, timing) for which a dam and its associated facilities are designed.

Initial Hydrologic Conditions
The hydrologic parameters at the time of initial breach (e.g. reservoir level, reservoir inflow, stored volume and downstream flow conditions).

Instrumentation
Instruments installed on or near dams for the purpose of dam safety performance monitoring.

Inundation Map
A map showing the estimated areal extent of flood inundation.

Large Dam
A dam that has a height of 4 or more meters, and holds 20,000 or more cubic meters volume of water or other fluid.

Monitoring
Observation and recording of instruments and other means (e.g. visual observation) to produce data which can be used to determine the performance of the dam and appurtenant structures. See also Surveillance.

Non-conformance
Where procedures and processes are not followed, or where established dam safety practices have not been implemented.

Operating Basis Earthquake (OBE)
The earthquake for which a dam, appurtenant structure and mechanical and electrical equipment that fulfils a dam safety function is designed to remain operational, with any damage being minor and readily repairable following the event.

Operator
An individual or organisation appointed by the Owner for the operation of the dam and its associated facilities.

Outlet Works
A combination of intake structure, conduit, flow control and energy dissipation device to allow the release of water from a reservoir.

Owner
The individual or organisation that holds the legal property title to the dam, dam site or reservoir. The dam Owner is responsible for the safety of a dam.

Peer Reviewer
An individual, or group of individuals, engaged by a client to complete an independent review of work completed by others. The scope of the review can vary depending on specific review requirements and can include a review of completed work, a review of completed work including the development of the work, or a review of a professional's competence to complete a specific work package.

Performance Criteria
Numerical values or other measures adopted by the dam engineering industry for aspects of dam design, evaluation and performance. It is important to note that technological advances or empirical evidence may lead to performance criteria changing with time.

Performance evaluation
The evaluation of a dam's actual performance relative to expected performance, including design expectations, characteristic behaviour and potential failure modes.

Physical infrastructure deficiency
Where equipment, access, instrumentation, communications or maintenance is insufficient to verify dam performance.

Population at risk
The number of people likely to be affected by an uncontrolled release of all or part of the stored water or other fluid due to a failure of the dam (assuming that no person takes any action to evacuate). Refer to Module 2 of these Guidelines for additional interpretation.

Potential Dam Safety Deficiency
A situation or condition where dam safety acceptance criteria may not be satisfied.

Potential failure mode
A mechanism or set of circumstances that could result in the uncontrolled release of all or part of the contents of a reservoir. These guidelines recommend that potential failure modes include component level failures to function and their effects on the safe performance of the overall dam system. At a general level potential dam failure modes include overtopping, erosion, contaminated seepage, instability and structural failure.

Potential Impact Classification (PIC)
A system of classifying dams according to the incremental consequences of dam failure, so that appropriate dam safety criteria can be applied.

Potential loss of life
The number of people expected to lose their life as a result of an uncontrolled release of all or part of the stored water or other fluid due to a failure of the dam. Refer to Module 2 of these Guidelines for further interpretation.

Probability
A measure of the degree of confidence in a prediction, as dictated by the evidence, concerning the nature of an uncertain quantity or the occurrence of an uncertain future event. It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event. This measure has a value between zero (impossibility) and 1.0 (certainty).

Probable Maximum Flood (PMF)
An estimate of a hypothetical flood (peak flow, volume and hydrograph shape) that is considered to be the most severe "reasonably possible" at a particular location and time of year. The estimate is based on a relatively comprehensive hydrometeorological analysis of critical runoff-producing precipitation (snowmelt if pertinent) and hydrologic factors favourable for maximum flood runoff.

Probable Maximum Precipitation (PMP)
The greatest depth of precipitation meteorologically possible for a given duration and a given size storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends. The PMP is an estimate of an upper physical bound to the precipitation that the atmosphere can produce.

Rainy Day Failure
A dam failure which occurs under conditions of a coincident flood, typically caused by the spillway capacity of a dam being exceeded or inappropriate operation of a spillway during the passage of a flood.

Regulator
Usually a government ministry, department, office or other unit of the national or provincial government entrusted by law or administrative act with the responsibility for the general supervision of the safe design, construction and operation of dams and reservoirs, as well as any entity to which all or part of the executive or operational tasks and functions have been delegated by legal power.

Reliability
The likelihood of successful performance of a given project element. It may be measured on an annualised basis or for some specified time period of interest or on a per demand basis.

Mathematically, Reliability = 1 – Probability of failure.

Reservoir
The body of water, fluid waste or tailings that is impounded by a dam.

Reservoir capacity
The total or gross storage capacity of the reservoir at full supply level.

Reservoir drawdown
The lowering of the water level in a reservoir.

Residual risk
The remaining level of risk at any time before, during and after a programme of risk mitigation measures has been taken.

Resilience
The capacity of a structure or system to withstand changing conditions caused by sudden shocks, gradual stresses and cumulative change.

Return period
The reciprocal of the annual exceedance probability (AEP). Over a very long period of record, the return period equals the average elapsed time between occurrences of an event equalling or exceeding a specified magnitude.

Risk
A measure of the probability and severity of an adverse effect to life, health, property, or the environment. In the general case, risk is estimated by the combined impact of all triplets of scenario, probability of occurrence and the associated consequence. In the special case, average risk is estimated by the mathematical expectation of the consequences of an adverse event occurring (that is, the product of the probability of occurrence and the consequence, combined over all scenarios).

Risk analysis
The use of available information to estimate the risk to individuals or populations, property or the environment from hazards. Risk analysis generally contain the following steps: scope definition, hazard identification, and risk estimation.

Risk assessment
The process of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases.

Risk criteria
The terms of reference against which the significance of a risk is assessed.

Risk reduction
Actions taken to lower the likelihood of an occurrence or its adverse consequences, or both.

Safe dam
A dam which does not impose an unacceptable risk to people, property or the environment, and which meets safety criteria that are acceptable to the government, the engineering profession and the public.

Safety Evaluation Earthquake (SEE)
The earthquake that would result in the most severe ground motion which a dam must be able to endure without uncontrolled release of the reservoir, and for which the dam should be designed or analysed.

Spillway
A weir, channel, conduit, tunnel, gate or other structure designed to permit discharges from the reservoir.

Spillway crest
The uppermost portion of the spillway overflow section.

Standards-based approach
The traditional approach to dam engineering, in which risks are controlled by following established rules for defining design events and loads, structural capacity, safety coefficients and defensive design measures.

Stopbank
A man-made linear embankment that serves a flood routing function for an existing watercourse, or acts as a flood barrier at a coastal margin.

Subsidiary dam
A dam additional to the main dam which is constructed across a saddle or low point on the perimeter of a reservoir to provide reservoir containment.

Sunny day failure
A dam failure which occurs under conditions of normal dam operation without a coincident flood and is typically initiated by events such as uncontrolled embankment or foundation seepage, an earthquake, or inappropriate operation of a dam.

Surveillance
The close examination of dam behaviour, including systematic collection, analysis and interpretation of data through visual inspections and instrumentation.

Sustainability
Maintaining the viability of the planet, providing for equity with and between generations, and solving problems holistically.

Tailings
Residue produced from mining or metallurgical processes, typically comprise sand/silt/clay particles.

Tailings dam
A dam constructed to retain tailings or other waste materials from mining or industrial operations.

Tailwater level
The level of water in the discharge channel immediately downstream of a dam.

Technical adviser
An individual or company engaged by the Owner to provide discernment relative to ongoing dam engineering services including analyses, designs, evaluations or rehabilitations, in order to provide counsel and advice to the dam Owner on alternative courses of action.

Technical specialist
An individual who has the training and qualifications necessary to practice in their area of expertise, and is widely recognised for his/her specialist capability and experience.

Toe of dam
The junction of the downstream face of a dam with the ground surface (foundation). Sometimes 'heel' is used to define the junction of the upstream face of a dam with the ground surface (foundation).

Tolerable risk
A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk that we do not regard as negligible or as something we might ignore, but rather as something we need to keep under review and reduce it still further if and as we can.

Uncertainty
Result of imperfect knowledge concerning the present or future state of a system, event, situation or population under consideration. The level of uncertainty governs the confidence in predictions, inferences or conclusions. In the context of dam safety, uncertainty can be attributed to (i) inherent variability in natural properties and events, and (ii) incomplete knowledge of parameters and the relationships between input and output values.

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MODULE 1
LEGAL REQUIREMENTS

Abstract

Dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, operation, assessment and rehabilitation of dams in New Zealand are included in the Parent Document. The Parent Document also includes a glossary of terms used in these Guidelines.

This module of the NZSOLD's Dam Safety Guidelines (Guidelines) outlines New Zealand's legislative framework in 2023 for the development and operation of dams, and has been prepared to assist Owners, Designers and Contractors in meeting the requirements of the legislation. The module:

- Outlines the legal obligations and liabilities of those associated with the development, ownership and operation of dams.
- Outlines legislative requirements for the development and operation of dams.
- Provides comments on interpretation of the legislative requirements for the development and operation of dams.

Notice to reader

While this module has been configured to be, as much as practicable, self-contained from a technical perspective, the reader should be conversant with the principles, objectives and limitations expressed in the Parent Document prior to considering the information provided in this or any other individual module.

Document history

Release	Date	Released with
Original	May 2015	Parent and all modules
2023	December 2023	Updates to Parent and Modules 1, 2 and 5

Contents

1. Introduction

1.1 Objectives

New Zealand's legislative framework places a number of legal obligations on those associated with the development and operation of dams.

The objectives of this module are to provide Owners, Designers and Contractors with an appreciation of their legal obligations and to assist them in meeting the requirements of the legislation.

Note: The material presented in this module is not intended to cover all legal obligations and legislative requirements and, to ensure compliance, Owners, Designers and Contractors should refer to the relevant legislation and, if necessary, seek professional legal advice.

1.2 Scope of module

The module focuses on providing an outline of the legislative requirements for the development and operation of dams. The module has a strong focus on the requirements of the Building Act (2004) (Act (2004)) and Building (Dam Safety) Regulations 2022 (Regulations (2022)). It also includes an outline of legal obligations and liabilities associated with the following additional legislation:

- The Resource Management Act (1991) (RMA (1991)).
- The Building Regulations (1992).
- The Civil Defence and Emergency Management Act (2002).
- The Health and Safety at Work Act (2015).
- The Hazardous Substances and New Organisms Act (1996)
- The Local Government Act (2002).

There are a number of terms defined in the Act (2004) and the Regulations (2022) that are referred to throughout the module and due to their importance, are also listed in the Glossary at the end of this module.

2. Legal Obligations and Liabilities

The following subsections provide an outline of legal obligations and liabilities under common law, the RMA (1991), the Act (2004), the Civil Defence Emergency Management Act (2002), the Health and Safety at Work Act (2015), and the Hazardous Substances and New Organisms Act (1996).

2.1 Liability under common law

While liability for the escape of water is most often dealt with via legislation, it could also be dealt with either under the general tort of nuisance or the more specific (and easier to establish) legal principle strict liability as decided in the case of Rylands v Fletcher.

Liability at common law through the tort of nuisance requires a party to prove that the damage caused by the escape of water was due to the failure of the owner/operator to meet a required standard of care.

Liability for damage case by the escape of water can also arise for certain substances (e.g. water behind dams), where the activity is so inherently dangerous if a breach occurs, that for policy reasons liability can be found even where there is no negligence on the part of the Owner or Operator (i.e. here the Owner and/or Operator can be held strictly liable) provided the damage that results is foreseeable.

The lead case on strict liability is Ryland v Fletcher which dealt with water escaping from a reservoir into another property. Here, the House of Lords established the following principle of law:

> **… we think that the true rule of law is that the person who for his own purposes brings on his lands and collects and keeps there anything likely to do mischief, must keep it in at his peril, and if he does not do so, is prima facie answerable for all damage which is a natural consequence of its escape.**

This provides a clear basis for strict liability of the dam Owner. The water (or other stored material) is kept at the peril of the person responsible for keeping it there, and that person will be liable if the stored material escapes. Fault is not a necessary element for liability to be established. The risk is implicitly accepted by bringing a known dangerous substance onto the land.

In practice, Operators and Owners of dams, the basic principle is that in operating a potentially dangerous structure such as a dam, where it is reasonably foreseeable that loss would result from any failure, reasonable care must be exercised to avoid that risk. The focus will be on whether action taken during design, construction and operation of the dam was reasonable in the circumstances to ensure against such a failure occurring.

The Owner or Operator of a dam could be civilly liable for damage caused by processes which arise as a natural consequence of the existence of the dam. If the damage was the reasonably foreseeable result of the activity of damming the river, etc., then the Owner/Operator could be liable. In such cases, an “act of God” may be inadmissible as a defence.

The Ryland v Fletcher principle is limited by the requirement that the kind of harm or damage suffered must be foreseeable. This acts to limit liability under this rule; however, one may still be held liable notwithstanding all reasonable care to prevent the escape from occurring was exercised. That is, one should assume that despite conforming or even exceeding the highest standards it is probable that the Owner will be held responsible for any damage resulting from the failure of a dam.

2.2 The Resource Management Act (1991) (RMA)

2.2.1 RMA Reform

In February 2021 the Government announced plans to repeal the RMA and replace it with three new pieces of legislation:

- Natural and Built Environments Act
- Spatial Planning Act
- Climate Change Adaptation Act

Aspects of The Natural and Built Environments Act and Spatial Planning Act came into effect on 24 August 2023 and are expected to be phased in over the next 10 years.

2.2.2 RMA

It is not uncommon for resource consents relating to dams to have dam safety related consent conditions. The nature of these consent conditions have varied over time and across regulators; some are explicit in how the dam is to be maintained and operated, whilst others are higher level and essentially instruct that these Guidelines be followed. Where resource consents cover how the dam and reservoir are to be operated, it is important that these enable safe operation and maintenance of the dam. This may include provisions for operational sluicing, increased discharge during spillway gate testing, lowering reservoir levels for remedial or maintenance works.

The RMA provides for criminal proceedings for offence committed under it. Accordingly it is imperative to operate lawfully with all relevant consents applying to a dam, its maintenance and operation and otherwise in accordance with any conditions of the resource consent issued pursuant to section 108 of the RMA.

Section 341(1) makes the criminal provisions of the Resource Management Act strict liability, meaning it is not necessary to prove the defendant intended to commit the offence in order for there to be a contravention of the RMA. For example, with the failure of Opuha Dam in 1997, the Court held that neither foreseeability nor awareness were relevant in the context of offences of strict liability. Similarly, it was not necessary for the prosecution to show how the event occurred or why; all one had to show was that the event occurred.

The defences are very narrow and limited. Section 341(2) of the Act sets out the specific nature of statutory defences and which must be notified within 7 days after the service of the summons. In some limited circumstances sections 18 and 330 relating to emergency works and powers to take preventive or remedial action may be applicable.

When considering natural disasters, the courts will assess that the threshold above which a natural occurrence could be said to have been unforeseeable or impossible to provide against to be extremely high.

2.2.3 Penalties

Pursuant to section 339 the maximum penalty for every person who commits an offence is 2 years imprisonment (or $300,000) for a person and, in the case of a company, $600,000. There are also provisions to capture any continuous or ongoing offending.

Additional penalties may also be applicable, for example, the Court may impose an amount not exceeding 3 times the value of any commercial gain resulting from the commission of the offence if the Court is satisfied that the offence was committed in the course of producing commercial gain.

2.2.4 Personal liability of directors

Directors of companies that own or operate dams are unable to hide behind the body corporate if the Company is charged with an offence against the RMA which was authorised, permitted, or consented to by that Director. In particular, every person may likely be charged (e.g. the Company, Directors, Agents, Contractors) albeit the liability of principal for acts of agents may have additional defences pursuant to section 340 of the RMA.

The Company and its Directors all have a responsibility to ensure that there are dam safety procedures in place which are followed and designed to prevent the sort of occurrence which could give rise to a criminal prosecution under the RMA.

Senior managers, agents and contractors may also all share in the responsibility depending on the circumstances.

2.2.5 Remedies by litigants

Litigants who identify potential damage with no precautions in place may consider options ranging from “Quia timet” injunctions, brought to prevent the possibility of future damage or injury, to enforcement orders under the Resource Management Act.

2.3 The Building Act (2004) (Act (2004))

The Act (2004) provides for the control of building work and is focused with performance-based criteria relating to methods of construction.

It alsoprovides for offences in the event of breaches of its provisions such as:

- Failing to comply with directions given by persons authorised to give directions by the Act or regulations.
- Willful obstruction, hindrance or resistance to a person executing powers conferred on that person by the Act or regulations.

Regional Authorities are responsible for the administration of the Act (2004) with respect to dams and, as such, any proceedings for infringement offences under the Act (2004) are most likely to be initiated by Regional Authorities.

Sections 386 and 387 of the Act (2004) define vicarious liability provisions. Dam Owners are liable for offences under the Act (2004) committed by persons while acting as agents (eg a Consultant or Contractor) for the dam Owner unless the defendant proves:

(a) In the case of a natural person (including a partner in the firm), that –

(i) he or she did not know nor could reasonably be expected to have known that the offence was to be or was being committed; or

(ii) he or she took all reasonable steps to prevent the commission of the offence; or

(b) In the case of a body corporate, that –

(i) neither the directors nor any person involved in the management of the body corporate knew or could reasonably be expected to have known that the offence was to be or was being committed; or

(ii) the body corporate took all reasonable steps to prevent the commission of the offence; and

(iii) in all cases, that the defendant took all reasonable steps to remedy any effects of the act or omission giving rise to the offence.

Section 386 of the Act (2004) also states that if a body corporate is convicted of an offence against the Act (2004), every director and every person concerned in the management of the body corporate is guilty of the same offence if it is proved:

(a) that the act that constituted the offence took place with that person's authority, permission, or consent; and

(b) that he or she knew or could reasonably be expected to have known that the offence was to be or was being committed and failed to take all reasonable steps to prevent or stop it.

Section 379 of the Act (2004) provides for the situation where an offence under more than 1 enactment may arise. It ensures that no one is liable to be punished under both the Act (2004) and another Act in respect of the same act. That is, the informant must elect under which act to proceed and this section precludes an informant from proceeding against defendants, for example, under both the RMA and Act (2004).

2.4 The Civil Defence Emergency Management Act (2002)

The Civil Defence Emergency Management Act requires that a risk management approach be taken when dealing with hazards. In particular, it sets out the organisational structure under which national and local agencies manage emergencies, and requires every Regional Authority and Territorial Authority within that region to establish a local Civil Defence Emergency Management Group (CDEMG).

If the authorities charged with Civil Defence Emergency Management responsibilities determine that an emergency exists (e.g. during a dam safety incident or dam safety emergency) then they can declare an emergency. A state of emergency can be declared at a local level for either the whole area of a CDEMG or a district within the area of a CDEMG, or at a national level.. The Police can also initiate the process in the event of others not taking action.

Under a civil defence emergency the key point relevant to a dam is that the powers of CDEMGs include "to carry out or require to be carried out...works...or removing or disposing of, or securing or otherwise making safe, dangerous structures and materials". There is no upper limit to the powers to "carry out works."

Depending on the function of the dam and the Owner, Owners may also be lifeline utilities, in which case they have duties; refer to Section 60 of the Civil Defence Emergency Management Act (2002),

2.5 Health and Safety at Work Act 2015 (HSWA)

HSWA is New Zealand's primary health and safety law and was established, alongside Worksafe, in 2016 following significant reforms to workplace health and safety. WorkSafe is the primary health and safety regulator. HSWA defines and prescribes duties for four duty holders:

- Persons conducting a business or undertaking (PCBU)
- Workers
- Officers
- Other person at a workplace (e.g. visitors)

Whilst the HSWA does not relate directly to dam safety, the Owner of a dam has to ensure that the dam as a workplace is safe for operational employees, as well as for other persons, including members of the public, who enter the site where the dam is located. This includes investigation work, construction work and all operations, maintenance and surveillance work.

Dam Owners, whether they are PCBUs, Officers, or Workers, have responsibilities under the HSWA; the following is extracted from Worksafe (2019):

- **A PCBU must ensure, so far as is reasonably practicable, the health and safety of workers, and that other persons are not put at risk by its work. This is called the 'primary duty of care'**
- **Officers must exercise due diligence to ensure the PCBU meets its health and safety obligations.**
- **Workers have their own health and safety duty to take reasonable care to keep themselves and others healthy and safe when carrying out work.**

2.6 Hazardous Substances and New Organisms Act (1996) (HSNO)

Certain dams can contain hazardous substances (e.g. tailings or wastewater treatment dams) and the provisions of HSNO may apply depending on the substances within the tailings or reservoir.

HSNO Sections 115 and 116 define liability provisions. HSNO Section 115 states that employers, employees, principals and persons acting as agents for principals are liable for offences under HSNO unless the defendant proves:

(a) that –

(i) he or she did not know nor could reasonably be expected to have known that the offence was to be or was being committed; or

(ii) he or she took such steps as were reasonable practicable to prevent the commission of the offence; and

(b) that he or she took such steps as were reasonable in all the circumstances to remedy any effects of the act or omission giving rise to the offence".

HSNO Section 116 also states that if a body corporate is convicted of an offence against the Act, every director and every person concerned in the management of the body corporate shall be guilty of the same offence if it is proved:

(a) that the act that constituted the offence took place with his or her authority, permission, or consent; and

(b) that he or she knew or could reasonably be expected to have known that the offence was to be or was being committed and failed to take all reasonable steps to prevent or stop it.

3. Legislative Requirements for Dam Development and Operation

3.1 Introduction

The typical sequence for the development of a new dam, illustrating where legislative requirements related to dam safety are applied, is outlined in **Figure 3.1**. Virtually the entire sequence could also apply for an upgrade to an existing dam or the completion of rehabilitation works to correct an identified dam safety deficiency.

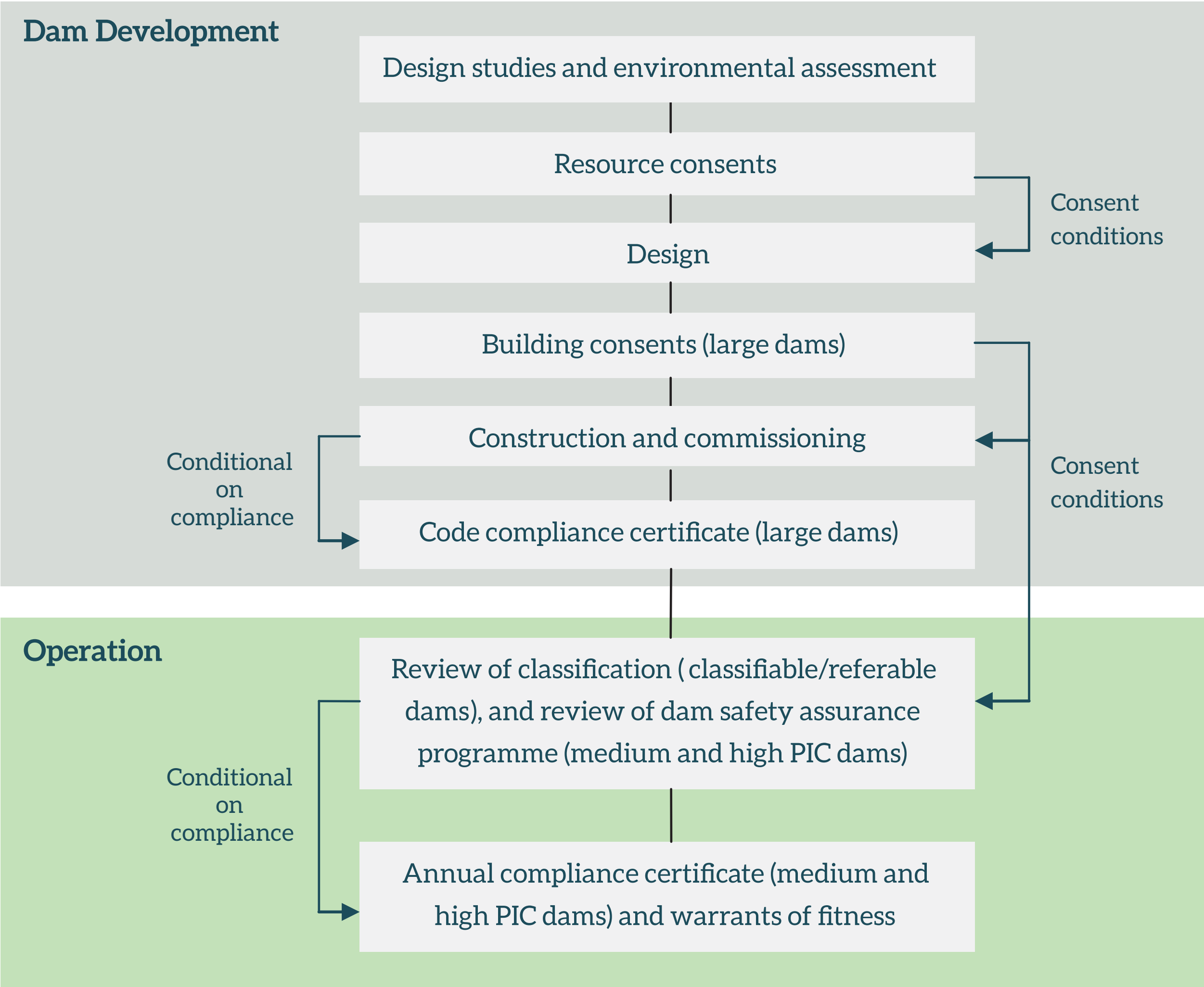

Figure 3.1: Legislative Requirements for Dam Development and Operation

The following sub-sections provide an outline of the legislative requirements of the RMA, the Building Regulations (1992), the Act (2004), and the Regulations (2002).

3.2 The RMA

The RMA enables conditions to be set on the design of building structures and therefore dams. Basically the RMA governs with respect to land and water use and the Act (2004) governs construction and subsequent use.

Water permits (e.g. to divert, take, use, discharge) and land use consents (e.g. for siting, altering, using materials) for dams are obtained through the RMA. These Guidelines do not outline all issues addressed in the RMA but highlights those aspects relevant to dam safety. A key step in the application for such permits and land use consents process is establishing actual or potential effects and avoiding, remedying or mitigating them to the satisfaction of the consenting authority. Effects include:

- Any potential effect of high probability, or
- Any potential effect of low probability but high potential impact.

Clearly the uncontrolled release of contents from dams could have a high potential impact. Any potential effect of significance and high probability clearly has to be avoided, remedied or mitigated.

The RMA lists matters to be considered during the consenting process including the risks and effects of natural hazards, the use of hazardous substances and installations and, where any discharge of contaminants may occur, the nature of the discharge and the sensitivity of the receiving environment to adverse effects.

An assessment has to be made of the risk to the environment. The following points are made:

- The terms “hazard” and “risk” are not defined in the RMA, but are generally understood to have the following meanings:
  - “hazard” is related to the potential for damage, and
  - “risk” is related to the probability and consequence of that potential being realised.
- “Hazardous substances” are not defined in the RMA but are covered by the HSNO. Stored natural water would not normally be considered a hazardous substance under the RMA, but stored fluids having an intrinsic property of “a capacity to oxidize, corrosiveness, toxicity or ecotoxicity” are hazardous substances under the RMA. Any consent application for a dam that was to store a hazardous substance would likely be dealt with under the RMA process, but the process would need to include consideration of the requirements of the HSNO.
- “Natural hazards” are not defined but generally are taken to be earthquakes, floods, volcanic activity, landslides, and the like.

It is an offence under the RMA to allow the release of a contaminant, or water into natural water without resource consent. It is vital therefore that the consents clearly prescribe the conditions under which any uncontrolled release of contents from the dam is permitted. This is highly relevant to consents for flood management during dam construction and the in- service capacities of spillways.

Dam safety planning for new projects starts with the assessment of potential effects, their likelihoods of occurrence and how to design for them to a standard society will accept via the RMA process. It is important to recognise the hazards and risks which apply during construction of the dam and during the long term in-service condition.

In the RMA consent process the applicant needs to demonstrate that the design, construction and operation practices for the dam will address hazards that have the potential to impact on the environment. Hazards may be natural hazards such as earthquakes or floods, construction hazards such as poor materials, or operational hazards such as sudden changes in river flow. Typical design, construction and operation issues that need to be addressed in consent application documents include:

- The site topography and how the dam will fit into or modify the topography.
- The regional and local geology which greatly influences structural safety, water retention and reservoir slope integrity.
- The proposed construction materials and dam arrangements to ensure safety during construction and operation.
- The flood risks at the dam and how floods are managed and passed through the structure during construction and operation.
- The seismic hazard and earthquake loads which the dam, with its stored contents, and the reservoir shoreline may experience.
- The surveillance, maintenance and operational procedures to ensure safe operation of the dam.
- Strategies for the management of other risks such as wind, slope stability upstream of the reservoir, and human error in design, construction, and operation of the project.
- The downstream effects of a potential dam failure and strategies for emergency management should the integrity of the dam be in doubt.

For new dams, detailed design is usually not complete at the resource consent stage. Accordingly, the information presented for RMA consents must demonstrate that the hazards are manageable and appropriate.

Safety issues associated with dams, particularly large dams, may be complex. It is therefore a recommendation of these Guidelines that, for new large dams whose failure would result in significant downstream effects, any consent hearing committee or commissioner should be assisted by a senior dam engineering specialist with appropriate experience in dam design and construction.

3.3 The Building Regulations (1992)

A dam is a building, as defined in sections 8 and 9 of the Act (2004).

The Building Regulations (1992) require all buildings to achieve specific performance criteria depending on the classified use or uses of the building.

Seven building types and classified uses are listed in Clause A1 of Schedule 1 (the Building Code) of the Building Regulations and those most relevant to dams are industrial buildings, outbuildings and ancillary buildings. Building importance levels are specified and the Building Code includes a number of performance criteria relating to stability, fire safety, access, moisture, the safety of users, services and facilities, and energy efficiency.

While dams and their associated facilities (e.g. appurtenant structures, power stations, pumping stations) are required to meet all relevant requirements of the Building Code, the performance criteria that are most relevant to dams are those that relate to the structure, the durability of the structure, access, safety from falling, and warning systems and signs.

3.4 The Electricity Act (1992)

Included within the Electricity Act (1992) are requirements for electricity generators and electricity suppliers in relation to public safety and prevention of damage to property. Section 61A of the Electricity Act (1992) contains requirements for safety management systems. Depending on the scale of generation, these requirements may extend to dams and waterbodies associated with electricity generation. The Electricity (Safety) Regulations (2010) provides further requirements for safety management systems including documentation, audits, certification, and offences.

Owners of dams used as part of electricity generation need to ensure they understand the scope and requirements of the Electricity Act (1992) to determine what their obligations are.

3.5 The Building Act (2004) (Act (2004))

The Act (2004) contains extensive provisions for dam construction and safety which must be read together with the Regulations (2022) which come into force on 13 May 2024.

Apart from the requirements of sections 157, 158 and 159 of the Act (2004) that relate to the avoidance of immediate danger and apply to all dams, dams that are less than the large dam threshold (as defined in the Act (2004)) are exempt from the requirements of the Act (2004) (refer 1st Schedule of the Act (2004)). Note, however, that dams smaller than the large dam threshold must meet the requirements of the Building Regulations (1992), and the Regulations (2022), and will likely require resource consents before construction.

3.5.1 Requirements for development and alteration of large dams

The Act (2004) includes the following requirements for the development of all new large dams and the alteration of existing large dams:

- An application for a building consent, from the Owner to the Regional Authority, for any building work (including alterations, demolition or removal). The application must be in the prescribed form and be accompanied by sufficiently detailed drawings, specifications, design reports and review reports to demonstrate compliance with the Act (2004), Building Regulations, Regulations (2022) and other guidelines or codes of practice considered appropriate by the Regional Authority.
- A project information memorandum, from the relevant Regional Authority to the Owner, which outlines planning and land use issues which relate to the building consent application.
- A building consent, from the relevant Regional Authority to the Owner, for any building work, except for those works listed as exempt in Schedule 1 of the Act and any building work which has to be carried out urgently "for the purpose of saving or protecting life or health or preventing serious damage to property."
- Where building work is carried out urgently the Owner must, as soon as practicable after the completion of the building work, apply for a certificate of acceptance from the relevant Regional Authority.
- An application for a code compliance certificate, from the Owner to the relevant Regional Authority, for all building work completed under a building consent.
- A code compliance certificate, from the Regional Authority to the Owner, following satisfactory completion of all building work completed under a building consent. While not specifically stated in the Act (2004), Regional Authorities may require confirmation of acceptable dam performance before issuing a code compliance certificate.

3.5.2 Producer statements

Producer statements were first introduced with the Building Act 1992. The Act (2004)2004 and the Building Amendment Act 2013 do not mention producer statements by name, but nevertheless they continue to be used by some Regional Authorities as a means of demonstrating compliance with the requirements of the Building Regulations (1992), the recommendations included in the Guidelines, and demonstrating that the dam has been constructed in accordance with the requirements of the building consent and its amendments.

Producer statement templates and guidance on the use of producer statements can be downloaded from the Engineering New Zealand and ACE New Zealand websites. The templates include:

- **Producer Statement PS1 Design**, which is intended for use by a suitably qualified design professional, where the Regional Authority requires a statement of opinion that the proposed building works will comply with the requirements of the Building Regulations (1992) and the recommendations included in the Guidelines.
- **Producer Statement PS2 Design Review**, which is intended for use by a suitably qualified design professional who completes a review of the design documentation, where the Regional Authority requires an independent statement of opinion that the proposed building works will comply with the requirements of the Building Regulations (1992) and the recommendations included in the Guidelines.
- **Producer Statement PS4 Construction Review**, which is intended for use by a suitably qualified design professional who undertakes construction monitoring of the building works, where the Regional Authority requires a statement of opinion that the building works have been completed in accordance with the building consent and its amendments.

Engineering New Zealand and ACE New Zealand also used to provide a PS3 Construction template; this is no longer the case. Instead, Schedule 6 of the NZS3910:2013, "Form of Producer Statement – Construction", which certifies that the building works have been completed in accordance with a contract. Schedule 6 is usually completed by the Contractor.

3.5.3 Requirements for dam safety

The Act (2004) also includes a number of dam safety requirements for dams set out in sections 133A to 162 (both sections inclusive). The requirements include:

- The notification of the size and location of classifiable or referable dams to Regional Authorities by dam Owners.
- The establishment and maintenance of registers of classifiable or referable dams in their regions, by Regional Authorities.
- The classification of classifiable dams, and the classification of referable dams which are located within a designated area and are required by Regional Authorities to be classified, to reflect the potential impact of dam failure on people, property and the environment.
- The classifications must be completed by Owners utilising the criteria and form included in the Regulations (2022) (refer section 3.4 of this module), certified by Recognised Engineers with the competencies included in the Regulations (2022), and submitted to Regional Authorities for approval.
- Owners must also review their dam classifications at intervals of not more than 5 years, or whenever modifications to dams could result in changes to the downstream effects that would likely follow dam failure. Reviewed classifications must be certified by Recognised Engineers with the competencies included in the Regulations (2022) and submitted to Regional Authorities for approval.
- The preparation and maintenance of dam safety assurance programmes for all dams with Medium or High Potential Impact Classifications (PICs). While dam safety assurance programmes for dams with Low PICs are not required by the Act (2004), it is in the interests of the Dam Owner and the Public that good dam safety assurance practice is applied to all classifiable , not just those with Medium or High PICs. Some dam Owners may choose to develop dam safety assurance programmes for Low PIC dams to support their asset management objectives. The requirements of such programmes and plans would typically be less onerous than those for Medium or High PIC dams, and would normally incorporate less detail and reduced inspection frequencies.

- The dam safety assurance programmes must be developed by Owners utilising the criteria and form included in the Regulations (2022) (refer section 3.4 of this module), be certified by a Recognised Engineer with the competencies included in the Regulations (2022), and be submitted to Regional Authorities for approval. A Regional Authority may refuse to approve a dam safety assurance programme only if the Regional Authority is satisfied that the engineer who provided the certificate referred to in section 142(1) (b) of the Act (2004) is not a Recognised Engineer.
- Owners must review their dam safety assurance programmes within 5 years (if a High PIC dam) or 10 years (if a Medium PIC dam) of the Regional Authority originally approving the dam safety assurance programme, and every 5 years (if a High PIC dam) and 7 years (if a Medium PIC dam) thereafter.
- Owners must also review their dam safety assurance programmes whenever modifications to dams could result in changes to the downstream effects that would likely follow dam failure.
- Reviewed dam safety assurance programmes must be certified by a Recognised Engineer with the competencies included in the Regulations (2022), and be submitted to Regional Authorities for approval.
- The completion of annual dam compliance certificates for dams with Medium or High PICs.- The certificates must be prepared by Owners in the prescribed form included in the Regulations (2022), signed by the Owner (if an individual) or by the Owner's Chief Executive (if a body corporate), certified by a Recognised Engineer with the competencies included in the Regulations (2022) and forwarded to Regional Authorities.
- The development, adoption and implementation of policies on dangerous dams by Regional Authorities.
- The completion of annual warrants of fitness where specified systems (e.g. lifts or fire sprinklers) are included in dams. The warrants of fitness must be prepared by Owners and forwarded to Regional Authorities.

A visual representation of the dam safety requirements included in Subpart 7 of the Act (2004) is provided in Figure 3.2.

3.5.4 Dangerous dams

Section 153 of the Act (2004) defines dangerous dams as dams with High or Medium PICs that are likely to fail in the ordinary course of events, in a "moderate earthquake", or in a "moderate flood". The terms "moderate earthquake" and "moderate flood" are defined in Section 19 of the Regulations (2022) and are listed in the Glossary at the end of the Parent Module. If a dam is determined to be dangerous the Regional Authority can require the Owner to carry out work on the dam within a specified time to reduce or remove the danger. If the work required is not initiated or completed within a reasonable timeframe, the Regional Authority may also apply to the District Court for an order authorising the Regional Authority to carry out the required work and recover the costs from the Owner. If a dam is likely to pose an immediate danger to the safety of people, property or the environment, the Chief Executive of a Regional Authority may issue a warrant to take immediate action to mitigate the danger.

Owners should be aware that a dam whose strength and capacity previously exceeded the stated thresholds for "moderate earthquake" and "moderate flood" events could sustain sufficient damage during a major event that reduced its strength and capacity to levels where it could be considered a dangerous dam.

Acting in accordance with the requirements of the Act (2004), Regional Authorities have developed policies for dangerous dams within their regions. The policies outline Regional Authority processes for the identification and assessment of potentially dangerous dams, dealing with dam Owners, and taking action on dangerous dams using the powers included in sections 154 to 159 of the Act (2004). Policies for dangerous dams are available on Regional Authority websites.

3.5.5 Earthquake-prone and flood-prone dams

Earthquake and flood-prone dams are defined in the Regulations (2022) as High or Medium PIC dams that are likely to fail in a "threshold event". The threshold events are defined in Section 19 of the Regulations (2022) and are listed in the Glossary at the end of this module.

The Act (2004) requires Regional Authorities to develop policies for "earthquake-prone" and "flood- prone" dams within their regions. If a dam is "earthquake-prone" or "flood-prone", section 146(2)(b) of the Act (2004) enables a Regional Authority to request a dam Owner to review their dam safety assurance programme.

Owners should be aware that a dam whose strength and capacity previously exceeded the stated thresholds for an "earthquake-prone" or "flood-prone" dam could sustain sufficient damage during a major event that reduced its strength and capacity to levels where it could be considered an "earthquake-prone" or "flood- prone" dam.

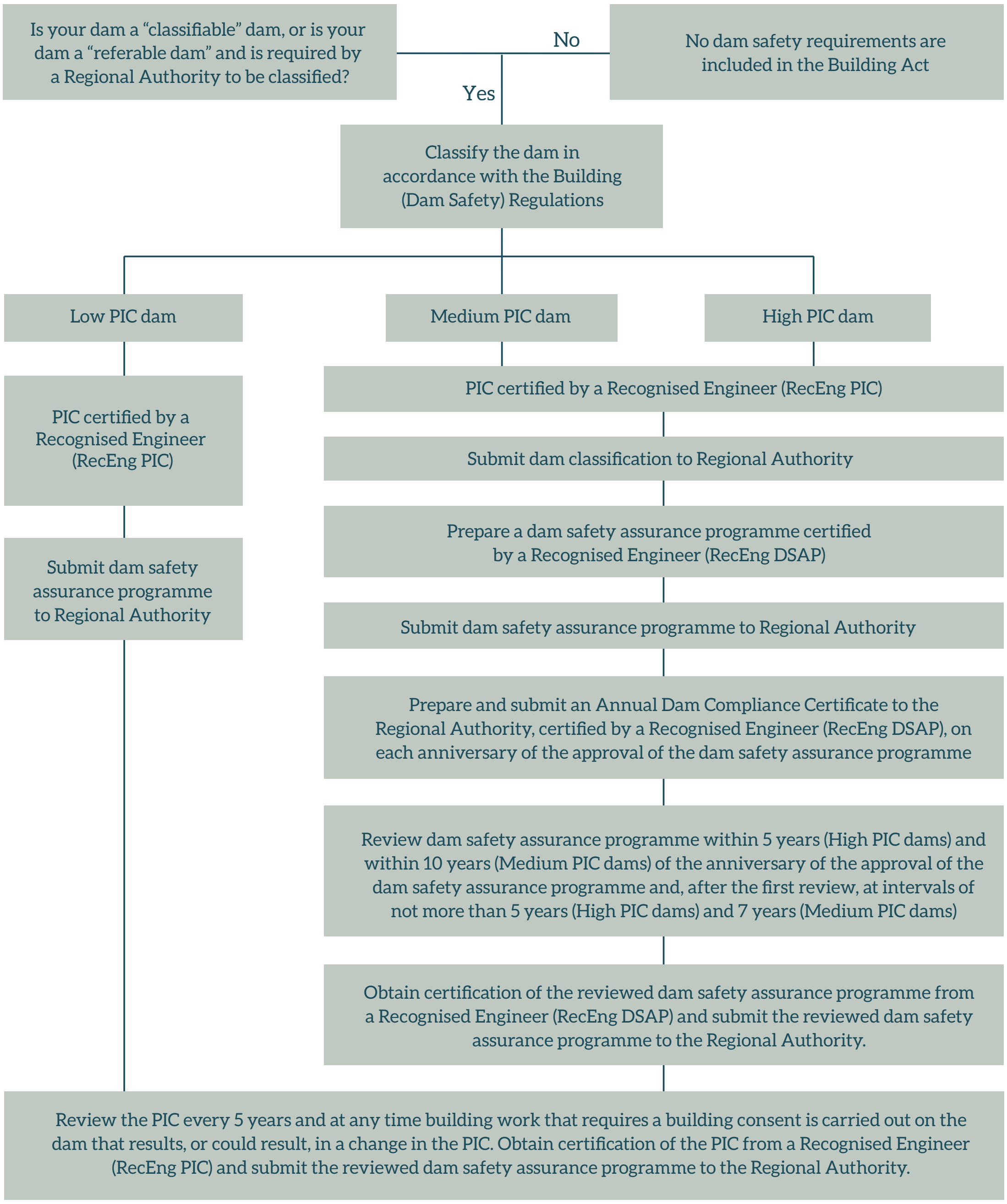

Figure 3.2: Dam Safety Requirements of the Act (2004) (Subpart 7)

3.6 The Building (Dam Safety) Regulations (2022) (Regulations (2022))

The Regulations (2022) enable the implementation of the legislation requirements relating to classifiable dams contained within the Act (2004). The Regulations (2022) include:

- A framework for the classification of dams, according to the potential downstream effects that would result from a dam failure. The framework is consistent with the intent of these Guidelines and has been adopted for the classification of dams (refer Module 2: Consequence Assessment and Dam Potential Impact Classification).
- Competency requirements for Recognised Engineers, defined in section 149 of the Act (2004) and sections 21–23 of the Regulations (2022).
- Criteria and standards for dam safety assurance programmes.
- Dam classification, dam safety assurance and annual compliance certificate requirements.

3.6.1 Classifiable dams

The Regulations (2022) were made on 12 May 2022 and come into effect on 13 May 2024 after which date Owners of classifiable dams will have:

- 3 months to submit, to Regional Authorities for approval, classifications for their existing classifiable dams (Form 1 of Schedule 3)
- 3 months after commissioning to submit, to Regional Authorities for approval, classifications for their new classifiable dams (Form 1 of Schedule 3).
- 12 months after the dam classification is approved to submit, to Regional Authorities, dam safety assurance programmes for their High PIC dams (Form 2 of Schedule 3)
- 24 months after dam classification is approved to submit, to Regional Authorities, dam safety assurance programmes for their Medium PIC dams (Form 2 of Schedule 3).
- To submit annual dam compliance certificates to Regional Authorities for their High and Medium PIC dams (Form 3 of Schedule 3).

Under the Act (2004), Low PIC dams only require classification and submission of the classification to the Regional Authorities, and 5 yearly review.

3.6.2 Dam safety assurance programme

The Regulations (2022) state that all Medium and High PIC dams are required to have a dam safety assurance programme which must contain effective procedures for:

- Dam and reservoir operations including training of operators, maintaining accurate records of reservoir operation, and maintaining functionality of the dam and reservoir.
- Frequency of surveillance, routine visual inspections, instrument monitoring, data evaluation, and reporting to the dam Owner.
- Requirements for Intermediate dam safety reviews. (IDSR).
- Comprehensive dam safety reviews (CDSR).
- Details of an emergency action plan.
- Inspection of appurtenant structures, including testing of gates and valves that contribute to reservoir safety.
- Recording, prioritisation, investigation, assessment, and resolution of dam safety deficiencies.

The Regulations (2022) imply that an acceptable dam safety assurance programme for a dam will be a single document that addresses the items listed above. While this may be appropriate for many Owners, it will be impractical for Owners of dams that incorporate complex facilities and for Owners with large portfolios of dams where dam safety assurance programmes are detailed across a number of documents (eg flood management procedures, maintenance and testing procedures for plant and equipment that fulfil dam safety functions, post-earthquake inspection procedures, and emergency preparedness procedures). In such cases, it would seem appropriate for Owners to submit summary documents that set out the elements included within their dam safety assurance programmes and refer to supporting documents that detail the processes and activities

3.6.3 Recognised Engineers

The Act (2004) requires the certification of dam classifications, dam safety assurance programmes and annual dam compliance certificates by Recognised Engineers. The Act defines a Recognised Engineer as someone who has no financial interest in the dam, is registered under the Chartered Professional Engineers of New Zealand Act 2002, and meets the competency requirements listed in the Regulations (2022). In carrying out their duties a Recognised Engineer is required to follow ethical principles such as not working outside their area of expertise or level of experience.

There are two categories of Recognised Engineer detailed in the Regulations (2022);

- PIC Recognised Engineer (RecEng PIC)
- DSAP Recognised Engineer (RecEng DSAP)A recognised engineer can be either, or both. Qualification and competency requirements for recognised engineers are detailed in Sections 21, 22 and 23 of the Regulations (2022). Assessment and registration of Recognised Engineers is managed by Engineering New Zealand. Additional information relating to Recognised Engineers, including how to become accredited and how to find a Recognised Engineer can be found on the **Engineering New Zealand website**

Key reference documents provided by Engineering New Zealand are:

- Recognised Engineer Competency Framework (Dam Safety) - Knowledge Base
- Recognised Engineer (Dam Safety) – Guide to Assessments
- Recognised Engineers – Liability Considerations

The Recognised Engineer role is limited to the certification of dam classifications, dam safety assurance programmes and annual dam compliance certificates. Recognised Engineers may, or may not, be suitably qualified and experienced to fulfil a dam design role or address a dam safety deficiency.

3.7 Compliance with the Act (2004) and the Regulations (2022)

As outlined in sections 3.5 and 3.6 above, the Act (2004) requires the certification of dam classifications and dam safety assurance programmes for High and Medium PIC dams by Recognised Engineers. The Regulations (2022) include a specified methodology for the determination of dam classifications, and criteria and standards for dam safety assurance programmes which provide a basis for Recognised Engineers to certify dam classifications, and certify dam safety assurance programmes.

The Act (2004) also requires the certification of annual dam compliance certificates for High and Medium PIC dams by a Recognised Engineer. The Regulations (2022) require the compliance certificate to be in a specific form and contain specific information, and certification that all procedures of the dam safety assurance programme have been complied with "except for any identified, minor items of non-compliance" (MBIE, 2023). The Recognised Engineer Competency Framework (Dam Safety) – Knowledge Base, available from Engineering New Zealand provides guidance on the types of information that are required in order for a Recognised Engineer to certify annual dam compliance certificates.

It is important for Owners to be aware that the Act (2004) and Regulations (2022) require substantive compliance. Accordingly, Owners should ensure that their programmes incorporate sufficient flexibility to accommodate possible delays in the completion of work activities. Possible disruptive factors could include extreme weather conditions, floods, staff leave, and the upgrading or repair of an item of equipment that fulfils a dam safety function.

4. Interpretation of legal requirements

The Ministry of Business, Innovation and Employment (MBIE) released the publication "Guide to complying with the Dam Safety Regulations" (MBIE (2023)) in November 2023; this was previously titled "Dam Safety Guidance, Guidance for dam owners, technical practitioners and Regional Authorities" and first published May 2022. The purpose of the document is to "...support the understanding of the Building (Dam Safety) Regulations 2022 (the regulations) for dam owners, technical practitioners and Regional Authorities, and to provide guidance to assist preparing for and fulfilling the requirements of the regulations". The MBIE document should be the first reference for any interpretation of the Act (2004) and Regulations (2022) and is available from MBIE's **Building Performance website**.

The following subsections provide some guidance to assist in the interpretation of specific aspects of the Act (2004) and the Regulations (2022). When interpreting legal requirements, it is important to recognise that the overriding intent of the legislation relating to dam safety is the protection of people and property downstream of the dam and that, accordingly, any assessment is made with appropriate consideration of the potential consequences.

Insoluble differences in the interpretation of terminology and the application of the Act (2004) or Regulations (2022) (say between an Owner and a Regional Authority) can be resolved using the MBIE determination process.

4.1 Dam measurement

Dam height and reservoir volume are required measurements under the Act (2004) for registering dams and to determine if they require classification. The overarching reason for measurement is to identify those dams with sufficient height and reservoir content to pose a risk to people, property and the environment downstream of the dam.

4.1.1 Dam height

The Act (2004) defines the height of the dam as "the vertical distance from the crest of the dam and must be measured:

(a) in the case of a dam across a stream, from the natural bed of the stream at the lowest downstream outside limit of the dam; and

(b) in the case of a dam not across a stream, from the lowest elevation at the outside limit of the dam; and

(c) in the case of a canal, from the invert of the canal.

The crest of the dam for the purposes of measuring height is also defined in the Act (2004) as

... the uppermost surface of a dam, not taking into account any camber allowed for settlement, or any curbs, parapets, guard rails, or other structures that are not part of the water-retaining structure; and for the avoidance of doubt, any freeboard is part of the water- retaining structure for the purposes of this definition.

The intent behind the legislative requirements is for the height to be determined in a straightforward and economic manner. It may be possible to measure the height of the dam in the field, or by reference to construction drawings showing the stream or river bed level.

4.1.2 Reservoir volume

Questions about measurement of the volume of a reservoir can arise when a dam volume is close to the threshold for dam classifications.

Bathymetry, pre-construction ground contours, or as- built ground contours (where fill for dam construction has been obtained from the reservoir area) provide the most accurate means for determining the volume of a reservoir. Anything less rigorous will only provide an estimate of the reservoir volume.

If bathymetry information, pre-construction ground contours or as-built ground contours are not available, a coarse estimate of the reservoir surface area and volume can be obtained using the simplified methodology included in MBIE (2023). The methodology is summarised in Figure 4.1; however, if the reservoir shape is complex and does not closely match a shape shown in Figure 4.1, other methods should be used to estimate the reservoir volume.

For all of the above methodologies, the volume of the reservoir should reflect the maximum hazard. Note that the dam crest definition included in the Act (2004) says:

... for the avoidance of doubt, any freeboard is part of the water-retaining structure...

This indicates that the crest of the dam should be used to determine the reservoir surface area, depth and volume.

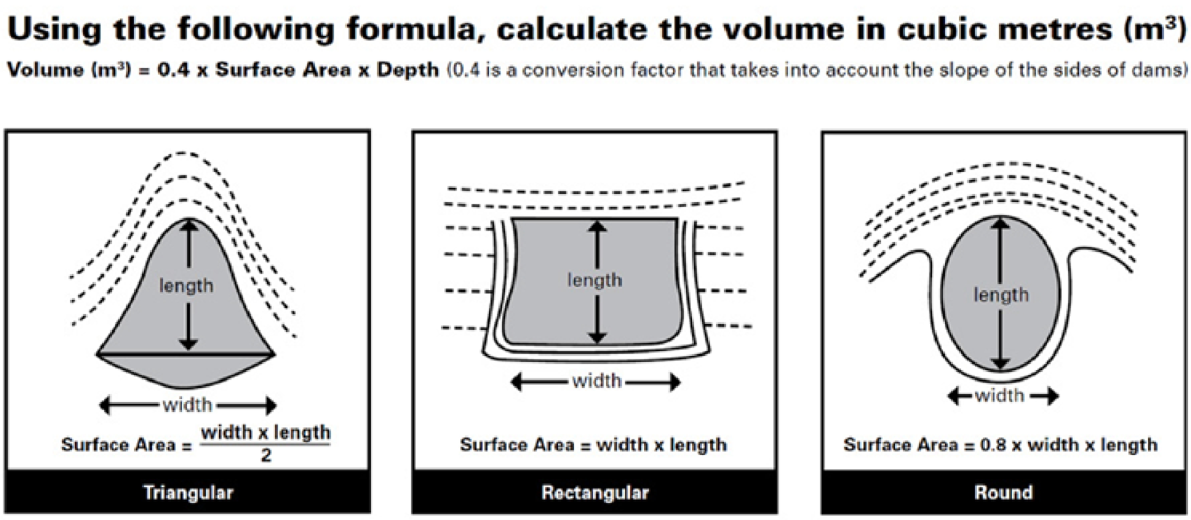

Figure 4.1: Simplified Calculation of Reservoir Volume. Source (MBIE, 2023)

4.2 Applying PICs to dam structures

The limits of a dam are usually defined by the natural country forming the abutments and the Act (2004) requires only one PIC per dam. This implies that different components of the same dam cannot have different PIC's. However, section 134BA of the Act does recognise the special case of a canal where different sections of a canal can have different PICs. Fill embankments between natural country where the canal is in cut, can be treated as separate dams, and therefore assigned different PICs that reflect the consequences of their failure. In addition, although unstated in the Act (2004), the two sides of a fill embankment on a canal could be assigned different PICs if the consequences of their failure were different (refer Module 2 of the Guidelines), but only if the failure of one side of the canal did not initiate a failure of the other side of the canal.

Secondary or saddle dams impounding the same reservoir as the main dam can have separate PICs to the main dam if the consequences of their failure are different (refer Module 2 of the Guidelines) and their failure does not initiate a failure of the main dam. Similarly, although unstated in the Act (2004), appurtenant structures separated from the dam could also have different PICs from the dam if the consequences of their failure were different and their failure did not initiate a failure of the dam.

Dam Owners should be aware that the PIC of a dam can change with time and that an increase in a dam's PIC could necessitate the completion of rehabilitation works to ensure the dam can safely accommodate increased loadings associated with the increased PIC. For example, community development downstream of a dam could increase its PIC from Medium to High and rehabilitation works may become necessary to ensure the spillway facility can safely accommodate the Probable Maximum Flood (PMF). Clearly, the costs of completing any necessary rehabilitation works would have to be met by the Owner.

The Act (2004) explicitly uses the PIC of a dam for the administration of legislation relating to dam safety assurance programmes and dam compliance certificates, and the identification of dangerous, earthquake-prone and flood-prone dams. It does not use the PIC of a dam to direct the scope of design activities necessary for obtaining a building consent. New Zealand has for many years used PIC as the basis for dam design and this is accepted national practice. It is also similar in principle to international practice. These Guidelines continue that tradition but the reader needs to clearly understand how the PIC is applied in dam design (refer to Module 3 of the Guidelines) in comparison to how it is applied in the legislation.

4.3 Identification of appurtenant structures

The Act (2004) defines an appurtenant structure as "…a structure that is integral to the safe functioning of the dam as a structure for retaining water or other fluid". This is interpreted to be primarily about the safe containment of the reservoir and the safe control of discharges from the reservoir and, as such, appurtenant structures are those structures at the dam site, other than the dam itself, that are designed and are required for the safe containment and control of the reservoir contents under all loading conditions.

Owners are required to include a list of all appurtenant structures in their dam safety assurance programmes for Medium and High PIC dams. The demarcation between appurtenant structures and other facilities at the dam, that are not essential for the retention of the reservoir and the safe operation of the dam, is therefore necessary.

Typical appurtenant structures include spillways, penstock intake structures, water intake structures, canal inlet structures, and low level outlet structures which have been designed to retain the reservoir and/ or fulfil a dam safety function (e.g. to discharge flood events or lower the reservoir level in a dam safety emergency). Appurtenant structures often incorporate mechanical and electrical plant (e.g. gates, valves, standby generators) for the controlled discharge or release of the reservoir contents, and equipment for the operation of the plant (e.g. power supplies, communication systems, control and protection systems).

Outlet facilities which do not retain the reservoir and are not required to fulfil a dam safety function are not appurtenant structures. If a pipeline or penstock is not required to fulfil a dam safety function and is protected by an upstream gate or valve that can close against flow, the pipeline or penstock is not an appurtenant structure; however, the upstream gate or valve facility is an appurtenant structure. If there is no upstream gate or valve facility then the pipeline or penstock and all components of the water passage down to the next control gate or valve is an appurtenant structure.

Buildings that house equipment that fulfils dam safety functions (e.g. PLCs, communication and control equipment, standby generators) are not appurtenant structures if adequate backup facilities are available for operation of the equipment. Where no backup facilities are available for operation of the equipment, the buildings that house the equipment are appurtenant structures.

For some water storage dams and tailings dams, diversion drains may fit the appurtenant structure definition if they have a dam safety function.

Clearly, Owners need to carefully consider the specific arrangements at each dam site and identify all structures that fulfil dam safety functions. The overriding consideration must be the safe retention and control of the reservoir contents, which is not necessarily the same as normal operation of the facility.

Glossary

The following definitions, which relate to terms used in this module of the Guidelines, are extracted from the Act (2004) and the Regulations (2022).

Appurtenant Structure
"In relation to a dam, means a structure that is integral to the safe functioning of the dam as a structure for retaining water or other fluid".

Classifiable Dam
"For the purposes of the Act, classifiable dam means a dam that-

a) has a height of 4 or more metres and stores 20,000 or more cubic metres volume of water or other fluid; or

b) has a height of 1or more metres and stores 40,000 or more cubic metres volume of water or other fluid"

Crest of a Dam
"In relation to a dam, means the uppermost surface of a dam, not taking into account any camber allowed for settlement, or any curbs, parapets, guard rails, or other structures that are not part of the water-retaining structure; and for the avoidance of doubt, any freeboard is part of the water- retaining structure for the purposes of this definition".

Dam –

a) "means an artificial barrier, and its appurtenant structures, that –
   - (i) is constructed to hold back water or other fluid under constant pressure so as to form a reservoir; and
   - (ii) is used for the storage, control, or diversion of water or other fluid.

(b) includes –
   - (i) a flood control dam; and
   - (ii) a natural feature that has been significantly modified to function as a dam; and
   - (iii) a canal; but

(c) does not include a stopbank designed to control floodwaters".

Dangerous Dam
"A dam is dangerous for the purposes of this Act if the dam:

a) is a high potential impact dam or a medium potential impact dam; and

b) is likely to fail –
   - i) in the ordinary course of events; or
   - ii) in a moderate earthquake (as defined in the regulations); or
   - iii) in a moderate flood (as defined in the regulations)".

Earthquake-Prone Dam
"A dam is an earthquake- prone dam for the purposes of this Act if the dam:

(a) is a high potential impact dam or a medium potential impact dam; and

(b) is likely to fail in an earthquake threshold event (as defined in the regulations)".

Earthquake Threshold Event

"For the purpose of section 153A of the Act (meaning of earthquake-prone dam and flood-prone dam),-

(a) in relation to a high potential impact dam, an earthquake that would result in ground shaking, at the site of the dam, at an intensity with an AEP of 1 in 500 (determined by normal measures of acceleration, velocity, and displacement) but not less than the 1 in 500 AEP shaking determined using a seismic hazard factor (Z factor) of 0.10; and

(b) in relation to a medium potential impact dam, an earthquake that would result in ground shaking, at the site of the dam, at an intensity with an AEP of 1 in 250 (determined by normal measures of acceleration, velocity, and displacement) but not less than the 1 in 250 AEP shaking determined using a seismic hazard factor (Z factor) of 0.10"

Flood-Prone Dam

"A dam is a flood-prone dam for the purposes of this Act if the dam:

(a) is a high potential impact dam or a medium potential impact dam; and

(b) is likely to fail in a flood threshold event (as defined in the regulations)".

Flood Threshold Event

(a) "in relation to a high potential impact dam, a flood that would result in water or other fluid flowing, into the reservoir formed by the dam, at a flow rate with an AEP of 1 in 500; and

(b) in relation to a medium potential impact dam, a flood that would result in water or other fluid flowing, into the reservoir formed by the dam, at a flow rate with an AEP of 1 in 250".

Large Dam

"Means a dam that has a height of 4 or more metres, and holds 20,000 or more cubic metres volume, of water or other fluid".

Lifeline Utilities

As defined in the Civil Defence and Emergency Management Act (2002): "means an entity named or described in Part A of Schedule 1, or that carries on a business described in Part B of Schedule 1". A list of lifeline utilities is included in Part A of Schedule 1 in the Act. Part B of Schedule 1 in the Act includes entities that generate electricity for distribution through a network and entities that supply or distribute water as "lifeline utilities".

Moderate Earthquake

(a) "in relation to a high potential impact dam, means an earthquake that would result in ground shaking, at the site of the dam, at an intensity with an AEP of 1 in 100 (determined by normal measures of acceleration, velocity, and displacement) but not less than the 1 in 100 AEP shaking determined using a seismic hazard factor (Z factor) of 0.10; and

(b) in relation to a medium potential impact dam, means an earthquake that would result in ground shaking, at the site of the dam, at an intensity with an AEP of 1 in 50 (determined by normal measures of acceleration, velocity, and displacement) but not less than the 1 in 50 AEP shaking determined using a seismic hazard factor (Z factor) of 0.10."

Moderate Flood

(a) "in relation to a high potential impact dam, means a flood that would result in water or other fluid flowing into the reservoir formed by the dam at a flow rate with an AEP of 1 in 100; and

(b) in relation to a medium potential impact dam, means a flood that would result in water or other fluid flowing into the reservoir formed by the dam at a flow rate with an AEP of 1 in 50."

Population at Risk
"means the number of people likely to be affected by an uncontrolled release of all or part of the stored water or other fluid due to a failure of the dam (assuming that no person takes any action to evacuate)"

Recognised Engineer
"In relation to a dam, means an engineer who meets the requirements in section 149 of the Building Act. Section 149 of the Building Act states that -

(1) A recognised engineer is an engineer who –

  (a) has no financial interest in the dam concerned; and

  (b) is registered under the Chartered Professional Engineers of New Zealand Act (2002); and

  (c) has –

    (i) the prescribed qualifications; and

    (ii) the prescribed competencies.

(2) In subsection (1)(a), financial interest does not include –

(a) involvement in the construction of the dam as a fully paid engineer; or

(b) entitlement to a fee for undertaking an audit".

Note – Refer to Sections 21, 22 and 23 of the Building (Dam Safety) Regulations for the prescribed qualifications and competencies referred to in subsection 1(c) of Recognised Engineer.

Regional Authority
(d) regional council

(e) a unitary authority.

Regional Council
As defined by section 5(1) of the Local Government Act 2002.

Territorial Authority
A city council or district council named in Part 2 of Schedule 2 of the Local Government Act 2002

Unitary Authority
As defined by section 5(1) of the Local Government Act 2002

References

New Zealand Legislation:

- Building Act (2004), version as at 23 August 2023.
- Building Amendment Act (2013), reprint as at 1 January 2015.
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- Building Regulations (1992), version as at 24 August 2023.
- Civil Defence Emergency Management Act (2002), version as at 24 August 2023.
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MODULE 2
ASSESSMENT OF DAM FAILURE CONSEQUENCES AND POTENTIAL IMPACT CLASSIFICATION

Abstract

Dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, operation, assessment and rehabilitation of dams in New Zealand are included in the Parent Document. The Parent Document also includes a glossary of terms used in these Guidelines. This module principally details the system and constituent methods for assessment of dam-break flood hazard consequence assessments and classification of dams in New Zealand.

Assessments of dam-break flood hazard consequences and classification of dams are essential to ensure that appropriate performance criteria are used in the design and safety evaluation of dams, and that an appropriate level of care is reflected in their operational procedures. Furthermore, dam-break flood hazard and consequence assessments assist Owners in emergency planning and preparedness, in understanding the risks posed by the presence of dams, and in developing risk reduction measures to address unacceptable risks.

A dam's classification, termed its Potential Impact Classification (PIC), is purely a function of the consequences of a hypothetical failure breach or other uncontrolled release of the stored contents. It has no correlation with the probability of the dam failing or experiencing a dam safety incident.

In broad terms, the process for PIC requires the assessment of the damage level to community buildings, historical and cultural places, critical or major infrastructure and the environment, as well as the potential life safety impacts to people who may be present within the flood inundation zone resulting from a hypothetical dam failure or dam safety incident. The combination of the maximum overall damage level across all damage level categories and the potential life safety impact is used to determine the PIC of a dam. The potential damage levels and life safety impacts can change with time and, given the long life expectancy of most dams, their PICs need to be reviewed periodically to ensure the classification remains consistent with the potential hazard.

This module includes limited discussion on the role of Regulators in respect of dam safety. Reference should be made to Module 1: Legal Requirements for a more complete description of their role and responsibilities.

Notice to reader

While this module has been configured to be, as much as practicable, self-contained from a technical perspective, the reader should be conversant with the principles, objectives and limitations expressed in the Parent Document prior to considering the information provided in this or any other individual module.

Document history

Release	Date	Released with
Original	May 2015	Parent and all modules
2023	December 2023	Updates to Parent and Modules 1, 2 and 5

Contents

1. Introduction

1.1 Principles and objectives

Assessment of dam-break flood hazard consequences and classification of dams are essential to ensure that appropriate performance criteria are used in the design and safety evaluation of a dam, and that an appropriate level of care is reflected in operational procedures. Furthermore, dam-break flood hazard and consequence assessments assist Owners in emergency planning and preparedness, in understanding the risks posed by the presence of the dam, and in developing risk reduction measures to reduce any unacceptable risks. Principle 1 in the Parent Document states:

The consequences of a dam failure should be understood so that appropriate design, construction and management actions can be applied to protect people, property and the environment.

Dams store water or other fluid at a height elevated above downstream topography and therefore have the potential for uncontrolled release of their contents in the unlikely event of either a component failure or a dam failure[1]. Dams therefore pose a potential hazard to people, buildings, infrastructure, historical and cultural places, and the environment in the downstream area that could be affected by the release of stored contents. In addition, dam failure can have a range of other impacts such as reputational and financial impacts on the dam owner, decline in economic activity and output within the flood-affected areas, impacts on the wellbeing of people and disruption to the flow of goods and services.

Generally, where the consequences of a dam failure are greater, the design, operational and maintenance processes associated with the dam should be more robust and resilient to reduce the likelihood of dam failure.

The objectives of this module are to provide guidelines to support a consistent assessment of dam break flood hazard, consequence and classification of dams in New Zealand, and a consistent interpretation of requirements under the Building (Dam Safety) Regulations (2022).

The primary focus of this module is on dam-break flood hazard and consequence assessment for water storage dams. Specific guidance related to breach analysis for tailings dams and dams with highly sedimented reservoirs is provided in Section 5.9 although the general principles of dam-break flood hazard and consequence assessment still apply to such facilities.

1.2 Dam classification system

A dam classification system that reflects the consequences of a dam failure, together with engineering design and assessment criteria appropriate to the hazard posed by the dam, provides the framework for establishing an appropriate level of safety for a dam.

A dam's classification is termed its Potential Impact Classification (PIC). Other countries may use terms such as hazard category, hazard rating, or consequence category. However, the objective of classifying a dam according to its potential impact, hazard or consequence, is consistent. A dam's classification is purely a function of the consequences of a hypothetical failure breach or other uncontrolled release of the stored contents. It has no correlation with the probability of the dam failing or experiencing a dam safety incident.

Legal requirements for the classification of dams in New Zealand are described in Module 1: Legal Requirements.

1. In these Guidelines, the terms 'dam failure', 'dam-break' and 'dam breach' are used interchangeably, but in all cases relate to an uncontrolled release of water, or other fluid, from a reservoir through failure of a dam or its appurtenant structures, as a result of a structural failure or deficiency.

1.3 Breach scenarios and incremental consequences

The breach scenarios for a dam vary depending on the nature of its design, construction, hazards specific to the site (refer Module 3: Investigation, Design and Analysis) and the conditions under which it may fail. For example, a dam failure occurring under dry weather conditions (when the reservoir is full and under normal inflow conditions) is commonly referred to as a 'sunny day failure', while a failure occurring under flood inflow conditions is referred to as a 'rainy day failure'. Refer to Section 2.3.3 for further discussion on 'sunny day' and 'rainy day' failure scenarios.

The incremental consequences of potential dam failure, which are the consequences directly attributable to dam failure, are the key consideration in determining a dam's PIC. These consequences are assessed relative to a base 'no dam failure' condition. For a 'sunny day' dam-break flood, the incremental consequences are the total damages incurred as a result of that hypothetical occurrence. For a 'rainy day' dam-break flood, the incremental consequences are based on the total damages incurred by the hypothetical dam-break flood less any damages incurred by the base flood without dam failure.

Dam classification should consider both sunny day and rainy day breach scenarios which are appropriate to the particular dam, and the PIC determination should be based on the scenario that predicts the greatest magnitude of incremental adverse consequence. The PIC should be determined separately for each scenario. The PIC assigned to the dam should be based on the scenario that predicts the greatest magnitude of incremental consequences.

1.4 Scope of module

The module addresses:

- The assessment of dam-break flood hazards and consequences (Section 2)
- The determination of a dam's Potential Impact Classification to reflect the consequences of potential dam failure (Section 3).
- The determination of Potential Impact Classification of subsidiary dams, canals and appurtenant structures (Section 4).
- Other issues and factors that should be considered for dam-break flood hazard and consequence assessments (Section 5).

Figure 1.1 presents an overview of the dam classification process as outlined in this module.

A list of reference documents cited is included in Section 6 at the end of the module to assist owners and their technical advisers in the assessment of dam failure consequences and the classification of dams.

Where specific sources of information have been cited in this module, it should be understood that these sources may be revised, updated or superseded by advancements in knowledge and practice. Technical advisers should use as required the latest and most appropriate sources of information aligned with these originally cited sources.

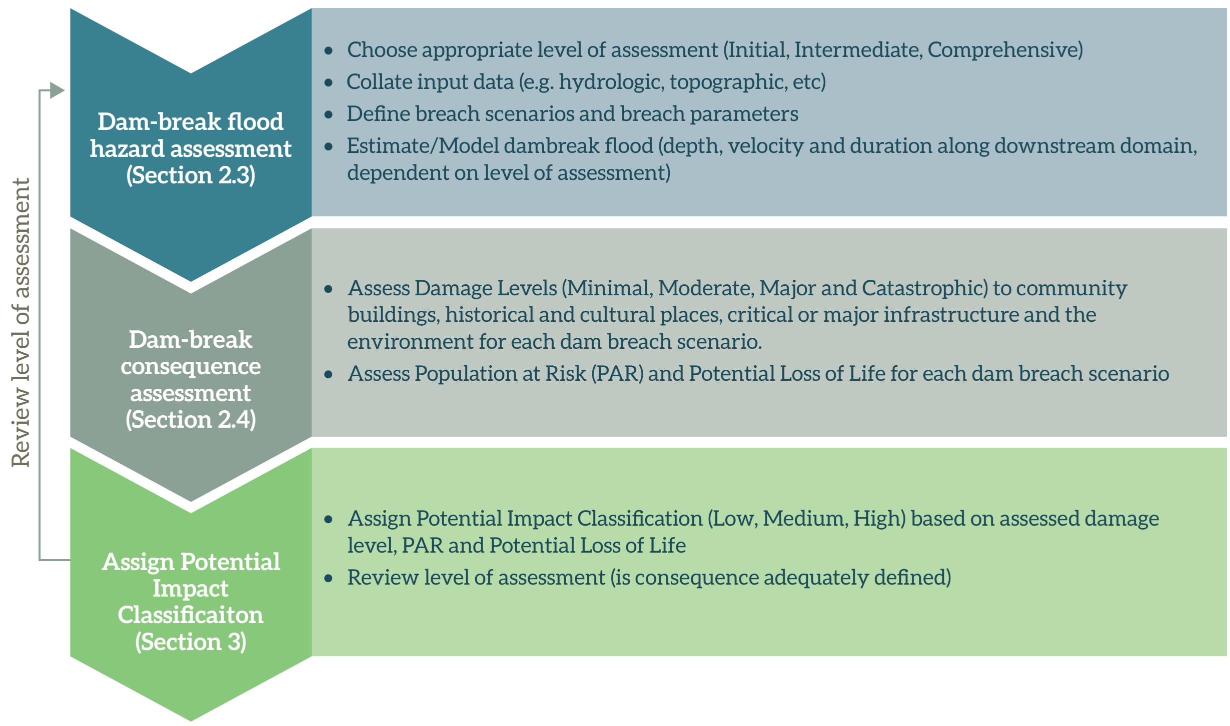

Figure 1.1: Overview of the dam classification process

2. Dam-break flood hazard and consequence assessments

2.1 Overview

Dam-break flood hazard and consequence assessments by experienced and qualified Technical Advisors are key items required to determine the Potential Impact Classification of a dam.

Dam-break flood hazard and consequence assessments are also useful in:

- Understanding the potential consequences and hazard from a hypothetical dam failure (refer Principle 1 in the Parent Document).
- Emergency planning and preparedness, by identifying the potential consequences of dam failure and response actions to avert failure or mitigate the consequences of failure (refer Module 6: Emergency Preparedness).
- Providing input on the consequences of failure for risk assessment studies or business risk determinations (refer Module 7, Section 4.5).

Guidance for completing dam-break flood hazard and consequence assessments, including inputs, procedures and outputs is provided in the following sub-sections.

Dam-break flood hazard and consequence assessments should be carried out for worst case 'sunny day' and 'rainy day' failure scenarios for the main dam to determine a dam's PIC. However, in addition to this, similar assessments may need to be carried out for a hypothetical failure of a portion of the main dam other than the maximum section, a subsidiary reservoir retaining structure (e.g. saddle dam, thrust block) or an appurtenant structure (e.g. spillway). Refer to Section 4 for further guidance on PIC determination for such structures.

2.2 General considerations

2.2.1 Levels of assessment

Procedures for evaluating dam break flood inundation extents and the consequential impacts downstream for a hypothetical dam failure can vary from engineering judgement to sophisticated methods of analysis. As such, there are many potential choices when performing dam-break flood hazard and consequence assessments to determine a dam's PIC or to develop dam-break flood inundation maps for emergency preparedness plan documents. Because dam-break flood hazard and consequence assessments will not always require the most sophisticated tools available, different levels of assessment can be completed (initial, intermediate or comprehensive).

In general, the level of dam-break flood hazard and consequence assessment should correlate with the scale and complexity of the dam and the nature of the downstream area potentially impacted by a hypothetical dam breach flood. Assessment of dams that are anticipated to have a Medium or High PIC and located upstream of populated areas or highly developed floodplains should use more sophisticated modelling and analysis tools to properly assess the consequences of a dam failure. Assessment of dams that are anticipated to have a Low PIC and are situated upstream of sparsely populated areas could rely on more approximate assessment methods.

In some circumstances it may be self-evident that a particular dam has a High PIC (for example a very large dam upstream of a densely populated area). A dam owner may elect to take a presumptive approach and assign a High PIC to their dam without completion of a formal dam-break flood hazard and consequence assessment. However, even if this approach is followed, it is highly likely that a dam-break flood hazard and consequence assessment will be required for other purposes. For example, to support the development of an Emergency Action Plan (refer to Module 6), or to facilitate the selection of the Inflow Design Flood (refer to Module 3, Section 4.2).

Figure 2.1 provides an overview of the selection process for different levels of assessment for a dam-break flood hazard and consequence assessment process. The following sub-sections provide a general discussion of the different levels of assessment (initial, intermediate or comprehensive). Section 2.2.2 provides an overview of the general process for an initial assessment and Section 2.2.3 for both intermediate and comprehensive levels of assessment.

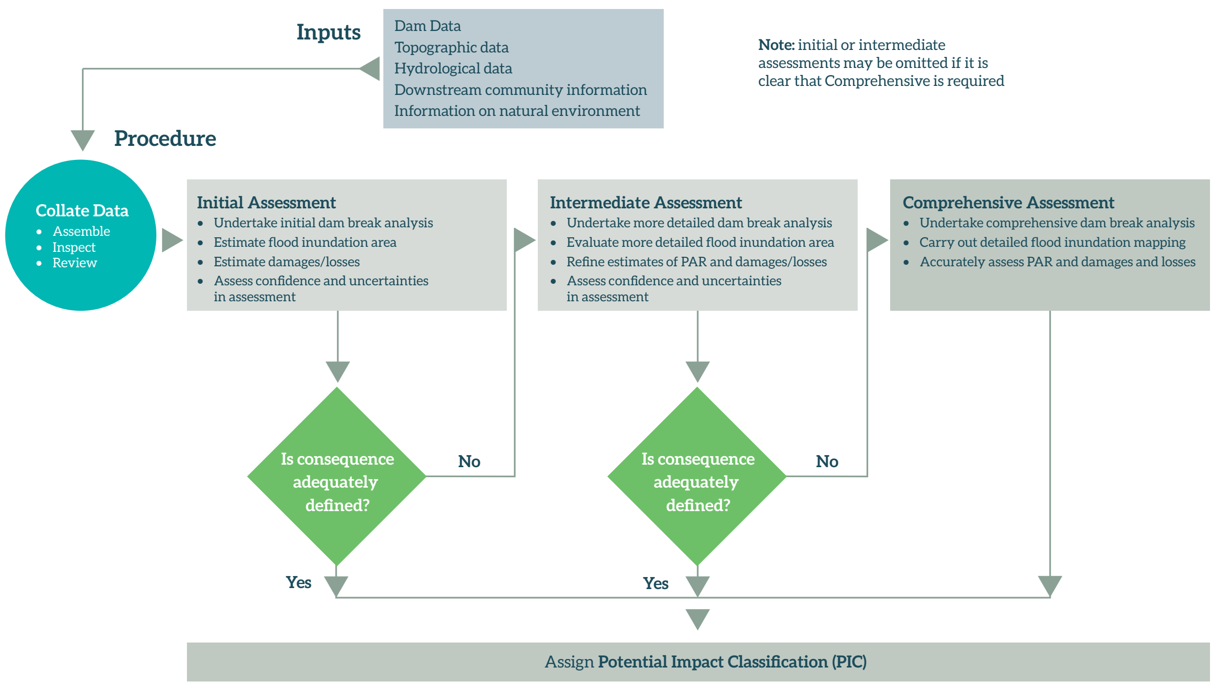

Figure 2.1: Overview of the selection process for different levels of assessment for a dam-break flood hazard and consequence assessment

2.2.1.1 Initial

An initial dam-break flood hazard and consequence assessment may be sufficient to determine the PIC of a dam from existing knowledge and information. This could be from an estimation of the magnitude of a potential dam-break flood supported by basic calculations to determine the peak breach outflow, and use of topographic maps and aerial photographs to evaluate the flood path and its potential impacts on people, buildings, infrastructure, historical and cultural places, and the environment.

Such an assessment should be completed conservatively and is often restricted to the consideration of a hypothetical, conservative potential failure mode that results in dam failure. However, the initial assessment may raise uncertainties (e.g. in open flat areas and where buildings, infrastructure or occupied locations are close to the edge of inundation) that can only be resolved by undertaking an intermediate or comprehensive assessment.

Initial assessments can be justified for dams when there is little doubt as to the dam's PIC (in terms of potential failure impact to the downstream Population at Risk, Potential Loss of Life and damage level to community buildings, critical or major infrastructure, historical or cultural places and the environment). The cost of a higher level of assessment may be deemed unnecessary in relation to the potential benefits of a higher level of assessment.

Initial assessments may also be appropriate as a first level screening for dams anticipated to have a Medium or High PIC, and prior to completion of an intermediate or comprehensive assessment which would be needed to develop flood inundation maps for emergency preparedness plan documents.

2.2.1.2 Intermediate

An intermediate dam-break flood hazard and consequence assessment requires a more quantitative assessment of the magnitude of the potential dam-break flood hazard and the downstream consequences than that required for an initial assessment. An intermediate level assessment should include the estimation of breach parameters to a greater level of detail (e.g. considering breach size and development time appropriate to the dam type and the nature of the foundation) and some dam-break flood routing, usually with the aid of a computational hydraulic model, to establish the likely extent of downstream flood inundation from which the Population at Risk, Potential Loss of Life and the damage level to community buildings, critical or major infrastructure, historical or cultural places and the environment.

However, if there continues to be a lack of certainty or confidence in the results of an intermediate assessment, then a comprehensive assessment should be completed. For example, a comprehensive assessment may be required to determine the PIC where the results of an intermediate assessment indicate that the PIC is on the borderline between Low and Medium, or Medium and High.

2.2.1.3 Comprehensive

A comprehensive assessment is typically required for dams that have high consequences, and therefore require detailed consequence outputs for emergency planning and preparedness, or the development of risk reduction measures. A comprehensive assessment may also be required to establish the PIC of a dam where it is borderline between Low and Medium, or Medium and High.

The process for a comprehensive dam-break flood hazard and consequence assessment is similar to that for an intermediate assessment. However, the completion of a comprehensive assessment usually requires the identification and consideration of potential failure modes (refer Section 2.2.5), dam-break flood routing, mapping of the extent of flood inundation, and evaluation of the peak flood depth, flow velocity, time of flood arrival, time of flood peak and inundation duration at key locations (e.g. buildings and infrastructure). It would usually also require the completion of a detailed dam-break consequence assessment, unless the PIC was clearly above the threshold for a High PIC dam and detailed information on the dam-break consequence was not required.

2.2.2 Process for initial assessments

The following process should be considered for initial dam-break flood hazard and consequence assessments:

- Collate readily available and existing information on the dam, downstream topographic data and hydrological data.
- Estimate the peak dam breach outflows for sunny day and rainy day failure scenarios as appropriate to the dam type (e.g. using Froelich (2016a) approach for embankment dams).
- Estimate the resulting downstream flood inundation extent using engineering judgement and inspection of downstream topographic maps and aerial photographs, supported by limited hydraulic calculations as required.
- Estimate the Population at Risk, Potential Loss of life and damage levels to the categories listed in Table 2.2, based on general information available from existing topographic maps, inspection of aerial photographs and supplemented with local knowledge.

- Population at Risk and Potential Loss of Life are estimated within broad range categories (refer to Table 2.6) based on judgement which considers the dam-break flood flow characteristics at locations where the presence of people can be reasonably expected. Note that where Population at Risk and Potential Loss of Life estimates do not clearly fit within one of the categories listed in the PIC determination tables, further assessment at an intermediate or comprehensive level would normally be required.
- Assess the dam PIC based on the estimated Population at Risk, Potential Loss of Life and assessed damage levels.
- Identify and communicate any uncertainties that may need to be resolved by an intermediate or comprehensive assessment.

2.2.3 Process for intermediate and comprehensive assessments

The following process should be considered for intermediate and comprehensive dam-break flood hazard and consequence assessments:

- Collate information relevant to assess the effects of a potential dam failure.
- Identify and build an understanding of the typical initiating events and mechanisms by which the dam could fail (potential failure modes should be identified and considered for a comprehensive level of assessment).
- Estimate the dam breach characteristics and the magnitude of the breach outflow flood (peak discharge, time to peak discharge, and time to empty the impounded reservoir). If the various potential failure modes result in different locations or types of breach, it may be necessary to estimate breach characteristics for more than one breach. The steps outlined below apply for each selected breach.
- Evaluate the movement and spread of the flood released by a dam failure and the resulting downstream inundation (flood travel times, peak flow depths and velocities, and the extent of flood inundation).
- Estimate damages to buildings, critical or major infrastructure, historical and cultural places and environmental damages (refer guidance in Section 2.4.2).
- Estimate the Population at Risk and the Potential Loss of Life (refer guidance in Section 2.4.3).
- Assess the dam PIC based on the estimated Population at Risk, Potential Loss of Life and assessed damage levels (refer guidance in Section 3).
- Communicate the potential consequences in an easily understood form for use by relevant parties for the particular dam as needed (such as the dam Owner, Regulators, and emergency agencies (e.g. Civil Defence)).

These processes are discussed more fully in the following sections. FEMA (2013) and Appendix A of ANCOLD (2012) provide further information on methods for undertaking the differing levels of dam-break flood hazard and consequence assessment.

2.2.4 Collation of relevant data

Relevant data should be collated for a dam-break flood hazard and consequence assessment including information on:

- The dam and its impounded reservoir.
- The topography downstream of the dam.
- Hydrological data.
- The downstream community.
- Historical and cultural places.
- The natural environment.

Table 2.1 summarises the information in each of the above categories that may be required to be collated. The level of detail required for this information will be influenced by the level of dam-break flood hazard and consequence assessment being undertaken.

Table 2.1: Information that may be required for Dam-Break Flood Hazard and Consequence Assessments

Type of data	Specific information
Dam and reservoir	• Layout of reservoir and/or river system • Reservoir capacity (including reservoir depth/storage information if available) • Reservoir bathymetry • Layout of dam and appurtenant structures • Type of dam (construction materials) • Dam dimensions (maximum height, crest width and length, crest level) • Spillway characteristics, dimensions, crest level and flood capacity • Low-level outlet dimensions, layout, inlet and outlet invert levels • Dam foundation conditions • Dam history (age, level of engineering in original design, operational history including any dam safety incidents/issues) • Dam potential failure modes (where they exist, or develop as appropriate) • Breach characteristics for each relevant potential breach
Topographic data	• Characteristics of downstream valley (shape and slope) or plain (slope and direction of slope) • Maps (appropriate scale topographic maps) • Topographic data in digital terrain model form (primarily for intermediate and comprehensive level assessments) • Surveyed river / stream cross-section data • Potential controls on downstream flood flows (bridges, culverts, road embankments, other dams, gorges, and vegetation) • Downstream dams and reservoirs • Major downstream tributaries
Hydrological data	• Hydrological characteristics of catchment • Recorded rainfall or streamflow data • Flood inflow estimates for reservoir • Flood estimates for downstream tributaries • Historic flood information (levels and flows)
Downstream community	• Locations and sizes of downstream centres of population • Temporal patterns of population (itinerants) • Locations and types of community facilities (schools, hospitals, other institutions, residential dwellings, industrial, commercial and retail areas, camping areas) • Potentially affected infrastructure (e.g. roads, bridges, airports, railway lines, water, flood protection assets, power and communication systems) • Emergency service facilities (Police, Fire, Ambulance, Civil Defence) • Hazardous substance processing or storage facilities • Land use and development types
Cultural places	• Historical or cultural places listed on the New Zealand Heritage List / Rārangi Kōrero • Historic sites listed on the Department of Conservations National Register
Natural environment	• Vegetation type and cover • Waterways and wetlands • Rare or endangered species habitats • River morphology • Other features of environmental significance (national parks, conservation areas, regional parks, reserves)

2.2.5 Potential dam failure modes

An understanding of the initiating events and mechanisms that can lead to a dam failure (potential failure modes) is important for dam-break flood hazard and consequence assessments. The potential failure modes for a dam will influence the nature of breach development and the conditions under which downstream consequences of failure are evaluated. The identification and assessment of potential failure modes is addressed in Module 3: Investigation, Design and Analysis and Module 5: Dam Safety Management.

Detailed consideration of the most credible potential failure modes for a given dam can be used to obtain an improved understanding of the likely breach characteristics and development of the breach outflow hydrograph. For example, the breach characteristics and outflow hydrograph for a failure of a concrete dam would be different from that for a failure of an embankment dam. There are many and varied dam arrangements, each with their own unique features that require careful consideration when identifying potential failure modes and determining likely breach characteristics and resulting outflow hydrographs.

Credible potential failure modes for a dam should be used to develop 'sunny day' and 'rainy day' dam failure scenarios. In general, the potential failure modes that lead to the largest downstream flooding, for both the 'sunny day' and 'rainy day' scenarios, should be selected.

2.2.6 Cascade failure

If one or more dams are located downstream of the dam being analysed, the dam-break flood hazard assessment should consider the potential for a cascade failure where the failure of the upstream dam could cause overtopping and failure of the downstream dam(s). In some cases, this can have a 'domino' effect causing multiple dams in a chain or 'run-of-river' system to fail.

As an example, in Figure 2.2 the failure of Dam C could cause a cascade failure of Dams D and E. In such a situation the assessment of the consequences of dam failure should include the cumulative effects of any downstream dam failures. Conversely, there are situations where the existence of a downstream dam can result in reduced downstream consequences. This occurs where the dimensions of the downstream reservoir (including the available freeboard at the downstream dam) are such that the reservoir provides sufficient attenuation, or even complete containment, of the discharge resulting from an upstream dam failure. As an example, in Figure 2.2 the discharge from failure of Dam B could be contained within the downstream reservoir impounded by Dam C, without a failure of Dam C, if the reservoir contained sufficient flood storage above normal reservoir operating level.

Ultimately, each dam and its upstream and downstream environment will be unique and should be reviewed on its own merits.

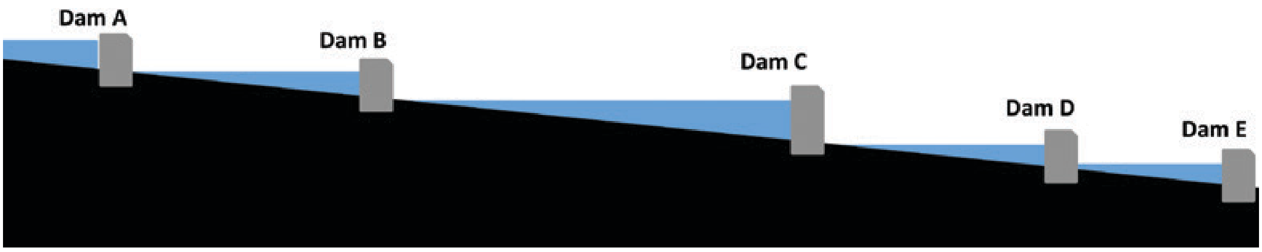

Figure 2.2: Example multi-dam system with the potential for a cascade failure

2.2.7 Records/documentation

Both dam-break flood hazard and consequence assessment, involve elements of judgement. It is therefore important that the methods and rationale used in the estimation methodologies are thoroughly documented with sufficient evidence to justify and ensure transparency of the outputs.

2.3 Dam-break flood hazard assessment

2.3.1 Process

Figure 2.3 provides an overview of the dam-break flood hazard assessment process. The following sub-sections provide guidelines for each step in the process. These sub-sections relate primarily to dam-break flood hazard assessments for water retaining dams. Refer to Section 5.9 for discussion on tailings storage facilities.

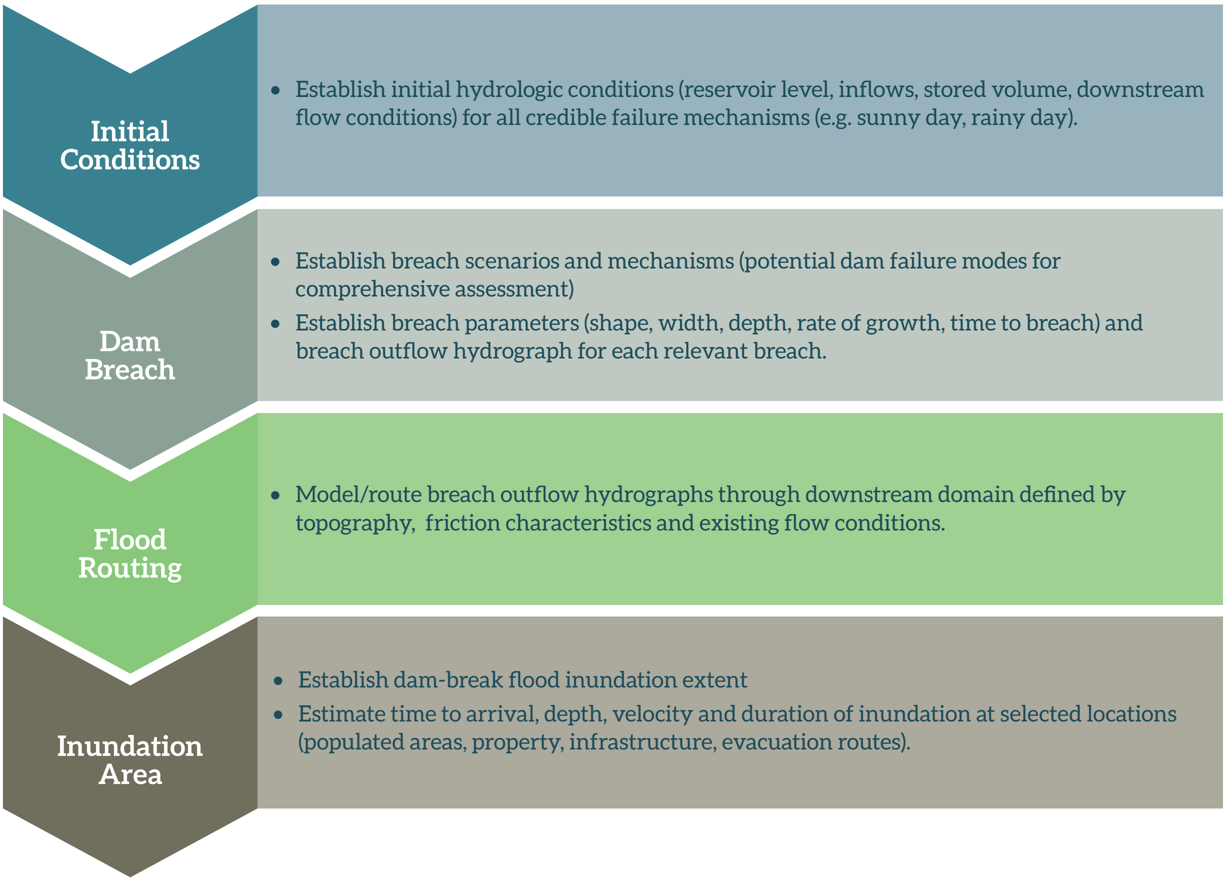

Figure 2.3: Overview of the Dam-Break Flood Hazard Assessment Process

2.3.2 Purpose

A dam-break flood hazard assessment evaluates the rate of release of the reservoir storage volume through a hypothetical breach and estimates the movement and spread of the resulting flood wave downstream. The objective of the assessment is to determine the characteristics of the dam-break flood wave and the likely downstream effects of a hypothetical dam failure. The flood wave characteristics of most interest are the maximum extent of downstream flood inundation, the time of flood arrival, the time to flood peak, the peak flood depth, the peak flow velocity, the maximum value of the product of depth and velocity and the duration of inundation at key locations. The effects of greatest interest are to people (including potential life loss) and the damage to buildings, infrastructure, historical and cultural places, and the environment.

The dam-break flood hazard assessment should extend to a location downstream where the effects of a dam-break flood would be negligible. Refer to Section 5.4 for further discussion on selection of the downstream extent of a dam-break study.

2.3.3 Initial hydrologic conditions

Evaluation of the rate of release of the reservoir storage volume through a hypothetical breach (the breach outflow hydrograph) and the movement and spread of the resulting dam break flood wave (flood wave routing) requires the evaluation of initial hydrologic conditions, and the estimation of likely breach size and its rate of development. The key hydrologic parameters to consider are reservoir level, reservoir inflow, stored volume, and downstream flow conditions.

For all assessments the following two failure modes should typically be considered (except for flood detention dams, as outlined in Section 5.7):

- 'Sunny day' failure – the dam failure occurs when the reservoir is full and under normal inflow conditions.
- 'Rainy day' failure – the dam failure occurs under flood inflow conditions.

For comprehensive assessments, each identified credible potential failure mode and the specific breach characteristic of those potential failure modes should be assessed to develop the worst case 'sunny day' and 'rainy day' dam failure scenarios.

It is important that both 'sunny day' and 'rainy day' scenarios are considered as there may be a significant difference in the consequence arising from each that is not immediately obvious. For example, while flood depths and extent are likely to be greater for a 'rainy day' failure, downstream communities may be more exposed to the hazard resulting from a 'sunny day' failure because people may be more likely to be present around watercourses (e.g. for recreational purposes) at the time of failure than under 'rainy day' failure conditions. As noted in Section 1.3, the incremental increase in flooding due to a hypothetical 'rainy day' dam-break flood may be lesser, or have lesser consequences than the flood resulting from a hypothetical 'sunny day' dam failure.

Reservoir inflows and levels, and downstream watercourse flows, should be those most likely to occur coincident with an assumed potential dam failure mode. For example, for a 'sunny day' failure, the assumption of the reservoir being at spillway level or at the maximum normal operating reservoir level and median annual flow conditions in the downstream channel (including tributary watercourses) is reasonable.

For a 'rainy day' dam failure, it is important to identify the hydrological base case against which the 'rainy day' failure scenario should be compared. For new dams, or existing dams, where the PIC has yet to be established, the Inflow Design Flood (IDF) is not defined until the consequences of dam failure have been assessed and the PIC assigned. The IDF therefore cannot initially be used in the assessment. If failure is assumed to be due to overtopping of the dam crest, it is recommended that the Dam Crest Flood is used as the base flood for carrying out the consequence assessment. If a peak flood level lower than the dam crest level is likely to cause failure of the dam, such as excessive seepage through an embankment crest above core level or due to instability of a concrete dam, then this flood should be used for the base flow conditions.

For a 'rainy day' dam failure, it is also important to take account of the tributary inflows from catchments downstream of the dam. Judgement should be exercised to define the magnitude of concurrent tributary inflows relative to the magnitude of the selected IDF taking account of the relative size of the tributary catchments and the nature of the storm giving rise to the assumed 'rainy day' dam failure. For example, while a Probable Maximum Flood (PMF) may be assumed as the IDF for a hypothetical 'rainy day' dam failure, the downstream tributary catchments could be located well downstream from the dam catchment and the centre of the storm giving rise to the assumed 'rainy day' failure sufficiently far away from them that it is appropriate to assume concurrent inflows of lesser magnitude from the tributary catchments.

In some cases, there may not be a credible 'rainy day' failure scenario (e.g. dams impounding off-river storage reservoirs) and this should be stated in the dam-break flood hazard assessment report. Equally, for structures such as flood detention dams there may not be a credible 'sunny day' scenario (refer Section 5.7 for further information on flood detention dams).

2.3.4 Dam breach characteristics

2.3.4.1 Considerations

The magnitude of the flood resulting from a hypothetical dam breach depends on the dam type, the breach location within the dam structure, the breach size and the rate of breach development. The breach characteristics are determined by considering likely initiating events and analysing potential failure modes. Estimation of the breach shape, size and timing requires consideration of the dam type:

- **Earthfill and rockfill embankment dams** – tend to fail in a progressive manner in which, once a breach has initiated, the outflow erodes a part of the dam gradually until the reservoir is emptied or the outflow is insufficient to erode the breach further. Unless the impounded reservoir is extremely large and the dam small, an eroded breach may be limited to a part of an earthfill or rockfill dam. Concrete structures embedded in the embankment may limit the breach growth and soft foundations may allow the breach to extend beyond the limit of the dam foundation.
- **Concrete faced rockfill dams** – may sustain considerable discharge through the rockfill before the rockfill starts to erode (from concentrated leakage). When the eroded rockfill material forming part of the embankment can no longer support the upstream face, an abrupt failure of the concrete face slab will occur allowing a breach to develop. So long as the upstream face slab does not fail, seepage outflows may be able to be safely accommodated by the downstream rockfill.
- **Concrete gravity dams** – tend to fail in an abrupt manner with failure assumed to occur near-instantaneously. Case histories show that many concrete gravity dam failures have involved foundation discontinuities or weaknesses. A potential failure mode analysis should be used to estimate the breach size. It should be noted that more than one third of historical concrete dam failures have resulted in breach widths greater than 30 percent of the dam length.
- **Concrete arch dams –** also tend to fail in an abrupt manner with failure assumed to occur near-instantaneously. Based on case histories, concrete arch dams are more likely to fail in their entirety, usually as a result of abutment failure and the subsequent loss of arch support.

2.3.4.2 Key parameters

Key parameters for describing breach development include the breach shape, width and depth, the rate of growth over time, and the time to reach the ultimate or critical breach depth. Generally, for dams impounding very large volume reservoirs, the critical parameter for determining the size of a dam-break flood is the ultimate breach size. For dams impounding very small reservoirs, the reservoir drawdown rate may be quite fast, and the critical parameters determining the size of a dam break flood are the rate of breach erosion over time and the reservoir storage volume. For canal embankments, parameters influencing the size of a canal breach flood may include the concurrent canal flow (inflows may or may not be able to be controlled), the rate of breach erosion over time, the ultimate breach size and the critical flow capacity of the canal cross-section.

The estimation of breach parameters for dams is an inexact but very important aspect of dam-break flood evaluation. Fortunately, there are considerable empirical data which can be used to estimate breach parameters. In addition, there are mathematical models which can be used to predict the development of a breach over time and the subsequent dam-break flood hydrograph.

The identification and assessment of potential failure modes will provide information on the nature and likely location(s) of hypothetical dam breaches. For embankment dams, geotechnical assessments should provide information on likely erosion mechanisms and erosion rates for embankment materials. For earthfill and rockfill embankment dams it is common to assume a trapezoidal breach shape and a linear rate of breach growth. However, the best guide for estimating breach parameters is to use data from historical failures. Wahl (1998) and Froehlich (2016a) & (2016b) provide guidance on breach parameter estimation and a comprehensive dataset of dam, reservoir and breach parameters from historical embankment dam failures. Veale & Davison (2013) provide a database of concrete dam failures and useful guidance on estimating breach geometries for concrete gravity dam failures.

Due to the inexact nature of breach parameter selection for a hypothetical dam failure, sensitivity analyses should be considered to assess the effects of different breach sizes and rates of development on:

- The peak discharge and duration.
- The ensuing effects of the dam break flood on the downstream area.

Consideration should be given to 'ground-truthing' peak breach outflow predictions against historical failure data for dams of similar composition, size and reservoir storage capacity. This should be done prior to specifying the breach parameters that are to be used in mathematical dam-break flood models and undertaking sensitivity analyses of dam breach outflow hydrograph predictions to breach parameter estimates.

2.3.5 Dam breach outflow hydrograph

2.3.5.1 General

A dam breach outflow hydrograph describes the rate that the stored volume is released from the reservoir through the breach with time. While estimation of the peak breach outflow using empirically-based methods (such as those described by Wahl (1998) and Froehlich (2016a) for embankment dams) will generally be sufficient for an initial dam-break flood hazard assessment, a more rigorous breach outflow hydrograph should be estimated for intermediate and comprehensive assessments. The characterisation of a breach outflow hydrograph requires an understanding of a dam's potential failure modes, the likely size of a breach, the rate of breach development, and the hydraulic behaviour of the outflow for a given breach geometry, initial reservoir level and downstream topography.

2.3.5.2 Estimation methods and considerations

Methods for evaluating a breach outflow hydrograph include:

- Simple triangular-shaped hydrograph approximations based on an estimated peak breach outflow and the total reservoir storage volume.
- Reservoir routing based on a level reservoir assumption and a modified weir outflow relationship for flow through a developing breach.
- Analytical solutions for a hypothetical failure of a concrete gravity or arch dam.
- Flood routing models based on commercial software programmes in which the breach formation parameters and the geometry of the downstream channel are defined.

There are several factors other than the shape and size of a breach, the breach formation time and the rate of breach growth that influence a dam breach outflow hydrograph. The following should be considered:

- The size and shape of the upstream reservoir, and whether drawdown of the reservoir should be modelled with a level pool or dynamic approach (Goodell & Wahlin, 2009).
- Whether or not inflows can be controlled, which is important for diversion structures or canals where inflows are large relative to stored volumes.
- The downstream tailwater level at the time of dam failure.
- The variation in downstream tailwater level as a dam breach develops over time.
- The downstream topography.

Figure 2.4 provides an example breach outflow hydrograph for a 'sunny day' failure of an earthfill or rockfill embankment dam. The hydrograph reflects a progressive dam failure where the size of the dam breach gradually increases over time as the breach outflow erodes more dam material. Eventually a peak outflow condition is reached. The peak outflow is a representation of either:

- The "equilibrium" breach size, where the combination of reservoir elevation and breach size produce the maximum outflow that will be achieved, and further erosion may occur but the decreasing reservoir level will result in a lesser discharge, or
- The "maximum" or "ultimate" breach size, where the breach reaches a maximum size when the reservoir outflow is insufficient to erode it further (laterally or deeper).

The "equilibrium" breach size is the typical control for dams with lesser reservoir volumes and the "maximum'" breach size is the typical control for dams with larger reservoir volumes.

In either case the reservoir will continue to drain until it is either empty (where the breach is eroded down to the breach invert level) or it reaches the invert of the eroded breach (where the breach is formed over a part of the dam height). Throughout the entire breach development process for an earthfill or rockfill dam, the level of the upstream reservoir remains approximately horizontal with weir type outflow occurring through the dam breach.

In contrast to earthfill or rockfill dams, the breach outflow hydrograph for a sudden (near-instantaneous) concrete dam failure has a different shape to that shown in Figure 2.4 with the peak outflow occurring at a time close to zero as shown in Figure 2.5. The evaluation of such hydrographs requires special consideration as the assumptions of a level reservoir surface and weir type outflow through the dam breach are no longer valid. An analytical solution may be required to evaluate the breach outflow hydrograph. USACE (1997) provides guidance for relatively long and narrow rectangular channels where the dam is completely removed. A concrete dam failure will produce a much higher peak breach outflow than an earthfill or rockfill dam for the same reservoir storage volume, dam height and maximum breach size.

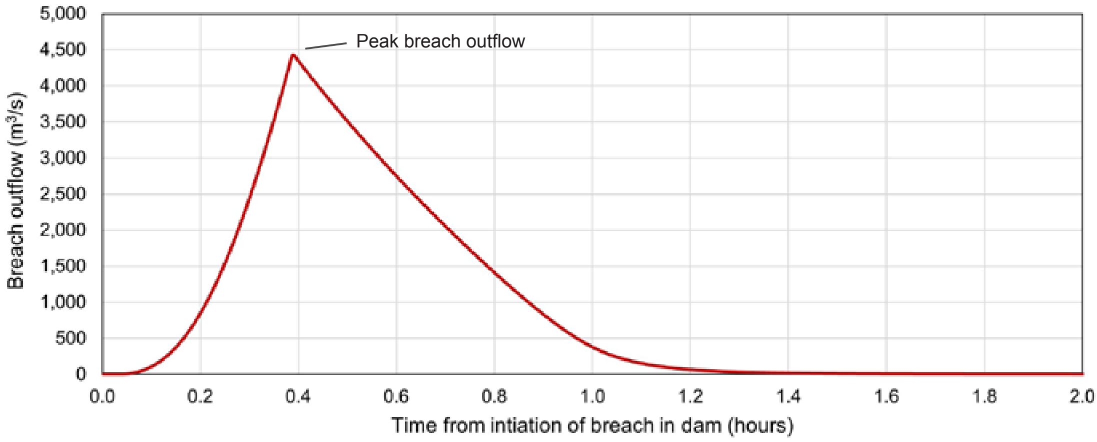

Figure 2.4: Example breach outflow hydrograph for a sunny day failure of an earthfill or rockfill embankment dam

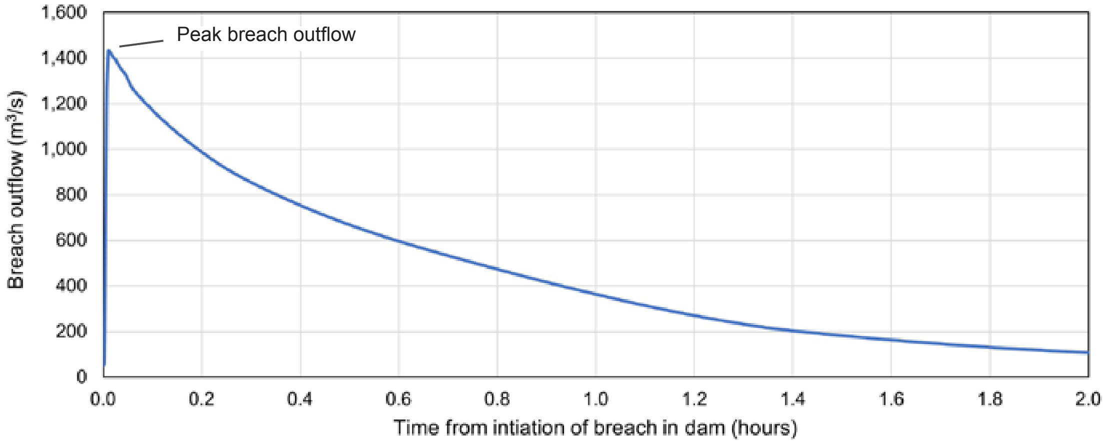

Figure 2.5: Example breach outflow hydrograph for a sunny day failure of a concrete gravity or concrete arch dam

2.3.6 Flood wave routing

The propagation of a dam-break flood wave downstream to evaluate the extent of flood inundation is referred to as flood routing. Flood routing methods range from the simple translation of a peak flood discharge (including estimation of flood peak attenuation) to the use of computational hydraulic modelling. The method should be appropriate to the type of dam-break flood hazard assessment being completed (initial, intermediate or comprehensive) and the level of accuracy required.

The key input to any flood wave routing analysis is the description of the downstream domain that a hypothetical dam-break flood wave will flow through. At a simple level this information can be obtained from topographical maps, or at a more detailed level the information can be obtained from site or aerial-based survey or scanning methods. As a dam-break flood is commonly several orders of magnitude larger than any historic natural flood event, experience and judgment is required in defining the downstream domain from available topographic data and other information. As such, while historic flood levels and flow characteristics provide useful data to inform the assessment, care should be exercised in assuming such characteristics will persist for larger dam-break flood flows.

The other key input to any flood routing analysis is an assessment of the frictional characteristics of the downstream domain as defined by its surface roughness characteristics. Experience and judgment are required. A site visit is very informative for making such an assessment, and understanding the downstream topography and any other features that could affect the movement of a dam- break flood wave through the downstream domain. Land use maps and data are useful for assisting in determining the surface roughness and therefore likely flow characteristics of the project area.

The selected flood routing method is then applied to the defined domain to evaluate the movement of the dam break flood wave downstream. Sensitivity analyses should be used to assess the potential variations in flood travel times and peak depths that result from uncertainty in the frictional characteristics of the domain. For off-stream storage dams and canal embankments the downstream domain may not be a defined channel (as for a dam impounding a waterway) and different considerations may be required.

Backwater effects from hydraulic structures, with the potential to obstruct the path of the dam-break flood wave (e.g. bridges, road and rail embankments, culverts, stopbanks etc.) need to be carefully considered and included in the model as required. For example, bridge waterways and culverts could be assumed to block due to snagging of woody debris or sediment build-up, and road or river embankments could be assumed to fail due to overtopping flows. Assumptions regarding the behaviour of hydraulic structures need to be documented in the modelling report (refer Section 2.2.7). Sensitivity analyses may be required to understand the impact of the assumed behaviour of hydraulic structures on estimated dam-break flood characteristics (i.e. flood travel times, peak flow depths and velocities, and the extent of downstream flood inundation).

2.3.7 Flood wave routing software

Comprehensive dam-break flood hazard assessments require analytical or computational hydraulic modelling methods referred to above which employ detailed hydrodynamic evaluation of a dam breach outflow hydrograph and routing of the resulting flood wave downstream. Various commercial computational hydraulic modelling software packages are available on the market for such purposes.

The breach development component of a software package evaluates the breach outflow hydrograph based on a prescribed breach development description (breach shape, initial size, final size and development time), the assumption of a horizontal upstream water surface as the upstream reservoir drains, and the assumption of weir outflow through the breach. As such, the breach development component is generally not suitable for the evaluation of near-instantaneous concrete dam failures. The flood routing component of a software package routes the resulting dam breach flood through the downstream valley and floodplains accounting for the effects of downstream domain friction, tributary watercourses, and hydraulic controls such as gorges, bridges and dams.

Separate software packages may be used to perform each of the above functions where they are appropriately coupled.

Computational hydraulic modelling software packages are typically one-dimensional (1D), two-dimensional (2D) or a linked 1D-2D model. Further description of these types of models is provided in Book 6, Chapter 4 of ARR (2019). A one-dimensional modelling approach is appropriate where the downstream flood path is formed by a clearly defined valley and the direction of flow is assumed to be predominantly parallel to the valley. 1D computational hydraulic modelling tools define the downstream domain by means of channel cross-sections. The channel cross-sections are used as calculation nodes at which flood levels and discharges are evaluated over the course of the passage of a flood wave. A two-dimensional modelling approach is more appropriate where the downstream flood path for a flood wave crosses a floodplain, or where the dam breach outflow may not travel by an obvious flow channel, or the exact location of the flood path is uncertain. 2D computational hydraulic modelling packages define the downstream topography by means of a grid, typically consisting of triangular and/or quadrilateral shaped cells, with each cell having a specified constant ground level and differing directions of inflow and outflow across each cell face. Such models provide outputs of flood depth, water level and velocity at each grid cell as a function of time.

2.3.8 Dam-break flood inundation mapping

Dam-break flood inundation maps, that show the maximum extent of inundation resulting from a hypothetical dam-break flood, are necessary for the assessment of downstream flood inundation effects (refer Figure 2.6). Inundation maps and supporting dam-break flood information also form an essential part of an Emergency Action Plan (refer Module 6: Emergency Preparedness). For emergency planning and preparedness, and interaction with Regulators and emergency response agencies, the inundation maps that are developed and used should be based on the potential failure modes that produce the maximum peak outflows for the 'sunny day' and 'rainy day' dam failure scenarios (typically a breach through the maximum section). However, for risk assessments and/or a more complete understanding of the consequences of a dam failure, inundation maps for other credible potential failure modes may be required to be developed.

To enable an assessment of the consequences of dam failure to be completed, the maps should show the locations of all buildings, infrastructure and other property, and provide details of flood arrival times, times to flood peak, and peak flood depths or levels at key locations of interest. It is important to choose locations of interest that are representative of areas where the expected consequences would be significant, such as populated or developed areas and key infrastructure such as bridges and roads that provide evacuation routes.

Inundation maps should be produced for both 'sunny day' and 'rainy day' dam failure scenarios (except for flood detention dams, as outlined in Section 5.7). 'Rainy day' failure flood inundation maps should identify the underlying extent of the base flood assumed to give rise to the hypothetical dam failure, but without that failure occurring.

The scale of any required inundation mapping will depend on the characteristics of the dam and downstream catchment, and the magnitude of the hypothetical dam-break flood. Standard 1:50,000 scale Land Information New Zealand (LINZ) topographic maps are typically adequate as base maps. However, when preparing maps for input to an Emergency Action Plan, it is recommended that Civil Defence Emergency Management (CDEM) and other end users of the maps are consulted to check that the maps are sufficient for their purposes. FEMA (2013) provides guidance on the preparation of dam-break flood inundation maps for differing levels of assessment and accuracy.

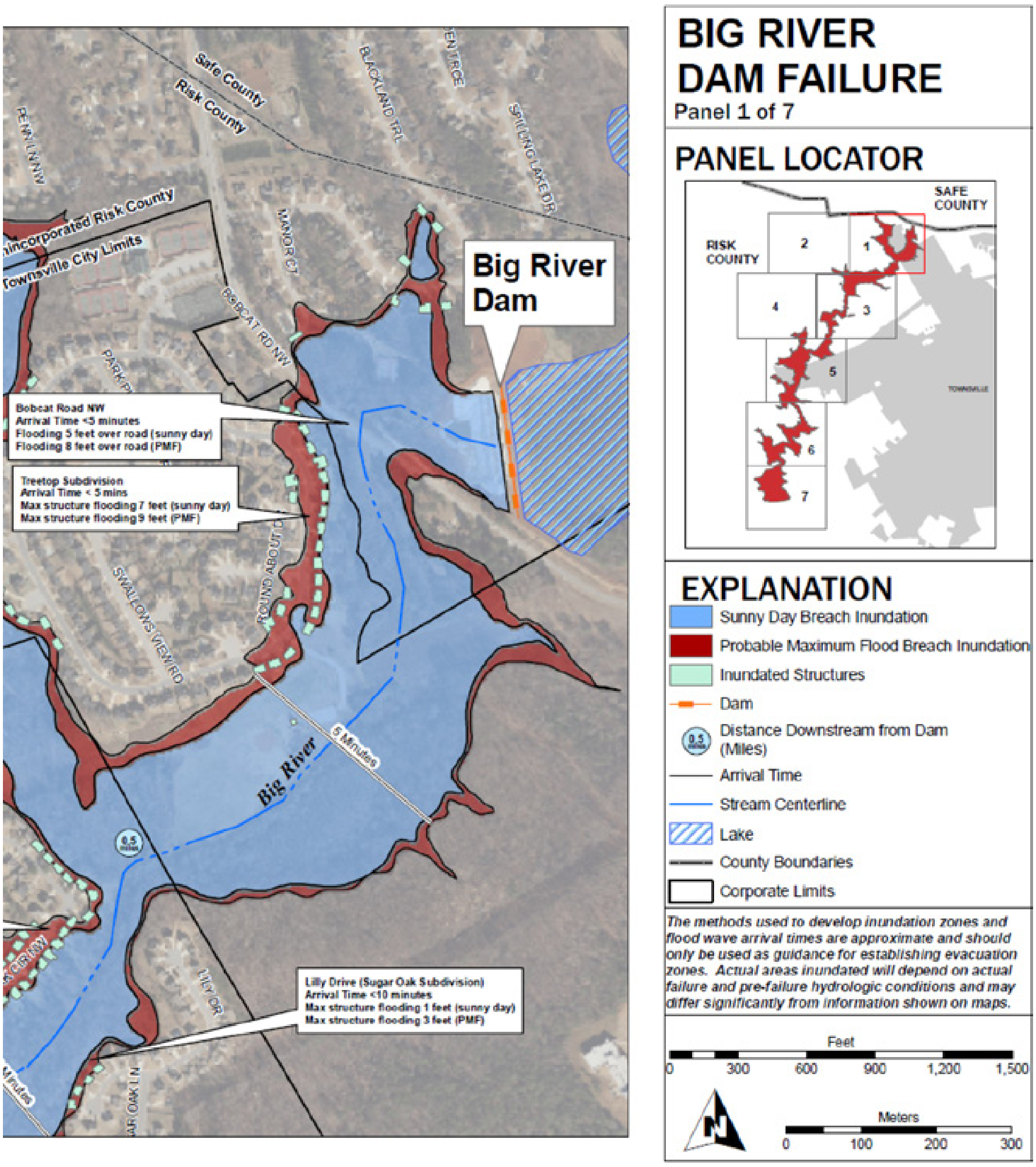

Figure 2.6: Example Dam-Break Flood Inundation Map (from FEMA (2013)).

2.4 Dam-Break Consequence Assessment

2.4.1 Purpose

A dam-break consequence assessment involves estimation of the potential impact of hypothetical dam failure using the results of the dam-break flood hazard assessment.

The consequences resulting from the uncontrolled release of the stored volume of a dam can be wide ranging. As outlined in Figure 2.7, Stephens (2019) categorises the consequences from dam failure as either tangible or intangible. Figure 2.7 also indicates tangible damages are further sub-categorised as direct or indirect. However, there is no established rule that specifies how such consequence categorisations should be broken down and other practitioners use different categorisations (e.g. Hartford & Baecher (2004)).

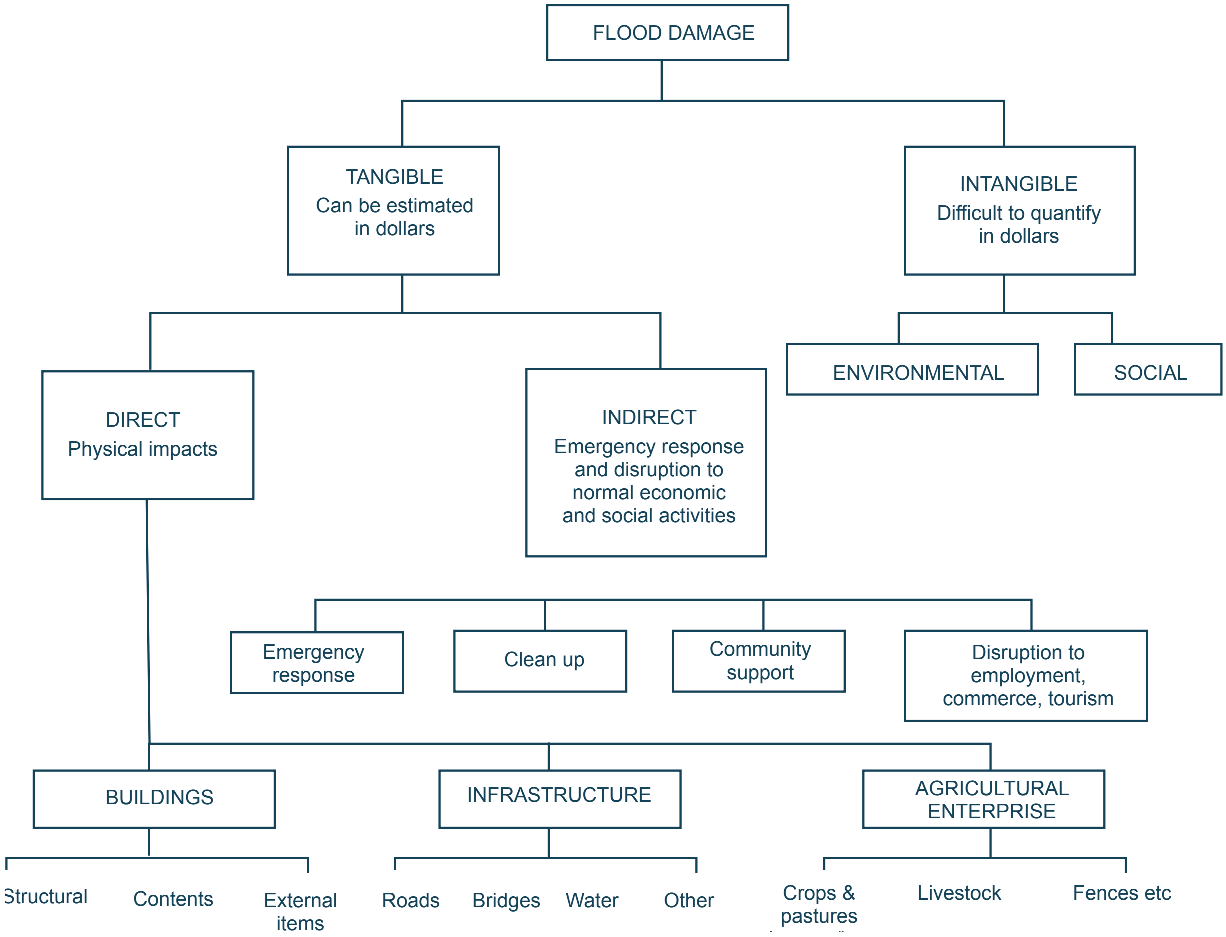

Figure 2.7: Flood damage classifications (from Stephens, 2019)

In some cases, a dam owner may wish to understand specific types, or even the full range, of consequences such as those outlined in Figure 2.7 (e.g. for consenting, consultation, insurance or other purposes). However, for PIC assessment purposes, the objective of a consequence assessment is to determine the damage level exclusively for the following 'specified categories' listed in Table 2.2 and summarised as follows:

- Community buildings (i.e. households, commercial or industrial and community facilities).
- Historical or cultural sites.
- Critical or major infrastructure (including the time to restore operation of the damaged infrastructure).
- Natural environment.

Additionally, potential impacts to life safety, which are measured by the Population at Risk and Potential Loss of Life, are required to be estimated.

Guidance on consequence assessment in the following sections is restricted to processes used to determine damage levels for the categories listed in Table 2.2 and potential impacts to life safety for PIC assessment purposes. The following Section 2.4.2 outlines guidance to estimate damage levels for the categories listed in the Table 2.2. Section 2.4.3 outlines guidance to estimate potential life safety impacts for PIC assessment purposes. The process to determine a dam's PIC is provided in Section 3.

Table 2.2: Determination of Assessed Damage Level

Damage Level	Specified categories				
	Community	Cultural	Critical or major infrastructure		Natural environment
			Damage	Time to restore to operation 1	
Catastrophic	One or more of the following apply: • 50 or more household units rendered uninhabitable. • 20 or more commercial or industrial facilities rendered inoperable. • 2 or more community facilities rendered inoperable or uninhabitable.	Irreparable loss to 2 or more historical or cultural sites.	Two or more critical or major infrastructure facilities rendered inoperable.	One year or more.	Extensive and widespread damage, with permanent, irreparable effects on the natural environment.
Major	One or more of the following apply: • 4 or more but less than 50 household units rendered uninhabitable. • 5 or more but less than 20 commercial or industrial facilities rendered inoperable. • 1 community facility rendered inoperable or uninhabitable.	One or both of the following apply: • irreparable loss to 1 historical or cultural site. • loss to 1 or more historical or cultural sites where it is possible, but impracticable, to fully restore the site.	One critical or major infrastructure facility is rendered inoperable.	Three months or more but less than 1 year.	Extensive and widespread damage where it is possible, but impracticable, to fully restore or repair the damage.
Moderate	One or more of the following apply: • 1 or more but less than 4 household units rendered uninhabitable. • 1 or more but less than 5 commercial or industrial facilities rendered inoperable. • loss of some functionality of one or more community facilities.	Significant loss to 1 or more historical or cultural sites where it is practicable to restore the site.	One or more critical or major infrastructure facilities are affected by the loss of some functionality.	Less than 3 months.	Significant damage that is practicable to restore or repair.
Minimal	Minor damage that does not materially affect the functionality of any household unit, commercial or industrial facility, or community facility (or no damage).	Loss to 1 or more historical or cultural sites that will require minor restoration only (or no loss to any historical or cultural site).	Minor damage to 1 or more critical or major infrastructure facilities (or no damage).	One week or less.	Only minor rehabilitation or restoration may be required or recovery is possible without intervention (or no damage).

Notes:

1. The estimated time required to repair the damage sufficiently to return the critical or major infrastructure to the normal operation that the infrastructure had immediately before the failure of the dam

2.4.2 Assessment of damage levels

2.4.2.1 Determination of Damage Levels

For initial level dam-break consequence assessments, estimation of damage levels would involve the preliminary identification of buildings, cultural and heritage sites, critical and major infrastructure and environmental areas within the expected downstream extent of dam-break flood inundation from topographic maps and aerial photographs. Damage to assets identified would be qualitatively assessed according to each of the four damage level descriptions provided in Table 2.2 . Initial assessments should adopt a conservative approach and, depending on the results, findings may need to be confirmed through more detailed assessments at an intermediate or comprehensive level.

For intermediate and comprehensive level dam-break consequence assessments, estimation of damages for each of the four categories listed in Table 2.2 would typically utilise dam-break flood inundation information (e.g. flood inundation extents, maximum flood depths, maximum flow velocities and/or maximum values of the product of flood depth and flow velocity, DV) in combination with geospatial information (e.g. topographic maps, aerial photos, land parcel boundaries, District Plan land use maps etc.) to identify affected assets within the dam-break flood inundation extent. By overlaying this information, typically in a Geographic Information System (GIS) environment, the damage to each asset from the dam-break flood water can be estimated based on the degree of flooding at each asset. Note that a site inspection may be necessary to verify the characteristics of individual assets where it is not obvious from available geospatial information. Figure 2.8 provides a basic illustration of a dam-break flood inundation extent and the location of assets immediately downstream for an example dam failure scenario.

The processes described above can be broken down into two components: identification and analysis. Table 2.3 lists the activities involved in each of these components.

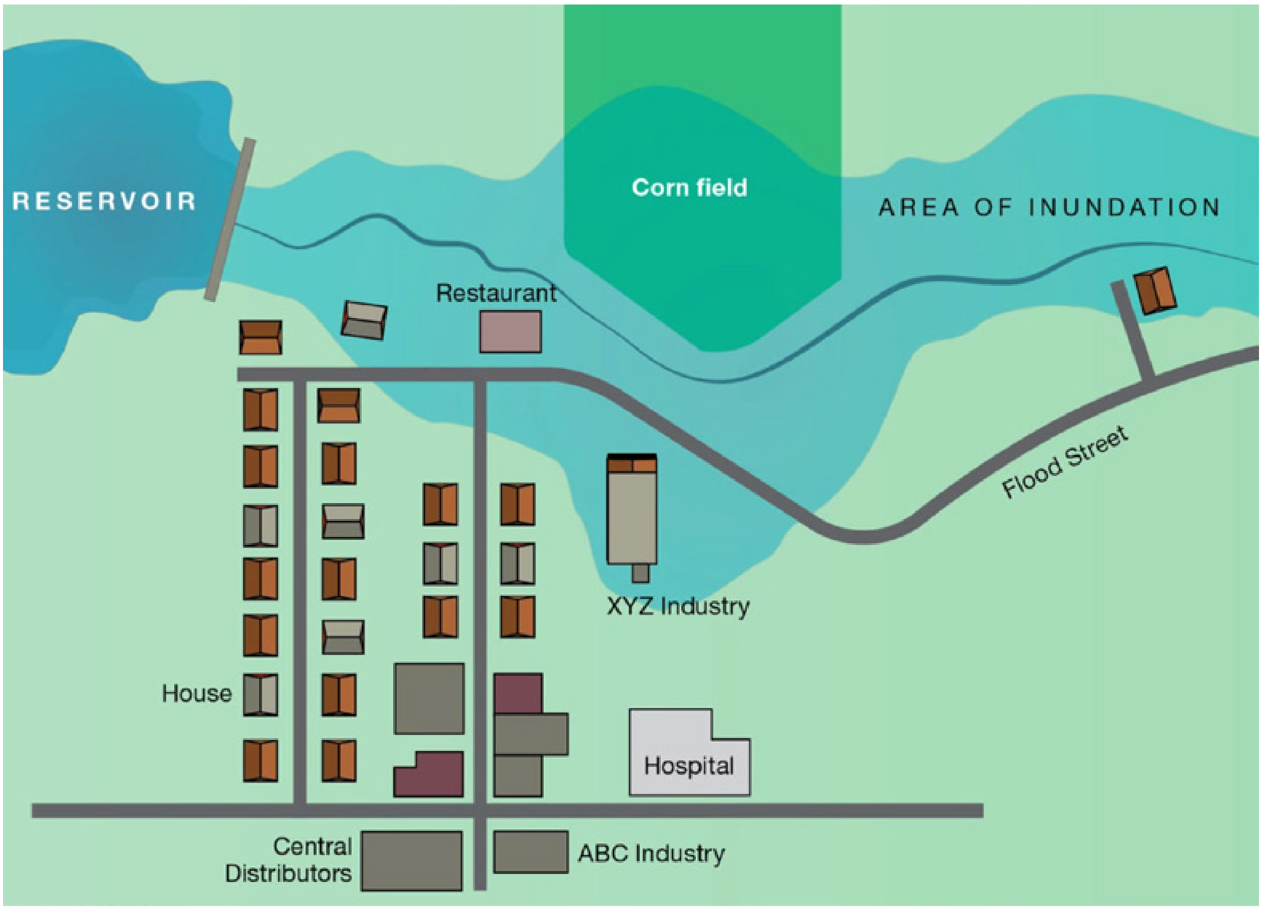

Figure 2.8: Example of dam-break flood inundation area in relation to downstream assets (from FEMA, (2012))

Table 2.3: Activities involved in damage level assessments

Component	Activity
Identification	• Identifying the extent of inundation associated with each dam-break flood scenario, refer guidance in Section 2.3. • Identifying the forcefulness of the floodwater and its destructive power (i.e. flood depth and velocity information), refer guidance in Section 2.3. • Identifying the inventory of assets (primarily buildings, infrastructure, transport systems and other potentially affected locations) that will be inundated. • Identifying environmental areas/sites potentially subject to damage. • Identifying cultural and heritage areas/sites potentially subject to damage.
Analysis	• Estimating impact of each dam-break flood scenario in terms of damage to buildings (i.e. residential dwellings and commercial, industrial or community facilities) and critical or major infrastructure. • Estimating damages to environmental areas/sites • Estimating the damages to cultural and heritage areas/sites

For all assessment levels (i.e. initial, intermediate, comprehensive), potential damages should be grouped into the four 'specified categories' listed in Table 2.2 so that the appropriate damage level can be assigned (i.e. minimal, moderate, major, catastrophic). The highest damage level determined (across all four 'specified categories' listed in Table 2.2) is selected for use in the classification of a dam (refer Section 3).

For a 'rainy day' dam failure, the damage levels for PIC assessment purposes should be based on the total damages estimated for the dam failure occurring under flood conditions minus the estimated damages caused by the same flood conditions without dam failure (i.e. the incremental damages resulting from the additional flood inundation caused by the dam-break flood).

2.4.2.2 Damage to community buildings

For PIC assessment purposes, the degree of damage to each identified community building (i.e. residential dwellings, commercial, industrial and community facilities) needs to be established according to the descriptions provided in Table 2.2, as either:

- Rendered uninhabitable or inoperable.
- Loss of functionality.
- Minor damage that does not materially affect the functionality.
- No damage.

Estimation of the degree of damage to community buildings only considers the direct impact of a hypothetical dam-break flood on a structure. No estimate of the life safety of people inside or outside the building is required, as this is covered independently under the assessment of Population at Risk and Potential Loss of Life (refer Section 2.4.3).

For intermediate and comprehensive level assessments, where dam-break flood inundation depth and/or velocity information is available, the degree of damage to buildings can be established using building stability curves. Such curves relate the flow characteristics (e.g. maximum flood depth and/or maximum flow velocity) to the degree of damage expected for different building types. The following information sources provide building damage curves which may be useful for estimating the potential damage to buildings.

- The National Institute of Weather and Atmosphere (NIWA, 2010) provides potential damage curves as a function of building type and flooding depth, based on observed data from floods and tsunamis in New Zealand, Australia and the Pacific. Using this information, "damage states" DS0 to DS4 can be assigned to each flood affected building. For each damage state, different repair actions would be required to restore the structure to its pre-flood condition. Table 2.4 lists these damage states with their description, as well as the interpretation of the damage states relative to the descriptions provided in Table 2.2. Note that when assessing building damage states using the NIWA (2010) approach, flood depths are relative to the building floor level (and not the lowest ground level at the site).

Table 2.4: Building damage states from NIWA (2010) related to building damage descriptors from Table 2.2

NIWA (2010) Damage State*	NIWA (2010) Damage State Description	Table 2.2 Building Damage Description
DS0	Insignificant	No damage
DS1	Light — Non-structural damage, or minor non-structural damage	Minor damage that does not materially affect the functionality
DS2	Moderate — Reparable structural damage	Loss of functionality
DS3	Severe — Irreparable structural damage	Rendered uninhabitable or inoperable
DS4	Collapse — Structural integrity fails	Rendered uninhabitable or inoperable

Notes:
1. Refer to NIWA (2010) for method to determine damage states as a function of flood depth (relative to building floor level) for different building types.

- Smith et al (2014) provides thresholds for building stability in floods based on flood depth and velocity, from a comprehensive review of building stability thresholds from numerous publications. Figure 2.9 shows the combined hazard flood curves from Smith et al (2014) which categorise flood hazard into six hazard categories (H1 to H6). The thresholds for these categories are based on peak flood depth and velocity at a given building. Table 2.5 describes these five thresholds as well as the interpretation of them relative to the damage states provided listed in Table 2.2. This method is also suitable to determine the damage level to buildings. It differs from the NIWA (2010) approach, because it is informed by the influence of both flood depth and flow velocity at a building.

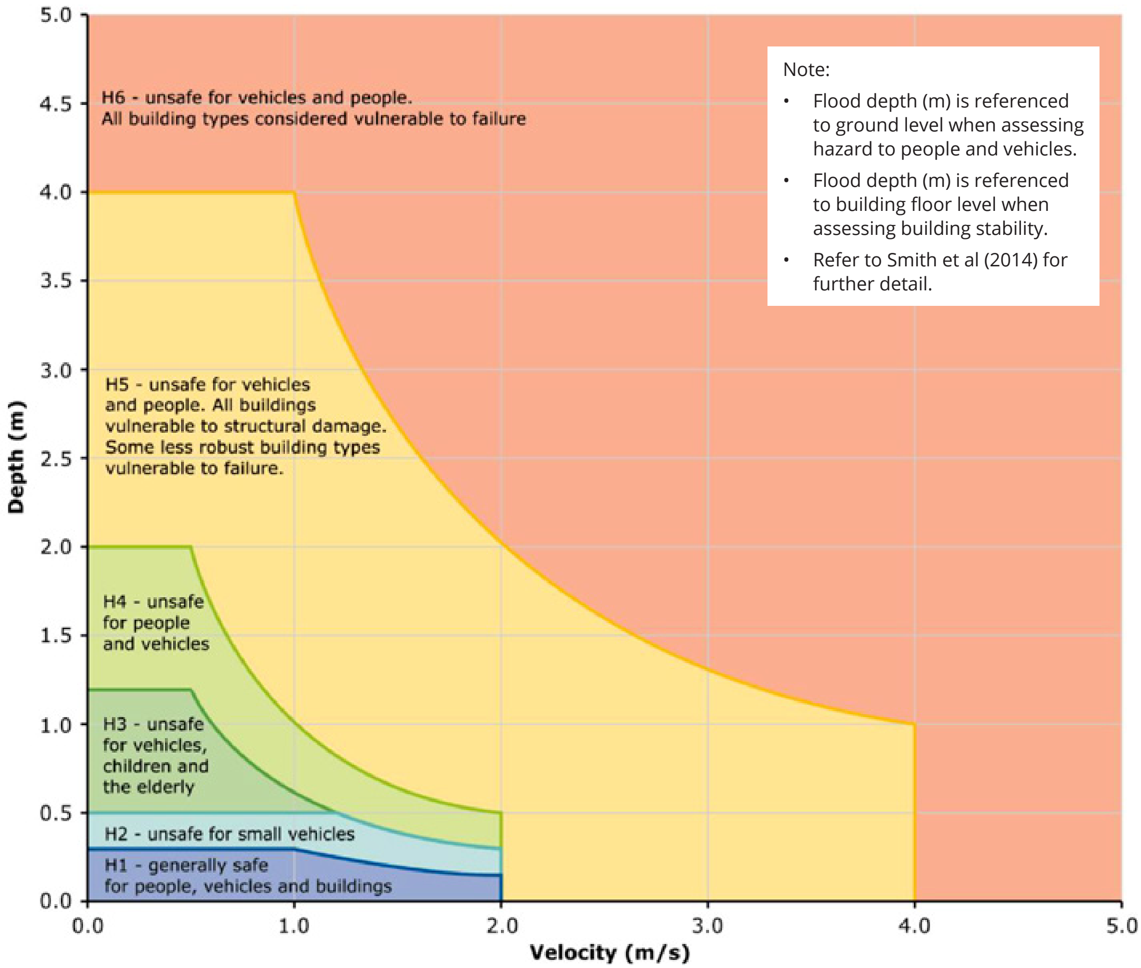

Figure 2.9: Combined flood hazard curves (from Smith et al (2014)).

Table 2.5: Hazard thresholds (from Smith et al (2014)) related to building damage descriptors from Table 2.2

Smith et al (2014) Hazard threshold*	Smith et al (2014) Hazard threshold description	Table 2.2 Building damage description
H1	Generally safe for vehicles, people and buildings	Minor damage that does not materially affect the functionality
H2	Unsafe for small vehicles.	Loss of functionality
H3	Unsafe for vehicles, children and the elderly.	Loss of functionality
H4	Unsafe for vehicles and people.	Either Loss of functionality or Rendered uninhabitable or inoperable**
H5	Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust buildings subject to failure.	Rendered uninhabitable or inoperable
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure.	Rendered uninhabitable or inoperable

Notes:

1. Refer to Smith et al (2014) and Figure 2.9 for flood depth and velocities that relate to different hazard thresholds for buildings.
2. Damage to buildings in the H4 category will depend on the building type (e.g. concrete or timber type structure).

2.4.2.3 Damage to cultural sites

For PIC assessment purposes, the degree of damage to each cultural place identified (i.e. historical and cultural sites) needs to be established according to the descriptions provided in Table 2.2, as either:

- Irreparable loss.
- Loss where it is possible, but impracticable, to fully restore the site.
- Significant loss where it is practicable to restore the site.
- Minor loss that will require minor restoration only.
- No loss.

Identification of cultural places should be restricted to those places which form a significant and valued part of Aotearoa New Zealand's historical and cultural heritage and which are either:

- Listed on the New Zealand Heritage List/Rārangi Kōrero.
- Listed on the Department of Conservation website entitled "National Register of heritage sites managed by DOC".

The intent is that only historical or cultural sites that have already been identified and designated as heritage sites of national or regional significance should be considered, rather than seeking out and introducing new ones.

The degree of damage to cultural sites which are buildings could be established using the same methodology outlined in Section 2.4.2.2. Where a cultural site is not related to a building (e.g. a site of archaeological significance, cemetery or urupā), the degree of damage will need to be established using judgement which considers the magnitude of the dam-break flood wave at the site. However, when the assessment of damage level could significantly influence the PIC of a dam, or if a more comprehensive level of assessment is required for other reasons, then consideration should be given to the use of a cultural specialist to assist with assessing the potential damage to the site.

2.4.2.4 Damage to critical or major infrastructure

For PIC assessment purposes, the degree of damage to identified items of critical or major infrastructure needs to be established according to the descriptions provided in Table 2.2, as either:

- Rendered inoperable.
- Affected by the loss of some functionality.
- Minor damage.
- No damage.

Critical or major infrastructure is restricted to the following definitions provided in the Regulations (2022):

a) a building or other infrastructure operated or used by a lifeline utility within the meaning of Section 4 of the *Civil Defence Emergency Management Act 2002*.

> Examples include water, wastewater and stormwater, power, gas, telecommunications and transportation networks.

b) a hospital building that is likely to be needed in an emergency (within the meaning of Section 4 of the *Civil Defence Emergency Management Act 2002)* to provide—

   i. emergency medical services; or

   ii. ancillary services that are essential for the provision of emergency medical services.

c) a building that is used to provide emergency response services (for example, policing, fire, ambulance, or rescue services)

d) buildings or infrastructure that are essential to the containment of a hazardous substance (as defined by Section 2 of the Hazardous Substances and New Organisms Act 1996):

e) the dam, another dam, or flood protection works if the service the dam, other dam, or flood protection works provide is critical to the community (for example, energy supply, drinking water storage, wastewater treatment, flood detention dams) and that service cannot be reasonably provided by alternative means.

Critical or major infrastructure that meets the definitions above are essential utility systems and components of transportation networks that serve communities. Any potential damage to such infrastructure from dam failure therefore needs to be identified.

For the purposes of PIC assessment, the interpretation adopted in these Guidelines, is that critical or major infrastructure associated with lifeline utilities are related to network mains and nodes rather than local connections. For example, State Highways and other roads which are critical for connection of communities would be considered to be critical or major infrastructure, whereas local roads would not normally be considered to be critical or major infrastructure. However, specific consideration may be required for cases where local infrastructure connections provide the only outside links for a community.

It should be recognised that there is a high level of dependence by other lifeline utilities on roading networks. For example, water, sewerage, power and telecommunications services all use the road corridor and often also rely on structures such as road bridges to run cables or pipelines across. A failure of part of the road network may not only result in the consequential loss of another service, but also make access more difficult to repair and restore the service.

The degree of damage to critical or major infrastructure assets which are buildings could be established using the same methodology outlined in Section 2.4.2.2. Where critical or major infrastructure is not related to a building (e.g. roads, bridges) the degree of damage will need to be established using judgement which considers the magnitude of the dam-break flood wave at the location of the specific infrastructure asset.

2.4.2.5 Damage to natural environment

For PIC assessment purposes, the degree of damage to the natural environment needs to be established according to the descriptions provided in Table 2.2, as either:

- Extensive and widespread damage, with permanent, irreparable effects.
- Extensive and widespread damage where it is possible, but impracticable, to fully restore or repair the damage.
- Significant damage that is practicable to restore or repair.
- Minor rehabilitation or restoration may be required or recovery is possible without intervention.
- No damage.

The natural environment will be affected by maximum flood depths, maximum flow velocities and duration of inundation over the flooded area. Potential damage to the following environmental aspects should be considered:

- Waterways, wetlands.
- Flora and fauna.
- Rare or endangered species.
- Deposition of sediment (e.g. release of sediments trapped behind the dam and/or from erosion of embankment materials during dam failure).
- Erosion of river and/or floodplain areas.
- Reduction of visual amenity (e.g. loss of natural landscape features, including the reservoir itself).
- Contamination, particularly in the case of tailings dams and dams associated with wastewater treatment.

Environmental information within the dam-break flood inundation extent is generally sourced from topographic maps, internet searches, discussion with local agencies and organisations, District Planning maps and searches of Department of Conservation databases.

Determination of the damage level to the natural environment for PIC assessment purposes is generally carried out qualitatively using judgement which is informed by the known damage sustained during significant historic natural flood events and which considers the magnitude of the dam-break flood at the location of any identified environmental feature or aspect. However, when the assessment of these damages could significantly influence the PIC of the dam, or if a more comprehensive level of assessment is required for other reasons, then consideration should be given to the use of an environmental specialist to assess the full range of attributes pertaining to the environment and to assist with assessing potential damage levels.

2.4.3 Population at Risk and Potential Loss of Life

2.4.3.1 Definitions

The table used to determine a dam's PIC is provided in Table 2.6 and introduces the terms Population at Risk (PAR) and Potential Loss of Life. The definitions of these two terms are provided in the Regulations (2022) as follows:

- Population at Risk: the number of people likely to be affected by an uncontrolled release of all or part of the stored water or other fluid due to a failure of the dam (assuming that no person takes any action to evacuate).
- Potential Loss of Life: the number of people expected to lose their life as a result of an uncontrolled release of all or part of the stored water or other fluid due to a failure of the dam.

These two terms, Population at Risk and Potential Loss of Life, provide metrics for assessing the potential life safety impacts of a hypothetical dam failure event. For PIC assessment purposes, they are required to be quantified into the categories listed in Table 2.6, that is:

For Population at Risk:

- 0 persons at risk.
- 1 to 10 persons at risk.
- 11 to 100 persons at risk.
- More than 100 persons at risk.

For Potential Loss of Life:

- No persons.
- One person.
- Two or more persons.

With respect to the definition of PAR, the interpretation adopted in these Guidelines of "likely to be affected" is people who are directly exposed to dam-break flood inundation which is potentially hazardous to life (i.e. has potential life safety impacts). Other persons who are either indirectly affected (for example through economic loss) or not exposed to flood inundation are excluded from a PAR estimate. Refer to Section 2.4.3.3 for guidance on flood hazard thresholds which are considered to be potentially hazardous to life.

With reference to Table 2.6, it is important to note that a dam is assigned a Medium or High Potential Impact Classification (PIC) if loss of life is expected to occur due to a hypothetical dam failure, irrespective of other damages or effects which might occur. An expected loss of one human life is sufficient to require a Medium PIC classification for a dam while an expected loss of two or more human lives is sufficient to require a High PIC classification.

The following guidance related to PAR and Potential Loss of Life is focused on procedures and methods for quantifying these parameters into the categories listed in Table 2.6 for PIC assessment purposes. It should be noted that alternative methods for quantifying PAR and Potential Loss of Life may be required for other purposes (e.g. for establishing the effectiveness of emergency response or for quantitative risk assessment where annualised life loss estimates are required). Such alternative methods are not covered by these Guidelines.

Table 2.6: Determination of Potential Impact Classification (PIC)

Assessed damage level	Population at Risk (PAR)				Potential loss of life
	0	1 to 10	11 to 100	100+	
Catastrophic	High	High	High	High	No persons
	N/A (see Note 1)	High	High	High	One person
	N/A (see Note 1)	High	High	High	Two or more persons
Major	Medium	Medium	High	High	No persons
	N/A (see Note 1)	Medium	High	High	One person
	N/A (see Note 1)	High	High	High	Two or more persons
Moderate	Low	Low	Medium	Medium	No persons
	N/A (see Note 1)	Medium	Medium	Medium	One person
	N/A (see Note 1)	High	High	High	Two or more persons
Minimal	Low	Low	Low	Low	No persons
	N/A (see Note 1)	Medium	Medium	Medium	One person
	N/A (see Note 1)	High	High	High	Two or more persons
Notes: 1. Not applicable. Population at risk is zero therefore no potential loss of life.					

2.4.3.2 General Principles

Some general principles for estimation of PAR and Potential Loss of Life for PIC assessment purposes are given below. The following Sections 2.4.3.3 and 2.4.3.4 provide further information on methodologies for estimation of PAR and Potential Loss of Life.

- The failure of any dam or water-retaining structure, no matter how small, could represent a danger to human life downstream. A situation can always be imagined where PAR and Potential Loss of Life is identified regardless of how remote the location of the dam or how remote the likelihood of persons being affected by its hypothetical failure. However, postulating every conceivable circumstance that might place a person in the dam-break flood inundation area should not be the basis for estimating PAR and Potential Loss of Life for PIC assessment purposes.
- PAR and Potential Loss of Life estimates should be considered for areas of any type that are known to be normally occupied. Examples of such normally occupied areas that are recommended to be considered are listed in Table 2.7, and further described in Section 2.4.3.3.
- In evaluating PAR and Potential Loss of Life estimates for PIC assessment purposes, no allowances for evacuation, early warning systems, or other emergency actions by the adversely impacted population should be considered. This is because it could lead to dam owners relying on untested assumptions about the effectiveness of emergency procedures and the responsiveness of emergency authorities in a dam failure situation to potentially lower the PIC of their dam. Emergency procedures should not be a substitute for appropriate design, construction, operation and maintenance practices and actions for dam structures (FEMA, 2004).
- Where the PAR and Potential Loss of Life in a 'rainy day' dam failure scenario is required to be estimated, the PAR and Potential Loss of Life should be estimated separately for both the 'base flood without dam failure' and the 'base flood with dam failure' cases. An estimate of the incremental PAR and Potential Loss of Life for the 'rainy day' dam failure scenario can then be obtained by subtracting the estimate for the 'base flood without dam failure' case from the estimate for the 'base flood with dam failure' case.

- In some cases, the PIC of a dam can be determined without the need for Potential Loss of Life estimates. For example, and with reference to Table 2.6, if a damage level of "major" has been estimated in combination with a PAR of 10 to 100, the dam has a High PIC regardless of any Potential Loss of Life estimate. In such cases, a Potential Loss of Life estimate would not be required to determine the dam's PIC. A PAR estimate is required in all cases, unless a "catastrophic" damage level is determined using the methods previously described in Section 2.4.2.

2.4.3.3 Population at risk

Estimation of PAR generally involves identifying buildings and other places of occupancy within the expected dam-break flood inundation zone from topographic maps and aerial photographs. Typical occupancy rates for each identified building and place of occupancy are assigned from user judgement and the PAR estimated within a broad range (e.g. 0, 1 to 10, 10 to 100, >100). Where any PAR estimate lies close to the boundary of one of these ranges, then assessment at a more detailed level should be considered.

For initial level assessments, a coarse estimate of PAR can be made. For example, it may conservatively be assumed that all people within the expected dam-break flood inundation area are counted as part of the PAR regardless of life safety impact. For intermediate and comprehensive level assessments, estimation of PAR will generally need to be established through a more detailed assessment of the life safety impact on all people within the expected dam-break flood inundation zone.

The typical procedure for intermediate and comprehensive level assessments of PAR should involve:

Identifying buildings and places of occupation within the dam-break flood inundation area

Building and places of occupation in the dam-break flood inundation area should be identified using a combination of topographic maps, aerial photographs, local information and internet searches and/or site inspections as appropriate. This is most efficiently done with a Geographic Information System (GIS).

When identifying places of occupation, both permanent and temporary populations should be considered. Permanent populations are those linked to a fixed location on a permanent basis (e.g. persons present in residential dwellings, places of work, schools and other regularly occupied community facilities, hospitals, and industrial, commercial and retail premises). Temporary populations are considered to be those that do not usually live or work within the dam-break flood inundation area but are present temporarily in the area (e.g. recreational users of recognised tracks, tourist or fishing spots, campers in recognised camping areas, road and rail users, seasonal workers, attendees at sports events or festivals). The possible presence of the dam owner's staff and contractors within the dam-break flood path should also be considered.

Table 2.7 includes descriptions of buildings and places of occupation that should be considered to identify permanent and temporary populations within the dam-break flood inundation area. Special consideration may be required if other buildings or places of occupation are identified within the dam-break flood inundation area but not included in Table 2.7.

Assigning occupancy rates to each building and place of occupation

Table 2.7 provides guidance on assignment of occupancy rates to buildings and places of occupation identified within the dam-break flood inundation area. In many cases, occupancy rates may need to be determined by verification with local information or a site inspection. The documentation of the dam-break consequence assessment should justify the occupancy rates used.

When assigning occupancy rates, it is important that they do not double count people (e.g. people both living in and working in the hypothetical dam-break flood inundation zone).

Determining time categories

A dam failure could hypothetically occur at any time of day, day of the week or season. However, both permanent and temporary populations within a dam break flood inundation area will vary depending on the time of day, day of the week and season as people move around for work, school, recreation or other reasons. To deal with this mobility issue, it is recommended that several time-based scenarios should be considered to identify the period of greatest consequence. The time-based scenario that results in the largest PAR should be used as the basis for subsequent PIC assessment.

The selection of time-based scenarios will be dependent on the range of buildings and places of occupation located within the dam-break flood inundation area. Consideration of different time-based scenarios will require appropriate adjustment of occupancy rates for day/night, weekday/weekend and summer/winter seasonal situations. Such occupancy rates should reflect a reasonable "snapshot" view of the number of people present within the dam-break flood inundation area for each time-based scenario considered.

Land that is temporarily used on a short term or intermittent basis (e.g. land used for outdoor events, or campgrounds which have a large summertime population but only a small wintertime population) may require special consideration. The time-based scenario which considers the greatest period of consequence should be used with occupancy rates related to the peak occupancy for those times (i.e. a full campground for summer day/night periods but near empty for day/night winter periods). Local information on such areas is likely to be required to determine the occupancy rates for different time periods.

Evaluating flood hazard at each building and place of occupation

The flood hazard at each building and place of occupation is evaluated by extracting computational hydraulic model simulation outputs of maximum flood depth and velocity at each building and place of occupation for each dam-break flood scenario considered (e.g. sunny day failure and rainy day failure scenarios with and without dam failure).

Determining the PAR

Figure 2.9 (previously introduced in Section 2.4.2.1) defines flood hazard classes for people, buildings and vehicles sourced from Smith et al (2014) which have been developed from extensive laboratory tests as well as field observations from natural flood events. The hazard assessment methodology defined by this information is widely used by government agencies and industry in both Australia and New Zealand for assessing natural flood hazards and has been incorporated into the Australian Rainfall and Runoff (ARR) national guideline document *A Guide to Flood Estimation, Book 6 Flood Hydraulics* (ARR, 2019).

People in building or places of occupation are included in the PAR if the dam-break flood hazard exceeds the "H2" category shown in Figure 2.9. Categories greater than "H2" reflect a degree of flood hazard which most people (including adults, children and the elderly) would not normally be able to safely withstand.

People in vehicles are included in the PAR if the dam-break flood hazard exceeds the "H1" category shown in Figure 2.9. Categories greater than "H1" are considered unsafe for small passenger vehicles.

The assessment procedure described above is typically carried out to determine the total PAR for each dam-break flood scenario analysed (e.g. sunny and rainy day dam failure scenarios) as well as for each of the time-periods selected. Where PAR in a 'rainy day' dam failure scenario is required to be estimated, the PAR should be estimated separately for both the 'base flood without dam failure' and the 'base flood with dam failure' cases. An estimate of the incremental PAR for the 'rainy day' dam failure scenario can then be obtained by subtracting the estimate for the 'base flood without dam failure' case from the estimate for the 'base flood with dam failure' case. In all cases, it is recommended that total PAR estimates are rounded to the nearest whole number.

Table 2.7: Guidance for assigning occupancy rates for different places of occupation by permanent and temporary populations

Place of occupation	Description	Guidance on assigning occupancy rates
Permanent populations in habitable structures	Any structure that is occupied or maintained in a condition that allows it to be occupied by humans. This includes residential dwellings, commercial buildings, industrial buildings and community facilities such as schools, childcare facilities, churches and other public facilities such as libraries and swimming pools.	Residential dwelling occupancy rates are typically derived from demographic (Census) data for the area. Occupancy rates for other habitable structures can be obtained from a variety of sources, including: • Local information (e.g. discussion with regional or local councils, local residents or community groups) • Site inspections • Typical occupancy rates for commercial office or retail buildings (e.g. persons per m2 of building floor area).
Temporary populations in recreational areas	Designated areas that attract people for recreational activities. Some designated recreational areas along rivers, streams and their floodplains feature man-made improvements and structures such as boat ramps, public toilets, buildings, and large established campgrounds. Other designated recreation areas along rivers, streams and their floodplains attract people by providing opportunities for fishing, swimming, hiking, rafting, kayaking, etc. Recreational facilities in urban areas can be parks, playgrounds, sports fields, golf courses and other similar open-air facilities designed and intended to attract people	Occupancy rates for recreation areas are typically site specific and are should be sourced from local information (e.g. discussion with regional or local councils, Fish & Game New Zealand, Department of Conservation, local residents or community groups). In some cases, it may be necessary to conduct surveys of the downstream area, over a period of time, to determine the temporary population. Where site specific occupancy rates are not available, typical occupancy rates (e.g. persons per km2 of land area) from references such as King & Cousins (2015) may be considered.
Temporary populations in agricultural and horticultural areas	People working on agricultural or horticultural land	Occupancy rates for agricultural and horticultural land are typically site specific and should be sourced from local information (e.g. discussion with regional or local councils or land owners). Where site specific occupancy rates are not available, typical occupancy rates (e.g. persons per km2 of land area) from references such as King & Cousins (2015) may be considered.
Temporary populations on roads, cycleways and railways	People travelling on designated transportation routes	Temporary populations on transportation routes should be estimated by methods which consider the average daily traffic count (AADT) on each transportation route and the length of route exposed. Examples of such methods are summarised in Appendix 11 of DNRME (2018).

2.4.3.4 Potential Loss of Life

General

The PAR approach outlined in Section 2.4.3.3 only identifies the number of people likely to be directly exposed to dam-break flood inundation that could cause physical injury or a threat to life safety. An important subset of the PAR is an estimate of the number of fatalities that could be expected to occur during a hypothetical dam-break flood. This is termed “Potential Loss of Life” in the Regulations (2022).

Potential Loss of Life estimates are inherently difficult to develop. They depend on many uncertain and variable factors, such as the dam breach parameters, the topography of the area downstream of a dam, flood wave travel time, depth of flow, flow velocity, time of day, the amount of warning time, the responsiveness of people to evacuate when warned, the presence of suitable evacuation routes, historical patterns of human activity, and the general mobility of the population.

No simple, reliable, or universally applicable methodology is available for estimation of Potential Loss of Life. Different methods can produce very different estimates. However, in all cases, there are two components to the question of whether Potential Loss of Life could occur in a hypothetical dam failure situation:

1. Would the presence of people be reasonably expected at a location of interest?
2. Are the flow characteristics expected to be lethal at this location in the event of dam failure?

Due to the inherent uncertainties in Potential Loss of Life estimation methods, the assumptions, reasoning, and any supporting calculations used to derive estimates should be clearly documented.

Guidance on different commonly practiced methods of estimation of Potential Loss of Life for PIC assessment purposes are outlined in the following sub-sections. For the reasons outlined in Section 2.4.3.2, no allowances for evacuation, early warning systems, or other emergency actions by the adversely impacted population should be considered when evaluating Potential Loss of Life for PIC assessment purposes.

Qualitative assessment

Estimation of Potential Loss of Life may involve a qualitative approach which considers the population present within buildings and in other places of occupancy within the expected dam-break flood inundation area, and the anticipated level of flood hazard at each populated location. Informed judgement is required to infer whether potentially lethal flooding conditions would occur in the areas identified as contributing to the PAR, and to establish if loss of life is expected to be “no persons”, “one person” or “two or more persons” based on the Potential Loss of Life categories listed in Table 2.6. In such cases, it is always prudent to adopt a conservative approach, with the assumptions and reasoning clearly documented.

A qualitative assessment may be appropriate for estimation of Potential Loss of Life where it is self-evident that failure of a particular dam could cause the Potential Loss of Life to be either “no persons” (i.e. a small dam in a remote area with negligible PAR downstream) or “two or more persons” (e.g. a large dam immediately upstream of an urban area within the dam-break flood inundation zone reflecting a large PAR).

A qualitative assessment should be considered as an initial approach for assessing Potential Loss of Life. However, where the Potential Loss of Life cannot be clearly established as “no persons”, “one person” or “two or more persons”, then a quantitative approach (as described below) can be used.

In general, a qualitative assessment of Potential Loss of Life should be sufficient for PIC assessment purposes in most cases. Reliance on quantitative assessment approaches (as described below) can be misleading and deceptive due to the inherent uncertainties in the methodologies and their inputs.

RCEM – Reclamation Consequence Estimating Methodology
To estimate possible life loss from a hypothetical dam failure in support of a portfolio dam safety risk assessment, the United Sates Bureau of Reclamation (USBR) uses an empirical methodology known as the Reclamation Consequence Estimating Methodology (RCEM). Note that USBR uses the RCEM Potential Loss of Life estimates in support of dam safety risk assessments (refer Module 7, Section 4.5) and not for life loss estimates for PIC assessment purposes (Feinberg et al (2016)).

The RCEM method is documented in USBR (2015) and the methodology is not reproduced in these Guidelines. In general, the RCEM method estimates loss of life using the product of flood depth and velocity (referred to as DV), at locations where a component of the PAR has been identified, from curves fitted to fatality rate data derived from case histories of historic dam failure and natural flash flood events. Different fatality rates are provided for two emergency warning time categories, "little to no warning" and "adequate warning".

If the RCEM method is used to estimate Potential Loss of Life for PIC assessment purposes, typically for comprehensive assessment levels, the following application principles should apply:

- Fatality rates provided in USBR (2015) for the upper bound of the "suggested limit" for the "little to no warning" category should be used.
- Where Potential Loss of Life values estimated using the RCEM method are near the threshold of "one person" or "two or more persons" and could change the PIC from Low to Medium or Medium to High, sensitivity testing of key inputs and assumptions should be considered to provide greater confidence in the estimate. In all cases, judgement should be exercised to check results are reasonable.
- When using the RCEM method, Potential Loss of Life estimates are commonly not a whole number. Potential loss of life values should be rounded to the nearest whole number for PIC assessment purposes (e.g. a value between 0.5 and 1 should be considered as equal to 1). Note that a Potential Loss of Life value of less than 1 should not be interpreted as a numerical probability.

Advanced modelling tools
In addition to the methods listed above, more advanced modelling tools have been developed to estimate Potential Loss of Life from natural and/or dam failure floods (e.g. LifeSim developed by the US Army Corps of Engineers and the Life Safety Model (LSM) originally developed by BC Hydro and now marketed by HR Wallingford).

Both the LifeSim and LSM models provide a spatially distributed, dynamic simulation of a developing flood situation This means they simulate the passage of a hypothetical flood event over time (considering warning and mobilisation of people potentially exposed to the flood hazard), and predict the likely spatial distribution of impacted people and property. These models are referred to as "agent-based" simulators as they can simulate the response of individual people, buildings and vehicles (i.e. agents) in a floodplain and their interaction with a hypothetical dam-break or natural flood event. They use outputs from two-dimensional computational hydraulic models (e.g. depth and velocity information as a function of time) and couple them in a Geographic Information System (GIS) environment with a simulator that models the interaction of these agents with the floodwaters. This simulated interaction is based on mathematical models which include representations of human and vehicle stability and the structural vulnerability of buildings in floodwaters.

These more advanced models can be used for comprehensive level assessments and where detailed estimates of Potential Loss of Life may be required for densely populated areas downstream of a dam. However, as discussed above, qualitative inference may be able to be used to establish the Potential Loss of Life in the latter circumstance sufficiently to establish a dam's PIC classification without having to resort to such advanced methods.

LifeSim or LSM models are well suited to assist with exploring options for improving the effectiveness of emergency planning and response, and to provide inputs to quantitative risk assessments.

If a LifeSim or LSM model is used to estimate loss of life for PIC assessment purposes, Potential Loss of Life estimates should be evaluated explicitly from simulations where the population downstream of the dam receives no warning for evacuation.

Both the LifeSim and LSM models deal with uncertainty in input data through use of Monte Carlo sampling. As such, these models output a range of Potential Loss of Life values (e.g. minimum, 25th quartile, median, 75th quartile and maximum values). Where Potential Loss of Life estimates obtained using LifeSim or LSM models are near the threshold of "one person" or "two or more persons" and could change the PIC from Low to Medium or Medium to High, judgement is required to determine which value within the range is appropriate for PIC assessment purposes.

Other quantitative assessment tools
Other quantitative methods, outside of the RCEM, LifeSim and LSM methods listed above, may be appropriate to estimate Potential Loss of Life for PIC assessment purposes. Any such methods need to be an established and industry accepted practice and considered appropriate by a Technical Specialist.

The same application principles described above for the RCEM methodology should apply to other quantitative methods for estimating Potential Loss of Life for PIC assessment purposes.

2.4.4 Uncertainties in the Consequence Assessment Process

Dam-break consequence assessments typically involve a number of inputs (of varying levels of detail) and assumptions which require elements of judgement. Where uncertainties arise from the consequence assessment which could affect the PIC, sensitivity testing for key inputs and assumptions should be considered to provide greater confidence in the assigned PIC.

In all cases, the documentation for dam-break and consequence assessments should explain assumptions made, methodologies used and identify the sources of the information consulted (also refer Section 2.2.7 "Records/documentation").

3. Dam Potential Impact Classification

3.1 Method

A dam's PIC reflects the potential consequences from a hypothetical dam failure and, as such, forms the parameter on which recommended criteria for dam design, construction and operational safety assurance are based, as described in the other modules within these Guidelines.

Table 2.6 provides the framework for determination of a dam's PIC. The three key inputs to the table are:

- The assessed damage level (refer Section 2.4.2).
- The assessed Population at Risk (PAR) (refer Section 2.4.3).
- The assessed Potential Loss of Life (refer Section 2.4.3).

To determine the PIC of a dam, Table 2.6 is used to align the assessed damage level with the assessed PAR and Potential Loss of Life.

3.2 Using the Potential Impact Classification

Using the methodology outlined in Section 3.1, a dam is assigned a PIC based on the consequences of its failure.

The PIC for a dam has two primary uses:

- Application of the dam safety requirements included in the Building Act (2004) and Regulations (2022) (refer Module 1: Legal Requirements). The PIC for a dam should be based on the worst case consequence assessment resulting from hypothetical 'sunny day' and 'rainy day' failures. The Act (2004) and Regulations (2022) include a number of specific dam safety requirements for dams that are linked to the PIC (refer Module 5: Dam Safety Management and Module 6: Emergency Preparedness).
- The determination of appropriate design proficiencies, design loadings, quality assurance procedures, investigation and design methods, construction expertise and commissioning procedures (refer Module 3: Investigation, Design and Analysis). The use of PIC for these aspects of dam development and rehabilitation is not required by the Act (2004) or Regulations (2022), but has been a longstanding practice in New Zealand.

Subsidiary dams and appurtenant structures, which also support the reservoir, should also be allocated a PIC which reflects the consequences of their failure (refer Section 4).

3.3 Review of dam Potential Impact Classification

It is important to note that the PIC for a dam may change during its life due to the nature and occupation of the downstream area, or land use in the upstream catchment. For a tailings dam, the PIC may change during various stages of development, operation and closure. PICs should therefore be reviewed every five years, or whenever modifications to dams or their operational procedures could result in changes to the downstream consequences of a dam failure. Section 139 of the Act (2004) requires that a dam's PIC must be reviewed:

- Within 5 years after the Regional Authority approves, or is deemed to approve, the classification, and;
- After the first review, at intervals of not more than 5 years.
- Any time, building work that requires a building consent is carried out on the dam, and;
- Any time building work results, or could result, in a change of the potential impact of a failure of the dam on people, buildings, infrastructure, historical and cultural places , and the environment.

Note that where a dam or appurtenant structure has previously been assessed as High PIC, and where a consequence assessment is not otherwise required for emergency preparedness or risk assessment purposes, the Owner may elect not to complete a PIC review on the basis that the dam classification cannot be increased. However, there may be legislative requirements for the completion of PIC reviews and Owners should refer to Module 1: Legal Requirements.

The following questions should be considered during the review of a dam's PIC:

- Are the assumed potential failure modes and dam breach characteristics still appropriate?
- Have there been any changes to operational use that might affect assumptions incorporated in the previous PIC determination?
- Have there been any changes to downstream populations, property characteristics or infrastructure?

4. Subsidiary dams, canals and appurtenant structures

In situations where a dam has a subsidiary dam (e.g. a saddle dam), or a separate appurtenant structure, the consequences of a potential failure of each structure (main and subsidiary dam(s) and appurtenant structure(s)) should be assessed and each should be classified with its own PIC. This recognises that while the structures share the same reservoir they may have very different failure consequences, as determined by their inherent features and potential breach outflow paths. The same applies to embankment 'fill' sections of a canal, where each section (and each side) of the 'fill' embankment could have a different PIC. Examples with different features and dam- break flow paths are shown in Figure 4.1 for a dam with a saddle dam and in Figure 4.2 for a canal with multiple embankment 'fill' sections.

Consequence assessments for subsidiary dams, appurtenant structures and canal 'fill' sections should carefully consider potential failure modes and possible failure locations, and clearly establish the dam-break flow paths and consequences for each structure (or constituent components which may include gates and valves).

Similarly, saddle dams blocking off low sections of natural ground around the perimeter of a reservoir, and which have potential failure modes that could result in the uncontrolled release of the reservoir contents, should be evaluated for consequences of failure. Natural saddle dams could also be present along reservoir shorelines and should also be evaluated.

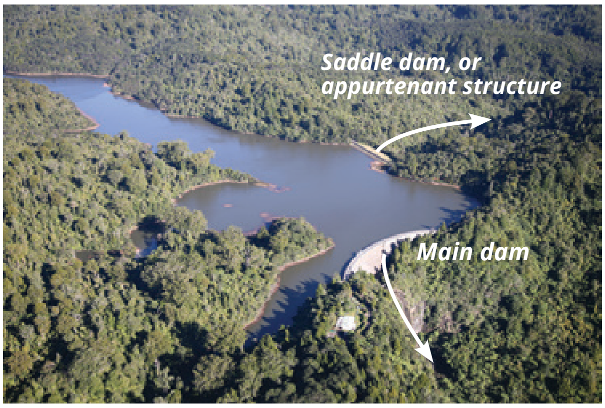

Figure 4.1: example of main and subsidiary dams with different features and dam-break flow paths (provided by Watercare Services).

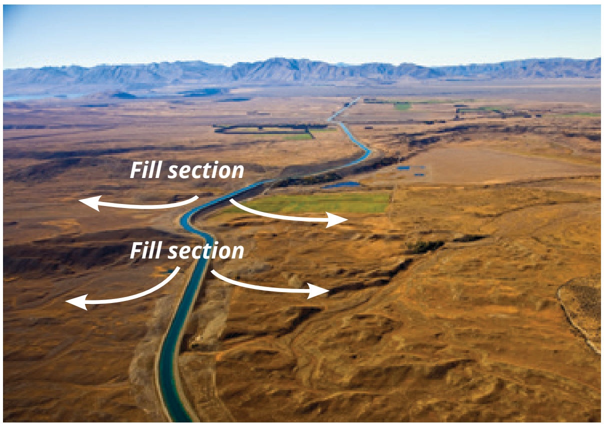

Figure 4.2: example of canal 'fill' sections with different features and dam-break flow paths (provided by Meridian Energy)

5. Issues to consider in dam- break flood hazard and consequence assessments

There are a number of factors that can lead to erroneous dam-break flood hazard and consequence assessments, thereby affecting the classification of a dam. The following insights are provided to reduce the likelihood of erroneous consequence assessments and dam potential impact classifications.

5.1 Choosing the right level of assessment

The level of consequence assessment should be commensurate with the indicated potential consequences of a dam failure. Typically, an iterative approach is appropriate where initial level qualitative analyses are utilised at the early stages, with decisions to proceed to more detailed levels of semi-quantitative and quantitative assessment being determined based on the emergent results of the earlier assessment. Refer to Section 2.2.1 for further guidance on levels of assessment.

Choosing an appropriate level of topographical information is also important and will have a significant bearing on the modelling of a dam-break flood wave. Where computational hydraulic modelling is considered to be warranted, the topographical information should be of a high enough resolution (e.g. a 1m Digital Elevation Model based on LiDAR topographic survey data) to allow the downstream area and potential dam-break flood inundation zone to be accurately represented in any model.

5.2 Concrete gravity and arch dams

Most dam breach modules within commercially available flood wave routing software packages assume that dam breach development occurs gradually over time. This assumption implies that quasi-steady weir flow occurs through the breach and that the surface of the reservoir remains approximately level as it drains through the breach. These behaviours are only appropriate for the failure of earthfill or rockfill dams.

For concrete gravity and arch dams, breach development occurs near instantaneously and the assumptions of quasi-steady weir flow through a breach and an approximately level reservoir surface as the reservoir drains through the breach are invalid. Special consideration needs to be given to the evaluation of a dam breach outflow hydrograph for a hypothetical failure of a concrete gravity or arch dam. The use of approximate analytical solutions is recommended for the evaluation of instantaneous or near instantaneous dam failures. USACE (1997) provides guidance for relatively long and narrow rectangular channels where the dam is completely removed.

5.3 Backwater effects in side valleys

It is important to consider the backflow of a dam-break flood wave and consequential inundation of side valleys (tributary waterways that join the main valley) downstream of a dam. While on initial appearance it may not seem likely that flooding could occur in downstream tributary valleys against the natural direction of flow, such valleys can be back-flooded with the flood inundation extending for several hundreds of metres or even kilometres depending on the valley slope.

In such situations, it is important to choose the right level of topographical information and ensure that side valleys are adequately covered within the domain of a computational hydraulic model.

5.4 Choosing the downstream extent of the assessment

When assessing dam failure consequences, it is important to choose an appropriate downstream extent for the flood hazard or consequence assessment. Not extending the downstream extent far enough can exclude effects further downstream and underestimate the population at risk and the level of damage.

An example is where a downstream river valley meets an open body of water. It should not be assumed that the body of water will not be affected by a dam-break flood wave passing through it. While the peak flow depths and velocities resulting from a dam break-flood wave through an open body of water may be significantly reduced, there could still be implications for recreational users on or near it. An understanding of the characteristics of the breach outflow hydrograph resulting from a hypothetical dam failure, and the hydraulic behaviour of the dam break flood wave through the body of water, are necessary to assess the likely effects of a dam failure on the body of water.

Care should also be exercised in selecting an appropriate downstream boundary condition for a computational hydraulic model for a dam-break flood hazard assessment. For example, for a tidal estuary, it may be appropriate to assume a constant water level corresponding to peak tide level if the size of the estuary is large relative to the size of the reservoir affected by the assumed dam failure. However, if the size of the tidal estuary is small relative to the size of the affected reservoir, then it may be necessary to shift the location of the downstream boundary in the model well beyond the mouth of the estuary into the open sea. For the 'rainy day' dam-break scenario, the effect of storm surge on the tidal boundary condition for a computational hydraulic model should also be considered.

The downstream extent of study should be established using the following criteria based on FEMA (2013):

- Dam breach flood flows are contained within a large downstream reservoir with no further downstream flooding;
- Dam breach flood flows are confined within the downstream channel; or
- Dam breach flood flows enter a bay or ocean (and downstream of any tidal estuary areas).
- The dam breach flood hazard is within the "H1" hazard threshold shown in Figure 2.9 and only affects a remote or sparsely populated area.

5.5 Time of day considerations

Consideration should be given to times during both normal working hours and after normal working hours, as the time of day can have a significant influence on the Population at Risk (PAR) exposed to a dam failure. For example, if the downstream area contains schools and commercial/retail areas, then the PAR may be much higher during normal working hours than after normal working hours. All consequence assessments used for determining the PIC of a dam should be based on the largest PAR, whether it occurs during normal working hours or outside of normal working hours. The methodology outlined in Section 2.4.3.3 provides a suitable framework for the estimation of population at risk taking into consideration temporal population movements.

5.6 Development changes

Development or a change in land use (e.g. conversion of farmland to residential subdivisions) or change in landform (e.g. due to mining activities) downstream of a dam can have marked effects on the consequences of dam failure and therefore the dam's PIC. Owners should periodically review their dam classifications to ensure they properly reflect any development changes in downstream catchments. As outlined in Section 3.3, PICs should be reviewed every 5 years, or whenever modifications to dams or their operational procedures could result in changes to the downstream consequences of a hypothetical dam failure.

5.7 Flood detention dams

Flood detention dams usually only impound water during storm inflow events although some such dams may impound a small permanent storage volume with an ability to store additional flood volume during storm conditions. For flood detention dams which do not have a permanent storage volume, there are no plausible 'sunny day' dam failure scenarios and consideration must be given to credible 'rainy day' dam failure scenarios. For flood detention dams which do have a small permanent storage volume, consideration must be given to both 'sunny day' and 'rainy day' failure scenarios which are credible.

Credible 'sunny day' failure scenarios for flood detention dams with a small permanent storage volume could include an internal erosion failure resulting from concentrated leakage along a crack through the dam body either adjacent to a concrete / fill interface or in the bulk fill material itself.

With flood detention dams, it is important to recognise that there is an inconsistency between the Inflow Design Flood (IDF) typically used for the design of flood detention dams in an urban environment (i.e. stormwater design standards) and the recommended Inflow Design Flood from a dam safety perspective (see Table 4.1 of Module 3). The IDFs from Table 4.1 are a function of the PIC of a dam, the downstream PAR impacted by a hypothetical failure of that dam, and the Potential Loss of Life arising from the dam failure.

The 'rainy day' failure scenarios considered may include the following cases:

- Failure during a moderate reservoir inflow flood (e.g. a 1 in 100 Annual Exceedance Probability (AEP)) at the "full impoundment" condition with no dam crest overspill and unblocked outlets.
- Failure during the IDF with a small amount of dam crest overspill.

The first case represents one typically used for stormwater design purposes. The second case represents a typical 'rainy day' failure scenario applied to other types of dams for PIC purposes and is extreme in stormwater management terms. It should include consideration of the potential for blockage or partial blockage of outlets by flood-transported debris.

The "no dam failure" scenario corresponding to each of these 'rainy day' dam failure scenarios also needs to be considered as it provides the base case from which the incremental effects of the 'rainy day' dam failure are determined.

For both a 'rainy day' dam failure scenario and the corresponding "no dam failure" scenario, careful consideration needs to be given to tributary inflows downstream of the flood detention dam (refer also to Section 2.3.4).

The selection of the extreme IDF for the second rainy day failure scenario above may require an initial guess at the PIC of a flood detention dam and the use of Table 4.1 in Module 3 to determine a suitable AEP for the IDF. A preliminary consequence assessment can then be carried out and a feedback loop applied to check the initial PIC guess and revise it if necessary. A final consequence assessment can then be completed to confirm the PIC of the dam.

It should be noted that it is not necessarily the most extreme IDF scenario that gives rise to the worst incremental consequences downstream for a 'rainy day' dam failure. Sometimes it is the 'rainy day' dam-break flood resulting from a smaller IDF which produces the worst incremental consequences downstream in terms of maximum incremental flood depths and extents.

The more extreme AEP values in Table 4.1 of Module 3 recommended for IDF selection well exceed those typically used for urban stormwater design. This will require extrapolation of the rainfall frequency data applied to any rainfall/runoff model used to evaluate the required IDF hydrograph.

The establishment of credible potential failure modes for a flood detention dam needs to consider a range of factors including:

- Possible blockage of the primary outlet facility by debris.
- The potential for an internal erosion type failure associated with the primary outlet facility through the dam body or through the dam foundation.
- The maximum reservoir impoundment level.
- The duration of impoundment relative to the time for a dam breach to be initiated and then progressively develop.
- The magnitude and duration of discharge from any secondary overflow spillway.
- The duration of any dam overtopping.
- The slope of the downstream face of the dam and the maximum flow velocities down that face.
- The erodibility of the dam materials and any grass cover.

Flood detention dams are frequently located in urban areas with a dense concentration of population downstream. In such cases, the dam-break consequence assessment needs to consider the complexity of the range of building types and places of occupation in an urban setting. People, property and other features on the reservoir rim, upstream of the dam, may be impacted due to the rise in reservoir water level under extreme flood conditions. These need to be accounted for as part of the dam-break flood hazard and consequence assessment process.

5.8 Dams with a large operational range

For dams with a large operational range (e.g. in the order of metres or tens of metres) that may vary from one extreme to the other seasonally or more frequently, the potential consequences of failure should be assessed assuming the impounded reservoir is full at its maximum design level at the time of dam failure.

5.9 Tailings dams and dams with highly sedimented reservoirs

Tailings storage facilities (TSF) can incorporate dam structures which impound by-products of mining or industrial and agricultural operations, often storing a zone of supernatant liquid on top of the tailing deposits (i.e. a supernatant pond). The properties of tailing deposits vary greatly between different TSF's, but in general the tailings exist as a mixture of water and solids. The physical properties of the tailings can also change over the lifecycle of a TSF due to a reduction in water content, consolidation and desiccation, or due to chemical effects.

A hypothetical failure of a dam retaining tailings at a TSF needs special consideration as the contents of the tailings pond may flow differently to water (i.e. as a non-Newtonian fluid flow) and contain potentially hazardous substances. Also the rheometric properties of the tailings material could influence the dam breach geometry, the released volume in the breach outflow, the peak discharge, the flood wave propagation and inundation extents.

Apart from the hazard resulting from propagation of the dam-break flood downstream, the release of the tailings material could also contaminate the downstream flood inundation area and have an adverse impact on the environment. The potential consequences of long-term ecological damage from contamination due to the release of tailings material into a downstream watercourse and valley should be taken into account when assessing the PIC of a tailings dam.

Dam-break flood hazard and consequence assessments for TSFs should be conducted using established and industry recommended practice such as that contained in the Canadian Dam Association guidance document "Tailings Dam Breach Analysis" (CDA, 2021).

Similar considerations may apply for water storage, irrigation and hydroelectric dams that have accumulated large amounts of sediment (and potentially hazardous substances) in their reservoirs.

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MODULE 3
INVESTIGATION DESIGN AND ANALYSIS

Abstract

Dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, operation, assessment and rehabilitation of dams in New Zealand are included in the Parent Document. The Parent Document also includes a glossary of terms used in these Guidelines.

This module provides a framework for the investigation and design of new dams, the analysis of existing dams, and the design of rehabilitation works for existing dams. It includes:

- An outline of various dam types and issues that should receive close attention during their design.
- Recommended personnel and quality assurance procedures for the design of new dams and the design of rehabilitation works for existing dams.
- A discussion on the assessment of hazards and threats to the safety of a dam, and recommended performance criteria for flood, earthquake and other hazards.
- An outline of investigation activities that should be addressed during the initial stages of dam design or the initial stages of a dam rehabilitation project.
- Recommended criteria for the design and evaluation of dams and appurtenant structures, and issues that impact on dam safety that should be carefully considered during the design process.
- Recommendations relating to the design and installation of instrumentation systems for the monitoring of dam performance.
- Recommendations relating to design involvement during initial construction, commissioning and rehabilitation, and design documentation.

A summary of the recommended performance criteria for Low, Medium and High PIC (Potential Impact Classification) dams is presented in Table 1.

Table 1: Recommended Performance Criteria for Low, Medium and High PIC Dams

Hazard	Performance Criteria	PIC		
		Low	Medium	High
Wind and waves	Adopted freeboard for embankment dams should be the largest of the following three freeboard requirements:			
	Freeboard at Maximum Normal Reservoir Level	Wind set up and wave run up for the highest 10% of waves caused by a sustained wind speed, which is dependent on the fetch, with an AEP(1) of greater than 1 in 100.		
	Freeboard at Intermediate Flood Levels	Freeboard should be determined so that it has a remote probability of being exceeded by any combination of wind generated waves, wind set up and reservoir level occurring simultaneously.		
	Freeboard at Maximum Reservoir Level during the Inflow Design Flood (IDF)	The greater of (a) 0.9m or (b) the sum of the wind set up and wave run up for the highest 10% of waves caused by a sustained wind speed, which is dependent on the fetch, with an AEP(1) of 1 in 10; .		
Flood	Inflow Design Flood (IDF)	1 in 100 AEP to 1 in 1,000 AEP	1 in 1,000 AEP to 1 in 10,000 AEP(2)	1 in 10,000 AEP to PMF(3)
Earthquake	Operating Basis Earthquake (OBE)	1 in 150 AEP		
	Safety Evaluation Earthquake (SEE)	50th percentile level for the CME(4) if developed by a deterministic approach, and if developed by a probabilistic approach then at least a 1 in 500 AEP ground motion but need not exceed the 1 in 1,000 AEP ground motion.	50th to the 84th percentile level for the CME if developed by a deterministic approach, and need not exceed the 1 in 2,500 AEP ground motion developed by a probabilistic approach.	84th percentile level for the CME if developed by a deterministic approach, and need not exceed the 1 in 10,000 AEP ground motion developed by a probabilistic approach.

Notes:

1. AEP is Annual Exceedance Probability
2. Recommended IDF is dependent on population at risk (PAR) and Potential Loss of Life.
3. Recommended IDF is dependent on Potential Loss of Life.
4. CME is Controlling Maximum Earthquake

Advances in knowledge and improved techniques continue world-wide and these Guidelines should be interpreted and applied accordingly. Validation of new and advanced techniques should be completed before they are adopted for use in New Zealand.

This module includes limited discussion on the role of Regulators in dam safety and reference should be made to Module 1 (Legal Requirements) for a more complete description of their role and responsibilities.

Notice to reader

While this module has been configured to be, as much as practicable, self-contained from a technical perspective, the reader should be conversant with the principles, objectives and limitations expressed in the Parent Document prior to considering the information provided in this or any other individual module.

Document history

Release	Date	Released with
Original	May 2015	Parent and all modules
2023	December 2023	Updates to Parent and Modules 1, 2 and 5

Contents

1. Introduction

1.1 Principles and objectives

There are a number of natural hazards (e.g. floods and earthquakes) that can affect the safety of a dam and cannot be controlled by the dam Owner. In addition, there are a number of threats relating to human activities (e.g. oversights, errors) that can affect the safety of a dam and can be controlled by the dam Owner. The investigation, design and rehabilitation of dams should identify and take into consideration all of the identified hazards and threats to dam safety and be cognisant of the associated consequences of dam failure. Principle 2 in the Parent Document states that:

All natural hazards, loading conditions, potential failure modes and any other threats to the safe design, construction, commissioning, operation and rehabilitation of a dam should be identified.

Natural hazards that can affect dam safety and therefore need to be considered in the investigation and design of dams include floods, earthquakes, landslides, high rainfall and/or wind events, lightning strikes and volcanic activity. Other threats to dam safety that can usually be controlled by the Owner may arise from errors and omissions in design, inadequate specification or supervision of construction, inappropriate operation, inadequate maintenance and inadequate surveillance. Other threats that cannot be controlled but can be addressed by the Owner include vandalism and security breaches.

Principle 3 in the Parent Document states that:

Dams and appurtenant structures should be designed, constructed, commissioned, operated and rehabilitated in a manner which ensures they meet appropriate performance criteria.

Design criteria should always be commensurate with the consequences of dam failure. In addition, care should always be taken to ensure that the design is not adversely affected by subsequent construction, commissioning and operational practices.

The competence and experience of participants in the design, construction and operation of a dam, and their relationship and continuity through investigation, design, construction and commissioning are key factors in successful dam ownership. Appropriate funding and work programmes should be applied throughout all investigation, design, construction and commissioning activities to ensure all issues critical to dam safety are appropriately considered and addressed. Effective quality assurance is essential to verify the design, to verify the design changes made in response to knowledge gained during design and construction, and to verify that the design intent is achieved during construction.

All designs must include a thorough evaluation of dam safety risks and the measures to control them, with a focus on providing affordable and resilient backup features and systems to support primary features and systems.

The objectives of this module are to provide guidance for Owners, Designers and Contractors responsible for the investigation, design, performance monitoring, evaluation and rehabilitation of dams.

Note: Specific investigation, design and analysis methods are not addressed; however, a list of reference documents is included at the end of the module to assist the Designer in the selection and completion of specific investigation and design tasks.

1.2 Design Considerations

1.2.1 Design Requirements

The Designer's objective is to design a dam and its associated structures, or a dam rehabilitation, in a manner that suitably reflects the characteristics of the site, the loading conditions applicable to the site, and the consequences of dam failure. To obtain a building consent for construction, the Designer must demonstrate that the design has considered all hazards at a level appropriate to the consequences of dam failure, and that the hazards are accounted for and their effects satisfactorily mitigated. The Designer must also demonstrate that the completed structure will meet durability requirements and achieve the specified intended life for the structure. Module 1 outlines New Zealand's current legislative requirements included in the Building Act and Building (Dam Safety) Regulations for the development and operation of dams.

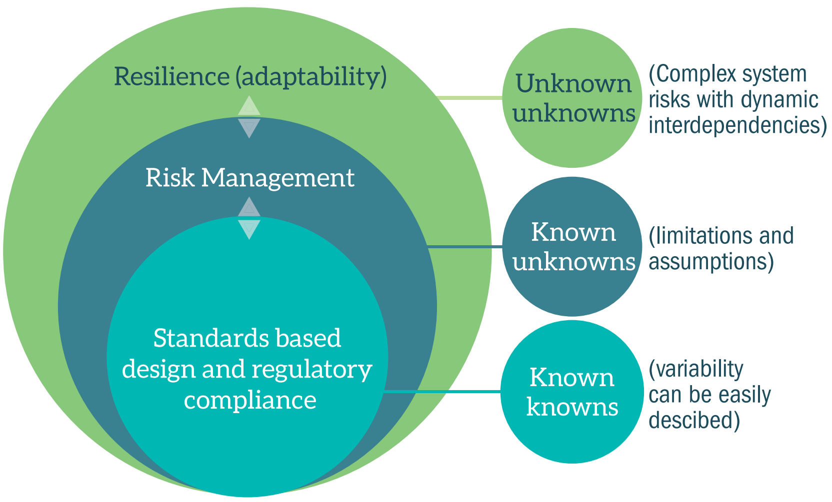
The Designer needs to recognise that not all elements of dam structures requiring design are adequately covered by design manuals or standards. The Designer is required to assess all realistic risks and demonstrate how the design will reduce risks to as low as reasonably practicable (i.e. to the point that risk reduction is impractical or its cost is grossly disproportionate to the improvement gained). Attention needs to be directed not only towards extreme event loads of very low probability, that place high structural demands on the dam, but also unforeseen combinations of usual events that could affect dam safety.

These Guidelines promote the use of robust and resilient features and systems to reduce the risk of dam failure from unexpected and unpredictable events and occurrences. Resilience in this context is the capacity of the structure or system to withstand changing conditions caused by sudden shocks, gradual stresses and cumulative change. This is not implying gold plating or gross conservatism, but sound and efficient design which provides long term dam safety assurance. Recognising the uncertainties associated with design parameters, such as the adoption of idealised design loads, the incorporation of resilient features should provide greater confidence in the facility meeting its performance criteria. Resilience may influence the type of dam selected, the dimensions of the dam, and the defensive design features adopted for the dam, and should be considered in the design or rehabilitation of any dam irrespective of its PIC.

Dams typically have a long operational life. Interventions and upgrades following initial commissioning can be expensive and result in increased dam safety risks during their implementation. Robust design, resilient features and a whole-of-life approach contribute significantly to ongoing dam safety assurance. The design lives of all components should be considered and elements with shorter design lives than the overall water retaining structure should ideally be readily replaceable without compromising the safety of the dam.

The relationship between the above considerations is shown in Figure 1.1.

Figure 1.1: Risk and Resilience in Design



Note: The boundaries in the diagram are not absolute. For example, standards based design usually incorporates the consideration of risk and resilience.

The context surrounding the physical dam structure needs to be considered in dam design. Dams are generally a component of a larger system (e.g. hydropower, water supply or irrigation) and the dam's role in the overall system is important. The loss of dam operation will affect the facility or infrastructure that it supports (e.g. no irrigation supply, reduced power generation, instability in the power transmission system, reduction in water supply, prevention of mining operations) and the design needs to consider the integral role and performance requirements for the dam in the overall system.

During the development of a design the Designer should consider health and safety issues that could arise during construction and operation. The design should be able to be constructed without introducing health and safety risks that a reasonably skilled Contractor cannot manage. Similarly, design features should not introduce health and safety risks that are unable to be effectively managed by operational personnel during the operational phase of the project.

These Guidelines provide guidance for the design of new dams, the evaluation of existing dams and the rehabilitation of existing dams. The design criteria, design considerations and design philosophy for the rehabilitation of existing dams are, in general, the same as those for the design of new dams.

The Owner may propose structural measures to reduce the risk of dam failure or non-structural measures to reduce the consequences of dam failure. Non-structural measures are more likely to involve other parties and stakeholders, and consultation with affected parties may be necessary during the development of proposed non-structural risk reduction measures. Consultation with affected parties may also be necessary before implementation of proposed structural rehabilitation works. The management of rehabilitation works is addressed in Module 7.

1.2.2 Consequences of Failure, PIC and Design Loads

In New Zealand the PIC is used to partition dams into broad hazard categories based on consequence assessment. Many countries use this approach to determine the level of design, construction and operational rigour that should be employed throughout the life of the structure. It is common in similar jurisdictions internationally that design and assessment criteria apply higher levels of dam safety when the consequences of dam failure are greater.

Module 2 provides guidelines for assessing the consequences of dam failure and determining the PIC for a dam. Both 'rainy day' and 'sunny day' failure scenarios should be considered, the consequences of each potential failure scenario should be assessed, and the PIC determination should be based on the scenario that has the worst consequence.

The resulting PIC for the dam drives the level of the design, construction and operational rigour that should be employed throughout the life of the structure. The design loads for the dam are primarily linked to the PIC for the dam, although the Designer may be able to demonstrate that lesser consequences could relate to a particular load case than the consequences that drove the PIC assessment. Such an example may be a flood detention dam which clearly has a function in an extreme flood event but is very rarely filled and therefore the exposure time to earthquake risk is very small. The premise in this module is that the design loads reflect the PIC of the dam, unless the Designer can demonstrate that a lower design load is appropriate.

Design loading conditions for various dam types are presented and discussed in various ANCOLD guidelines, Canadian Dam Association (2007), and various USACE and USBR engineering manuals. It is commonly accepted internationally that two extreme loading conditions do not need to be considered to occur at the same time. However, it is important to establish that the dam would not fail due to the effects of a combination of realistic loading conditions. Therefore, the Designer should consider the effects of one type of hazard occurring closely followed by perhaps a moderate event of the other type of hazard. For example, a dam damaged by a major earthquake may experience a significant aftershock or moderate flood before repairs can be completed. The dam should be able to withstand the second hazard in a damaged condition without failure.

Module 2 notes that separate PICs can be applied to a dam, subsidiary dam and appurtenant structure if the consequences of their failure are different. A gate and/or valve system (gate and/or valve together with its power supply and control/protection/communication systems) that fulfils a dam safety function, and is installed in a dam, subsidiary dam or appurtenant structure, is not assigned a PIC; however, the purpose of the gate and/or valve system must be understood and the design solution must ensure that the gate and/or valve system is able to perform its dam safety function. The dam, subsidiary dam or appurtenant structure must not fail due to a functional failure of the gate and/or valve system.

1.2.3 Potential Failure Modes

A potential failure mode is a mechanism or set of circumstances that could result in the uncontrolled release of all or part of the contents of a reservoir. Avoidance of a potential dam failure mode, or mitigation to prevent or reduce the likelihood of a potential dam failure mode eventuating, is a cornerstone of effective dam design.

While this has always been an inherent expectation of dam design, formal consideration of potential failure modes is promoted in these Guidelines as an informed approach to reduce the risk of dam failure; particularly those aspects not generally covered by standards based design. Identified potential failure modes provide valuable information about a dam which should be shared across design, surveillance and monitoring, safety review and rehabilitation activities. Identifying, describing and evaluating potential site-specific dam failure modes are arguably the most important steps in evaluating the safety of a dam.

1.3 Scope of Module

1. This module provides a framework for the investigation and design of new dams, the evaluation of existing dams, and the design of rehabilitation works for existing dams. It includes:

- An outline of various dam types and issues that should receive close attention during their design.
- Recommended personnel and quality assurance procedures for the design of dams and rehabilitation works.
- A discussion on the assessment of hazards.
- An outline of investigation activities that should be addressed during the initial stages of dam design or the initial stages of a dam rehabilitation project.
- Recommended design criteria for new dams and appurtenant structures, and the rehabilitation of existing dams and appurtenant structures, and issues that impact on dam safety and should be carefully considered during the design process.
- Recommendations relating to the design and installation of instrumentation systems for the monitoring of dam performance.
- Recommendations relating to design involvement during construction and commissioning, and design documentation.

A list of reference documents is included at the end of the module to assist Designers in the selection of appropriate analytical methods and the completion of specific design tasks.

2. Dams, dam types and related factors

Dams are mainly used for:

- Water storage (dams) and conveyance (canals) for community water supplies, irrigation and hydropower generation.
- Flood detention (special purpose dams and stopbanks).
- Storage of mine tailings and other wastes and residues.
- Pollution control and water treatment.
- Recreation.

The use and associated life of a dam can have a significant bearing on design requirements and standards, and need to be appropriately considered for each dam. Most references tend to approach dam design from the perspective of dams which normally have consistently high reservoir levels. However, flood detention and tailings dams usually vary from the usual condition and warrant a modified approach. By way of example:

- A flood detention dam has short exposure times to high reservoir levels which usually means that internal piezometric pressures that can develop during short-term high reservoir levels are substantially lower than those that exist in a dam that maintains a high reservoir level. Conversely, a low level conduit in a flood detention dam passes normal flows at valley floor level at all times, which may mean passing bed loads with significant erosion potential. Thus care needs to be taken in the design to account for the wide reservoir level variations and the longevity and practical repair of the low level conduit.
- River flood protection banks, usually called 'stopbanks' in New Zealand, constitute an elongated flood detention dam. While the Building Act (2004) specifically states that a dam "does not include a stopbank designed to control floodwaters", Owners and Designers of stopbanks should consider applying these Guidelines to stopbank design.
- A tailings dam has a relatively short operating life and is rehabilitated to a 'walk away' situation which is quite different from a 'normal' dam. The short operating life may warrant one set of design criteria and the rehabilitation condition will usually require different design criteria. The environmental hazard of potentially toxic materials in the dam structure, or stored upstream of the dam, may warrant a much higher level of material and seepage control than that required for a dam storing chemically neutral materials.

The above examples illustrate the need to identify and appreciate specific design factors and criteria and avoid the inappropriate application of text book designs.

There are various types of embankment and concrete dams which are described in sections 6.5 to 6.10 of this module. Some of the significant factors which should be recognised and addressed during the design, construction, evaluation and rehabilitation of the more common dam types are as follows.

Earthfill dams

- foundation materials that have low strengths and are prone to instability and excessive settlement (e.g. estuarine deposits and thick deposits of soft and compressible soils)
- foundations in Karstic areas (areas of irregular limestone in which erosion has produced fissures, sinkholes, underground streams and caverns).
- open joints in the foundation rock allowing seepage flow under the dam with little head loss and resulting artesian conditions at or downstream of the dam toe
- the need for foundation treatments at and along the contact with the embankment to ensure embankment materials cannot be piped into open joints or fractures in the foundation
- the importance of abutments with smooth profiles and without steps or irregularities that could result in arching or inadequate compaction at the foundation contact and encourage the development of preferential paths for seepage and seepage erosion

- the importance of good foundation preparation and appropriate design of filter and drainage materials for the effective control of seepage
- the potential for contamination of and/or segregation of filters and drains through poor production or placement techniques
- the potential for low levels of on-site supervision to result in near horizontal preferential seepage paths, high seepage flow volumes and velocities, or high internal pressures
- the vulnerability of certain New Zealand materials, such as loess and central North Island pumiceous deposits, to erosion or piping and the extreme care that needs to be taken in their use
- the care that needs to be taken in the use of dispersive soils.

Zoned earthfill and rockfill dams, and concrete faced rockfill dams

- the quality of the foundation for seepage control in upstream sloping core, central core or concrete faced rockfill dams requires close attention
- the foundation must be capable of withstanding high hydraulic gradients
- the transition materials in a sloping core or central core rockfill dam must be capable of preventing erosion and allowing effective drainage of seepage flows
- the durability, compressibility and permeability of the rockfill must be sufficient to limit face slab deflections and allow controlled drainage of seepage flows
- the care that needs to be taken in the design of the joint between the concrete plinth and the concrete face slab in a concrete faced rockfill dam to minimise the potential for deformation and leakage
- the care that needs to be taken in the design of transition materials downstream of the concrete facing and plinth in a concrete faced rockfill dam to restrict seepage flows through the dam in the event of damage to the concrete face slab.

Concrete gravity, hardfill and roller compacted concrete (RCC) dams

- the care that needs to be taken in the investigation, evaluation and treatment of foundation discontinuities (i.e. joints, shears and faults) that could individually or in combination affect the stability of the dam
- the use and effectiveness of foundation drains and internal drainage systems for the control of uplift pressures
- the choice of materials that will not degrade during the long term life of the structure due to their chemical reactivity or chemical attack from the stored reservoir contents
- the upstream facing system and lift joint treatments in hardfill and RCC dams for the effective control of seepage
- the design needs to appreciate the adverse effects that weak or deformable foundations, and uncontrolled heat of hydration may have on concrete stresses within the dam.

Concrete buttress dams

- the care that needs to be taken in the investigation, evaluation and treatment of foundation discontinuities (i.e. joints, shears and faults) that could individually or in combination affect the stability of the dam
- the foundations need to be able to withstand concentrated buttress forces, particularly under earthquake loading
- the foundation must be capable of withstanding high hydraulic gradients
- temperature effects are also important.

Concrete arch dams

- the care that needs to be taken in the investigation, evaluation and treatment of foundation discontinuities (i.e. joints, shears and faults) that could individually or in combination affect the stability of the dam
- the care that needs to be taken in determining the effective deformation modulus for the abutments and foundation, as a variation in the modulus will affect the ability of the abutments to support the arch thrusts and result in a redistribution of stresses in the dam and the loads on the abutments
- the foundations and abutments must be able to carry gravity loads and arch thrusts
- arch dam design is highly complex and requires a high level of specialisation in arch dam analysis
- the abutments and foundation must be capable of withstanding high hydraulic gradients
- the care that must be taken in determining piezometric pressures that develop along the planes of potential foundation and abutment failure blocks and wedges, as they can contribute both uplift and driving forces and reduce foundation and abutment stability
- temperature effects are also important.

3. Personnel and quality assurance

3.1 Introduction

It needs to be appreciated that dam engineering is a mixture of science and art. Although physics and mathematics play important roles, significant reliance is also placed on experience and engineering judgement. No matter how complete investigation and design methods may be, they can in no way replace the exercise of competent and experienced judgement.

Owners responsible for the development or rehabilitation of dams should seek advice on current dam engineering practice to ensure dam safety is not compromised by their decisions. In some cases Owner organisations with dam portfolios will have in-house personnel with sufficient experience to make sound decisions relating to the investigation, design, construction, commissioning, rehabilitation and operation of a dam. However, in other cases where in-house personnel experience is limited, an Owner should consider appointing an Owner's Engineer to assist in all decision making relating to the development or rehabilitation of a dam. Owner decisions that can have significant adverse effects on dam safety include:

- *The appointment of organisations and personnel with insufficient qualifications and experience for the investigation, design, construction, commissioning, evaluation, rehabilitation and operation of a dam.* All appointed personnel should be suitably qualified and experienced in the development and operation of dam projects similar to that proposed by the Owner.
- *The appointment of different organisations and personnel to complete the design, construction supervision, and performance review during the commissioning of a dam.* The continued involvement of design personnel during construction and commissioning is strongly recommended to ensure that the design intent is correctly interpreted and proper account is taken of the effects of any site conditions that prove to be different from those assumed in the design. Such changes may not be obvious to people other than the Designer or senior members of the design team. Quoting from the US Federal Guidelines for Dam Safety (FEMA #93) "the design function can never be considered finished as long as the dam remains in place - design involvement should continue throughout construction and operation of the project." While this statement extends into the operation of a dam, it is generally recognised that appropriately qualified and experienced personnel different from the original Designer may address design issues once the project is fully operational.
- *The allocation of insufficient funds for the investigation and design of a dam, or the rehabilitation of an existing dam.* The investigation, design and rehabilitation of dams must address a variety of knowns and unknowns, and sufficient funds must be allocated to ensure that dam safety is not compromised by inadequate practices. The Owner has legal responsibility for the dam, so inadequate funding for investigation, design or rehabilitation will reflect on the Owner in the event of a dam safety incident or dam failure. Proper investigation, design and rehabilitation require that all critical issues are identified, investigated and resolved.
- *The allocation of insufficient time for the investigation and design of a dam, or the rehabilitation of an existing dam.* Allowing or ensuring sufficient time for thorough investigation and design is sometimes overlooked in the pressure to make progress once a final decision to proceed is made. Owners must be realistic about the time necessary for the completion of investigation and design activities. It is considered prudent to assess the risk and cost implications of reduced effort in the investigation phase against the costs associated with the discovery of unforeseen foundation conditions during the construction phase. Projects which do not include a thorough investigation have a much higher likelihood of unexpected or adverse conditions arising during construction.

The following subsections outline appropriate personnel and quality assurance procedures for the investigation and design of Low, Medium and High PIC dams, and the rehabilitation of existing Low, Medium and High PIC dams.

3.2 Low PIC Dams

The Lead Designer should have had prior experience in the design of dams similar to the proposed dam type. The Lead Designer has an ethical duty to recognise any capability limitations in the design team and seek expert advice to address the capability limitations and any unforeseen conditions that arise during investigation or construction. Expert advice that should be available includes:

- Specialist hydrological support for the estimation of flood flows.
- Specialist geological/geotechnical support where the dam foundation incorporates unusual features.
- Specialist mechanical and electrical support where the project incorporates gate and/or valve systems that fulfil dam safety functions (e.g. spillway gates and their associated controls).

A formal peer review of the investigation and design, by an independent experienced engineer, is not considered essential but may be required in order to obtain a building consent. However, irrespective of whether or not an independent peer review is completed, the Lead Designer should have in place an appropriate in-house quality assurance system to regularly review the work and ensure that the investigation and design processes properly address all engineering issues relating to the project. In some cases it may be appropriate to seek support from technical specialists to address specific engineering issues, particularly during the initial conceptual phases of a project.

3.3 Medium PIC Dams

The Lead Designer should have had prior experience as a Lead Designer for a similar Medium PIC dam, or should have been a major contributor to the design of a similar Medium PIC dam. The design team should also include:

- Specialist hydrological support for the estimation of flood flows.
- Specialist geological and geotechnical personnel with prior experience in the assessment of dam foundations, the assessment of embankment materials, and the use of embankment materials in the design of dams.
- Specialist personnel with prior experience in the design and placement of concrete materials (concrete mix design, aggregate quality, durability and temperature control).
- Specialist personnel with prior experience in the design of hydraulic structures (e.g. spillways, intake structures).
- Specialist mechanical and electrical personnel with prior relevant experience in the design of equipment and control systems that fulfil dam safety functions (e.g. spillway gates and their associated controls).

A formal peer review of the investigation and design, by an independent experienced engineer, should be completed. It should include an early initial review, to ensure that the design concept is appropriate for the proposed site and available construction materials, and regular reviews at appropriate intervals during the investigation, design and construction.

Formal in-house systems for the planning, checking and reviewing of all investigation and design work should be in accordance with a Quality Plan. The Quality Plan, which will vary in scope and detail depending on the project, should include:

- A detailed investigation and design Brief setting out objectives, data sources and assumptions, engineering design criteria, standards, methods of analysis, and the like.
- Description statements of personnel responsibilities and interdisciplinary interfacing.
- A means for handling design changes that arise during design and construction.
- Communication and documentation requirements.

3.4 High PIC Dams

The Lead Designer should have had prior experience as a Lead Designer for a similar High PIC dam, or should have been a major contributor to the design of a similar High PIC dam. The design team should also include specialist personnel with appropriate qualifications and prior experience in all areas of investigation and design, including those identified above for a Medium PIC dam.

A formal peer review of the investigation, design and construction by an independent experienced engineer should be a mandatory requirement. The Reviewer(s) should have a sound background of experience in the type of dam being designed and constructed. There are some basic tenets which should be followed to achieve the most effective and co-operative peer review. They include:

- Appointing a Board of peer reviewers where the dam includes a number of features that cannot be effectively addressed by a single peer reviewer (e.g. dam embankment, spillway and low level outlet structures, gates and control systems).
- Commencing peer review early in the design process to ensure that the design concept and investigation are appropriate for the proposed site and available construction materials.
- Encouraging good and regular communication between the Reviewer and the Designer.
- Briefing the Reviewer to assess, discuss and provide formal comment on areas considered to be important for dam safety.
- Ensuring that the Reviewer does not become the 'Designer' of the dam by including this principle in the peer review contract, and ensuring all designs are developed and proposed by the Designer. Practice Note 2, published by IPENZ in June 2003, provides guidance for reviewing the work of another engineer.
- Having a mechanism agreed between all parties for resolving any areas where the Reviewer and Designer have strongly opposing views and the Designer does not support the Reviewer's proposals. For example, the Reviewer may propose a more expensive way of achieving a particular design objective. Ultimately all differences should be resolved.
- The design must remain the Designer's responsibility.

Formal in-house systems for the planning, checking and reviewing of all investigation and design work should be in accordance with a Quality Plan satisfying the requirements of an appropriate quality assurance system (e.g. ISO 9001:2008). The Plan should include those items outlined above for Medium PIC dams and additional detail to adequately cover all specialist inputs to the project. Adherence to the Quality Plan is of prime importance.

3.5 Producer Statements

Refer section 3.5 in Module 1: Legal Requirements.

4. Hazards, threats and performance criteria

4.1 Introduction

There are a number of natural hazards that can affect the safety of a dam. The primary natural hazard during the construction of a new dam, or the rehabilitation of an existing dam, is a flood that exceeds the discharge capacity of the diversion works during initial construction or the available discharge capacity during the completion of a rehabilitation project. Natural hazards during commissioning and operation are primarily floods and earthquakes; however, there are also a number of reservoir related hazards such as landslides, reservoir induced seismicity, high winds and waves, and seiches developed by fault movement or landslides into the reservoir that can affect dam safety. In some areas of New Zealand volcanic hazards are also present.

In addition to natural hazards, there are a number of threats relating to human activities that can affect the safety of a dam. Some of the threats (e.g. human errors, oversights, inadequate supervision) can usually be controlled by the Owner while others (e.g. security breaches and vandalism) cannot be controlled but can be addressed by the Owner.

Owners and Designers have an obligation to identify and assess all natural hazards and threats relating to a proposed development or a proposed rehabilitation project, and adopt procedures which reduce the hazards and threats to acceptable levels of risk. In dam engineering this is normally achieved through the classification of a dam, according to the consequences that would result from a dam failure, and the adoption of appropriate design criteria that reflect the consequences. These Guidelines utilise criteria that are closely aligned to those recommended in internationally recognised dam engineering publications. In some cases consent processes and legal precedents may set design criteria which are more stringent than those recommended in internationally recognised publications. For example, a consent process could result in far more stringent seepage control measures for a tailings dam than for a water supply dam. In addition, minimum design criteria could be set by the Owner's insurers.

In some countries risk assessment has been utilised as a tool to assist in establishing appropriate design criteria for hazard management (refer ICOLD Bulletin 130). While risk assessment can be used as a tool to assist in the identification of appropriate design criteria, these Guidelines provide design criteria which are closely aligned to recommended criteria in ICOLD Bulletins and countries with similar attitudes to risk as New Zealand (e.g. Canada, USA).

The following sections discuss hazards and threats, and include recommended design criteria for the management of hazards at Low, Medium and High PIC dams.

4.2 Flood hazards

4.2.1 Permanent works

The PIC for a dam and the incremental consequences of a dam failure (i.e. the consequences over and above the pre-breach condition) are the main determinants in selecting the Inflow Design Flood (IDF).

ICOLD Bulletin 82 includes a discussion on the selection of the IDF and lists IDFs adopted by a number of countries for particular dam classifications. FERC (1993) states that "the PMF should be adopted as the IDF in those situations where consequences attributable to dam failure for flood conditions less than the PMF are unacceptable. The determination of unacceptability is clearly necessary when the area affected is evaluated and indicates there is a potential for loss of human life and extensive property damage". Based on the above information, recommended minimum IDFs for Low, Medium and High PIC dams are listed in Table 4.1.

Table 4.1: Recommended Minimum Inflow Design Floods

PIC	Population at Risk	Potential Loss Of Life	AEP of IDF
Low	0 to 10	0	1 in 100 to 1 in 1,000
Medium	0 to 10	0	1 in 1,000
	0 to 10	1	1 in 2,500
	11 to 100	0 to 1	1 in 10,000
High	No limits	0 to 1*	1 in 10,000
	No limits	> 10*	PMF

1. **Note:** (*) If the Potential Loss of Life is between 1 and 10, the minimum IDF should be determined on a pro rata basis between the 1 in 10,000 AEP event and the PMF.

It is recognised that the estimation of extreme flood events in excess of the 1 in 100 AEP event can be difficult. Flood frequency analysis for gauged catchments (in which a standard probabilistic distribution is fitted to a long term series of annual flood maxima), and application of a regional flood frequency method for ungauged catchments using flood estimates scaled from other similar gauged catchments (McKercher and Pearson, 1989) are accepted flood estimation approaches for larger catchments (>10km^2) in New Zealand. McKerchar and Pearson (1989) also provide guidance on the reliability of extrapolated flood estimates based on a limited length of gauged flow record.

Rainfall patterns in New Zealand are highly influenced by orographic (i.e. altitude) effects so that larger catchments are commonly affected by rainfall gradients. Rainfall/runoff modelling, using rainfall frequency estimates, a rainfall temporal distribution and a uniform rainfall pattern across a catchment as inputs, is adopted for flood estimation for small catchments less than 10 km^2, larger catchments and where the duration of gauged flow records is inadequate or do not exist. Medium and High PIC dams are more likely to have larger catchment areas so that flood frequency analysis and the regional flood frequency method would generally be an appropriate flood estimation method.

McKerchar and Pearson (1989) describe suitable methods for the estimation of design floods for New Zealand catchments. Recommended methods for estimating the IDF for Low, Medium and High PIC dams are as follows:

- Low PIC dams – Flood frequency analysis where adequate data for gauged catchments is available. Alternatively, generally less rigorous methods of estimation of the IDF are appropriate such as the rational method in conjunction with a triangular-shaped flood hydrograph, other regional flood estimation approaches and rainfall/runoff routing.
- Medium PIC dams – IDFs should be determined using two or more recognised hydrological methodologies and appropriate judgement. IDFs should generally be determined either by a flood frequency analysis approach where the catchment is gauged and the gauged flow records are adequate, by a regional flood frequency approach where the catchment is ungauged or the gauged flow records are inadequate, or by rainfall/runoff routing . Whatever approach is adopted, the available base data (river/stream flows or rainfall) used to derive the flood estimates means that there will always be a degree of uncertainty in estimates of floods greater than the 1 in 100 AEP flood. In the face of this uncertainty, a conservative approach should be adopted in estimating the IDF.

- High PIC dams – IDFs should be estimated from a range of hydrological methods as recommended for Medium PIC dams. PMFs should be determined using the methodologies included in Tomlinson and Thompson (1991) and Campbell et al (1994). Comparisons should be made with flood estimates derived using the methodology included in G Griffiths et al (2014), which estimates extreme rainfall depths which can then be routed through catchments to determine IDFs included in Table 4.1.

Hydrological data records increase over time and increase the understanding of hydrological hazards. It is therefore highly likely that the estimated flood values for the return periods listed in Table 4.1 will change with time and could necessitate future upgrade works to increase the capacity of flood discharge facilities.

For existing dams the flood discharge facilities should be capable of safely discharging the IDFs listed in Table 4.1. If the flood discharge facilities are unable to safely discharge the recommended IDF, the discharge capacity is deficient and should be addressed. If the upgrade works to address a flood discharge deficiency are limited by practicality or practicable cost, the target flood capacity should be as high as reasonably practicable.

IDFs should always be estimated by hydrologists with experience in New Zealand hydrological conditions. In addition, appropriate established hydrological methodologies for New Zealand conditions should be employed for the assessment of IDFs up to the Probable Maximum Flood (PMF). Understanding the effects of climate trends on New Zealand floods (particularly extreme floods) is still in its infancy and, given the uncertainties associated with the estimation of IDFs, these Guidelines do not recommend inclusion of the effects of climate change in the estimation of extreme flood events. Future methodologies developed for the estimation of IDFs could include techniques for the assessment of climate change effects on flood magnitudes and frequencies. Two reports relating to climate change effects in New Zealand have been published by the Ministry for the Environment (MFE 2008 and MFE 2010).

If the reservoir is small and provides no opportunities for the storage of flood water during the IDF, the peak flow during the IDF is the only parameter necessary for the design of the permanent flood management facilities. Where the reservoir is sufficiently large for the storage of flood flows during the IDF, the hydrograph for the IDF should be determined to allow flood routing and the calculation of the peak lake level and outflow from the reservoir. A complex routing model involving more than one reservoir should be peer reviewed by a suitably experienced technical specialist.

Finally, due consideration should always be given to the effects of possible future land use changes on flood magnitudes. For example, deforestation and subdivision development in upstream catchments are likely to result in increased runoff and larger flood events.

4.2.2 Temporary works

Information on diversion flood frequencies adopted by various countries for the construction of embankment and concrete dams is included in ICOLD Bulletin 108A, and a discussion on the selection of an appropriate flood for the sizing of diversion works during construction is included in ICOLD Bulletin 144. There is no universally accepted method for selecting an appropriate flood for the sizing of diversion works during construction and the choice is generally based on the dam site, the dam type, the construction cost and the consequences if the diversion capacity is exceeded.

The performance criteria for diversion works during the construction of a dam, or the completion of rehabilitation works, should be as follows:

- For new dams the risk (likelihood x consequence) of loss of life during construction, as far as practicable, should be no greater than that over the life of the dam.
- For existing dams the consequences of dam failure should not be increased during the completion of any rehabilitation works.
- The design of any temporary works should include consideration of the PIC for any necessary cofferdams, and the design criteria for the cofferdams should be consistent with their PIC as recommended in section 6.3 of this module.

If there is insufficient upstream storage during construction to attenuate the peak diversion flood flow, the peak flow for the selected diversion flood dictates the required hydraulic capacity of the diversion works. However, if the diversion design relies partly on upstream storage to attenuate the peak flow, the total volume of the selected diversion flood should be estimated and the diversion design should include consideration of the possibility of the available storage volume being exceeded.

A risk-based approach provides an informed basis for selecting and sizing flood passage facilities during construction and risk reduction measures should be implemented where large reductions in risk are available for relatively low expenditure. In some cases it may be necessary to adopt risk reduction measures that are not justified on economic grounds; however, in all cases, the adverse effects of the risks should be made as low as reasonably practicable irrespective of any absolute criteria. By properly considering potential failure modes and applying 'as low as reasonably practicable' criteria, based at least in part on risk assessment, useful inputs can be provided for developing a defensible business case for dam safety decisions and an assurance that all reasonably foreseeable failure modes have been identified and adequately addressed.

The most obvious potential failure mode during construction is overtopping of the dam due to the inflow flood exceeding the capacity of the diversion facilities. Clearly the consequences of overtopping an embankment dam during construction would be far greater than those that would result from the overtopping of an equivalent concrete dam. The following subsections provide comment on the diversion works for concrete, embankment and concrete-faced rockfill dams.

Concrete Dams

For concrete dams, overtopping during construction would most likely lead to flooding of the work area and possibly some erosion of the dam toe. Provided the risk of toe erosion was not excessive, the main risks would be injuries or loss of life for construction personnel and damage to equipment. Because of the "block type" construction used for concrete dams, the level of potential damage and adverse effects can be managed and kept quite low. With an understanding of warning times and appropriate evacuation procedures the risks to personnel can be mitigated; however, damage to construction plant and the works and the tolerance for these costs are largely subject to the Owner's risk tolerance and/or an insurance matter.

If personnel and dam safety risks are adequately managed, a return period of 10 years may be appropriate for the sizing of the diversion works.

Embankment Dams

Embankment dams are highly unlikely to withstand sustained overtopping; hence the sizing of the diversion works is critical to dam safety during construction. A risk-based approach should consider the likelihood of overtopping of the partially completed structure (e.g. early in dam construction the consequences of overtopping should be significantly less than those when the dam is nearing completion), the consequences of dam failure at various stages of construction, and the risks to the construction works, the construction programme and construction personnel. Diversion and spill facilities should not concentrate discharge flows onto the dam body.

The size of the diversion works is critical until such time as the dam crest exceeds the invert levels of the permanent flood discharge facilities and, in some cases, temporary spillway facilities may be required to reduce the risk to an acceptable level. Exposure times to flood risk can be considered as part of the risk assessment process and emergency action plans, with appropriate evacuation procedures, may reduce the risk to public safety during construction. Emergency action planning is addressed in Module 6.

If a site-specific risk-based approach which considers exposure times and the downstream consequences of failure is not completed, the Owner and Designer should give consideration to the following guidelines for diversion capacity:

- If the incremental consequences of a dam failure during construction include no potential for the loss of life downstream of the dam, a return period of 50 years may be appropriate for the sizing of the diversion works.
- If the incremental consequences of a dam failure during construction include the likelihood of the loss of one or more lives downstream of the dam, a return period of 250 years or greater may be appropriate for the sizing of the diversion works.

Concrete-faced Rockfill Dams

Concrete-faced rockfill dams, with well compacted free draining rockfill shoulders, usually have a greater resistance to overtopping than most embankment dams.

The guidelines included above for embankment dams are also applicable to concrete-faced rockfill dams. However, added protection to the downstream face of a concrete-faced rockfill dam can reduce the likelihood of an overtopping failure (refer ANCOLD (1991)). If it can be demonstrated that proposed protection works on the downstream face will prevent dam failure, then it may be appropriate to include limited overtopping of the dam during the passage of the selected diversion flood event.

4.3 Seismic hazards

Seismic hazards include ground motions, fault displacements, liquefaction, landslides, seiches and tsunamis. Clearly tsunamis will not affect dams remote from coastal settings; however, seiches generated by strong ground motions and/or fault displacements beneath reservoirs can affect dam safety.

The following subsections outline recommended practices for the selection of appropriate seismic hazard parameters for dams. Ground motions, fault displacements and liquefaction are addressed. Landslides and seiches associated with seismic activity are addressed in section 4.5.

4.3.1 Terminology

A number of terms are commonly used in the assessment of seismic hazards and the definition of seismic performance criteria. They include the Controlling Maximum Earthquake (CME), the Operating Basis Earthquake (OBE), and the Safety Evaluation Earthquake (SEE).

Definitions for each of the terms are included in the Glossary at the end of this module. For simplicity these Guidelines use the CME, SEE and OBE which are defined as follows:

- **CME** – The maximum earthquake on a seismic source that is capable of inducing the largest seismic demand on a dam.
- **SEE** – The earthquake that would result in the most severe ground motion which a dam structure must be able to endure without uncontrolled release of the reservoir.
- **OBE** – The earthquake for which a dam, appurtenant structure and gate/valve system that fulfils a dam safety function is designed to remain operational, with any damage being minor and readily repairable following the event.

4.3.2 Seismic performance criteria

Industry practice for the seismic design and analysis of dams is to consider two levels of earthquake – the SEE and the OBE.

- The performance requirement for the SEE is that there is no uncontrolled release of the impounded contents when the dam is subjected to the seismic load imposed by the SEE. Damage to the structure may have occurred.
- The performance requirement for the OBE is that the dam and appurtenant structures remain functional and that the resulting damage is minor and easily repairable.

4.3.3 Ground motions

Ground shaking affects all structures, including gates and valves, above and below ground. Ground shaking at elevated structures on dams and features such as steep abutments can be amplified from the ground shaking that occurs at the valley floor.

Measures of ground shaking include peak ground motion (i.e. peak ground acceleration, velocity or displacement), response spectra or time-histories. Acceleration is the more commonly used parameter for ground motions in dam design, with typically less use of velocity and displacement parameters.

Annual Exceedance Probabilities and Design Ground Motions

The OBE has traditionally represented ground motions that have an annual exceedance probability (AEP) of about 1 in 150. Some owners may wish to adopt a higher standard for the OBE (e.g. an AEP of 1 in 500) to reflect the value of the asset or its importance for providing a service. Owners should reference other regulated requirements for essential infrastructure. For example, an Importance Level 4 facility in NZS1170 includes "essential facilities" and "buildings and facilities containing hazardous materials capable of causing hazardous conditions that extend beyond the property boundaries" (e.g. a dam failure of a tailings dam). NZS1170 requires Importance Level 4 structures with a design working life of 50 years to maintain operational continuity after a 1 in 500 AEP event.

ICOLD Bulletin 148 and L Mejia et al (2001) provide recommended SEE ground motion parameters for the design and analysis of dams. Both sources consider the PIC or hazard rating of the dam as a basis for setting recommended levels for the design earthquake. These Guidelines provide AEP ground motions at the mean value, developed from both references and are as follows:

- **All PIC dams** – the SEE ground motion parameters may be developed by either a deterministic or a probabilistic approach. The probabilistic approach is favoured by many seismic hazard experts because it provides a uniform basis for evaluating the hazard and more consistent results. The deterministic approach can sometimes result in overly conservative design ground motions for dams located near low activity Quaternary faults and unconservative design ground motions near young (Holocene) high activity faults. The Designer should take this into account when assessing seismic hazard.
- **Low PIC dams** – the SEE ground motion parameters should be estimated at the 50th percentile level for the CME if developed by a deterministic approach, and if developed by a probabilistic approach then at least a 1 in 500 AEP ground motion but need not exceed the 1 in 1,000 AEP ground motion.
- **Medium PIC dams** – the SEE ground motion parameters should be estimated at the 50th to the 84th percentile level for the CME if developed by a deterministic approach, and need not exceed the 1 in 2,500 AEP ground motion developed by a probabilistic approach. If the deterministic approach is used the Designer needs to consider the PAR, PLL and consequences of failure in determining the appropriate percentile deterministic estimates of ground motion.
- **High PIC dams** – the SEE ground motion parameters should be estimated at the 84th percentile level for the CME if developed by a deterministic approach, and need not exceed the mean 1 in 10,000 AEP ground motion developed by a probabilistic approach.

Methods for Estimating Ground Motion Parameters

ICOLD Bulletin 148 also provides guidelines for the selection of parameters to be used in the seismic design, analysis and safety evaluation of new or existing dams and their appurtenant structures. Recommended methods for estimating the SEE and OBE for Low, Medium and High PIC dams are as follows:

- **Low PIC dams** – unless the commercial consequences of dam failure dominate decision making, simplified seismic design will normally be sufficient. Site-specific probabilistic seismic hazard studies will not generally be warranted. Although NZS1170.5 (2004) was developed for building design, it provides probabilistic estimates of magnitude weighted seismic loads in terms of peak ground acceleration and spectral acceleration which can be adopted for the design and analysis of low PIC dams. NZS1170.5 is based on the National Seismic Hazard Model (NSHM) and updates may be issued periodically as the NSHM and new ground motion prediction models are developed. Estimates of unweighted peak ground acceleration and effective earthquake magnitudes can be obtained from the NZTA Bridge Manual (2013). Deterministic estimates of seismic hazard associated with the CME will require examination of published geological maps and fault databases to identify active faults and use of appropriate ground motion prediction models.
- **Medium PIC dams** – for most Medium PIC dams published data (e.g. NZS1170.5, 2004 and NZTA, 2013) can generally be used to obtain probabilistic estimates of seismic hazard for design and analysis. Deterministic estimates of seismic hazard associated with the CME will require examination of published geological maps and fault databases to identify active faults. If embankment fill materials or foundations could soften when subjected to strong earthquake ground motions (e.g. cyclic softening or potentially liquefiable soils), or there are weak foundations, the recommended approach detailed below for High PIC dams should be employed. Where complex analysis is being used to determine the seismic performance of a dam, the selection of acceleration time history records will require the completion of site-specific seismic hazard assessments as described below for a High PIC dam.
- **High PIC dams** – the long recurrence interval applied to High PIC dams cannot be obtained from published building related standards such as NZS1170.5. A site-specific seismic hazard assessment should be completed by an appropriate technical specialist, using both deterministic and probabilistic analyses. The design ground motions for the SEE and OBE should be selected based on the results of the analyses, and should include response spectra and possibly acceleration time histories, depending on the analysis method. Uncertainties and site amplification effects should be addressed. Epistemic uncertainties associated with earthquake sources and ground motion prediction equations should be considered. Recommendations for the selection and scaling of acceleration time histories are included in Canadian Dam Association Technical Bulletin: Seismic Hazard Considerations for Dam Safety (2007). The selection and scaling of time history records suitable for the site and the structure being analysed requires an experienced specialist.

Seismic Analysis Methodologies

In addition to the PIC for the dam, the type of dam and its potential modes of failure, the proposed seismic analysis methodology can affect the selection of appropriate ground motion parameters.

Analyses for dams can vary from simplified to more elaborate procedures, such as the finite element or finite difference methods. Peak ground motion parameters and response spectra will be sufficient if simplified evaluation procedures are adopted. Dynamic finite element response analyses may be performed using either response spectra or acceleration time histories where linear elastic behaviour is expected. Where nonlinear behaviour is expected time histories will be required. Both horizontal and vertical components of ground motion need to be considered for concrete dams and for embankment dams with very steep slopes. Vertical accelerations can be equal to or greater than horizontal accelerations when close to the earthquake source, so specialist advice is recommended in determining these parameters. Damping rates for concrete dams are usually in the range of 3% to 10% but for embankment dams are usually in the range of 5% to 20%.

ICOLD Bulletin 148 provides more detail on issues that should be considered in the selection of seismic parameters for the analysis and design of embankment and concrete dams. Time history records can be either actual earthquakes at another location in a similar tectonic setting (subsequently scaled to the site peak or more commonly spectral accelerations) or generated synthetically using specialist software. The source earthquakes should be of similar magnitude and distance from the source to represent the energy anticipated for the SEE. There are many methods for scaling time histories and for matching the design spectrum. Advice from a Technical Specialist is recommended. Designers usually require several (3 to 7) records with response spectra matched to the site target spectrum. Where 3 records are used the performance should be based on the maximum response. Where 7 records are used the performance can be based on the average response.

Aftershock Considerations

SEE shaking may lead to cracking, increased seepage and reduced strength. For high value assets and for all high PIC dams, the site-specific seismic hazard assessment should include the estimation of aftershock parameters. The information will enable the determination of dam stability following an aftershock. Following a major earthquake a number of aftershocks should be anticipated. For the purposes of dam safety assessments at least one aftershock of one magnitude less than the CME should be anticipated within one day of the SEE. Further aftershocks may be expected in the following days, weeks and months following the SEE. The characteristics of the aftershock earthquake sequence depend on the site specific CME fault characteristic.

Repeated aftershocks can result in cumulative damage and reductions in dam stability. The Owner and Designer should consider how the safety of the dam will be managed in the period through the aftershocks until repairs can be completed.

4.3.4 Fault Displacements

There is no universally accepted definition of an active fault. In New Zealand an active fault is defined in the Ministry for the Environment (July 2003) publication as “a fault that has moved one or more times in the last 120,000 years, and is therefore likely to move again in the future”. Other definitions exist around the world.

Displacements associated with an active fault located beneath a dam can result in damage to the dam and the development of potential seepage pathways. Fault displacement in the reservoir can result in the loss of freeboard and the generation of seiches. Fault geometry or orientation and sense of movement may also result in general landform deformation.

Active faults that can result in displacement beneath a dam can include primary active faults and secondary active faults. Primary active faults are faults that have seismogenic potential (i.e. they are sources of earthquakes). Secondary active faults are faults that move in sympathy or as a consequence of movement on a nearby primary active fault. Movements will be much less than on a primary active fault, but the displacement can still be sufficient to require consideration in the design of a dam.

For engineering design purposes it is generally not considered necessary to design for fault displacement where the annual probability of fault displacement is below a certain threshold. For dam design in New Zealand it is recommended that the threshold for design be based primarily on the PIC of the dam.

Annual Exceedance Probabilities

Design recommendations for fault displacements have been proposed by L Mejia et al (2001). They are primarily deterministic, based on the CME for the site, but include an upper limit of fault displacement based on AEP. The recommended performance criteria are summarised below:

- **Low PIC dams** –Fault displacements associated with the CME should be based on median (50th percentile) deterministic estimates, but the displacements need not exceed the value associated with a 1 in 2,500 AEP event determined from a probabilistic fault displacement hazard analysis. Active faults with recurrence intervals up to 5,000 years should be considered.
- **Medium PIC dams** – Fault displacements associated with the CME should be between the 50th and 84th percentile deterministic estimates, but the displacements need not exceed the value associated with a 1 in 2,500 AEP event determined from a probabilistic fault displacement hazard analysis. If the deterministic approach is used the Designer needs to consider the PAR, Potential Loss of Life and consequences of failure in determining the appropriate percentile deterministic estimate of fault displacement and the fault recurrence interval threshold level. For dams at the lower end of the medium classification 50th percentile estimates associated with active faults with recurrence intervals up to 10,000 years should be considered. For dams at the upper end of the medium classification 84th percentile estimates associated with active faults with recurrence intervals up to 120,000 years should be considered.
- **High PIC dams** – Fault displacements associated with the CME should be based on 84th percentile estimates, but the displacements need not exceed the value associated with a 1 in 10,000 AEP event determined from a probabilistic fault displacement hazard analysis. Active faults with recurrence intervals up to 120,000 years should be considered.

For low and most medium PIC dams it is not normally necessary to consider undertaking a probabilistic fault displacement hazard analysis and, for design purposes, the deterministic estimates associated with the CME can be adopted. Foundation fault displacement need not be considered for the OBE.

Methods for Estimating Fault Displacement Parameters

For Low and Medium PIC dams the locations of active faults can generally be obtained from the GNS Active Fault Database (**http://data.gns.cri.nz/af/index.jsp**), published geological maps and Territorial Authority hazard maps. These resources are being continually updated and the Designer should determine the currency and accuracy of the information being utilised for design.

For High PIC dams the characterisation of design fault displacement should be based on knowledge of the regional and site-specific geology and a careful study of any foundation faults. Site-specific studies should be undertaken to determine the potential for active faulting and to quantify fault hazards (i.e. direction, magnitude and recurrence of future faulting). Such studies should be undertaken by professionals with skills in the appropriate disciplines (e.g. paleoseismology, seismotectonics, geodetics). If possible, a predictive relationship should be established between a secondary fault and its primary active fault. Features on a dam site generated by older periods of tectonism may have little or no evidence of sympathetic movement to a displacement on a nearby active fault.

Design Considerations

Preferably, dams should not be located across or immediately adjacent to an active primary fault, but in the New Zealand geological setting faults can be very difficult to avoid. In some cases existing dams may be found to be located on either primary or secondary active faults after the dam has been constructed. The close proximity of an active fault to a potential dam site need not necessarily result in abandonment of the site. In such cases, design features that maximise resilience should be provided to adequately withstand the extent of anticipated fault movement, allowing for uncertainties in the fault displacement history.

If there is sufficient evidence that an active fault is located directly beneath a dam, the dam should be capable of safely accommodating the estimated potential fault displacement without an uncontrolled release of the impounded contents. For embankment dams Mejia(2013) states that recent practice has been to provide filter zones with thicknesses of at least 1.5 times the expected filter shear offsets corresponding to the design fault displacements. It is recommended that a similar factor be applied to estimates of fault displacement for the design of other critical elements of a dam.

Estimates of active primary fault displacement and earthquake magnitude for Low and Medium PIC dams can be obtained using empirical scaling relationships such as Wells and Coppersmith (1994) and Stirling et al (2013). Estimates of secondary fault displacements for strike-slip faults can be obtained using the empirical relationships developed by Petersen et.al. (2011). For High PIC dams estimates of primary and secondary fault displacements should be based on site-specific studies undertaken by professionals with appropriate skills.

4.3.5 Liquefaction and lateral spreading

It has long been recognised that loose saturated sands, silty sands and gravelly sands in a dam foundation, or inadequately compacted sands and silts in an embankment or tailings dam, are susceptible to liquefaction and that the liquefaction of a deposit could result in sufficient loss of shear strength to initiate a dam failure. Loss of strength under earthquake loads can also occur for more cohesive soils (e.g. silty clays and clayey sands) and these types of materials should also be evaluated.

Where such deposits are present in a dam foundation, or are proposed to be utilised for dam construction, their susceptibility to liquefaction should be assessed. Fell et al (2005) includes a simplified method for assessing the liquefaction resistance of soil deposits. There are many other publications in the literature that provide guidance on determining the potential for and consequences of liquefaction (e.g. Idriss and Boulanger, 2008 and 2014). In addition there are advanced numerical effective stress methods for analysing the dynamic response of soils with liquefaction potential; however, such analyses should only be undertaken by Technical Specialists. The state of art is evolving and Designers should determine the currency of methods before applying them to their particular situations. Typically, methods for assessing liquefaction potential are applied to level ground. The presence of an embankment results in additional shear stresses within the underlying ground and within the embankment that need to be considered when assessing liquefaction potential. Some guidance on how to account for this is provided by Idriss and Boulanger. These effects can also be accounted for by using advanced numerical effective stress analyses.

Where liquefaction is possible, post-earthquake stability analyses should be completed, using liquefied or residual strengths of the liquefied materials, to review the stability of the dam following the earthquake.

The consequences of liquefaction can be significant and so a conservative design approach is necessary. The design approach should be to achieve a foundation or embankment where the potential for liquefaction is extremely low. The factor of safety, using residual strengths of the liquefied materials, should be greater than or equal to 1.2 (lower factors of safety may be acceptable depending on the confidence in the accuracy of the residual strength), or the displacements predicted using advanced numerical effective stress methods should be acceptably small. To guard against liquefaction or strength loss during or following earthquake shaking, it is good practice to:

- Either remove all loose foundation materials from the foundation and replace them with highly compacted materials, or densify the loose materials by vibroflotation or other appropriate foundation improvement techniques.
- Thoroughly compact all zones of embankment dams.
- Not use fill materials which tend to build significant pore pressures during strong shaking in the upstream shoulders and cores of embankment dams, or below the phreatic surface in the downstream shoulders of embankment and tailings dams.

4.4 Volcanic hazards

Volcanic activity in New Zealand within the last 500 years has been restricted to the North Island. The most recent eruptions include Rangitoto in Auckland (1400), White Island (ongoing), Tarawera south-east of Rotorua (1886), Taranaki (1655), and Ruapehu (1995/96), Ngauruhoe (1974/75) and Tongariro (2012) in the Central Volcanic Plateau.

Those volcanic hazards most relevant to the engineering and operation of dams include pyroclastic flows, lava flows, lahars, lateral blasts and ash falls. Dams situated within close proximity of the above volcanoes could be directly affected by pyroclastic flows, lava flows, lahars and lateral blasts. Dams distant from the volcanoes could be affected by ash falls, lahars and floating pumice deposits. Ash falls are unlikely to directly affect the safety of a dam, although they could affect power supplies, communication systems and control equipment for the operation of gates and/or valves that fulfil dam safety functions. Pumice deposits can blanket lakes and block intake structures. Pyroclastic flows and lahars could result in extreme flood flows that exceed the discharge capacity of spillway facilities and overtop downstream dams. Similarly, extreme flood flows released from failures of upstream volcanic debris dams could release sufficient flood flows to overtop downstream dams.

Regional Councils have a statutory responsibility to identify and assess natural hazards in their regions and information on volcanic hazards is available from the Auckland, Waikato, Bay of Plenty and Taranaki Regional Councils. The available information on volcanic hazards should be considered in any proposal to develop a dam within close proximity of a known volcano. In some cases it may be necessary to complete a more detailed study to better understand volcanic hazards and their possible effects on the safety of an existing or a proposed dam. Probabilistic volcanic hazard quantification is currently in its infancy so resilient design features should be considered, especially for vulnerable equipment that fulfils a dam safety function.

4.5 Reservoir hazards

There is a tendency sometimes to focus on the dam and not pay much attention to the reservoir. Generally, in the case of Low PIC dams, the assessment of reservoir effects on dam safety will be largely based on judgement. However, for Low PIC dams where reservoir effects could affect dam safety and for all higher PIC dams, consideration should be given to the effects of landslides, reservoir induced seismicity, high winds and waves, and seiches generated by strong ground motions and/or fault displacement.

4.5.1 Landslides

The following should be considered:

- Whether there is any part of the reservoir perimeter (e.g. a narrow ridge) which may be more likely to fail than the closure dam.
- Whether there is any potential for landslide generated waves to affect communities adjacent to the reservoir.
- Whether any existing landslides may reactivate or new landslides may develop under any of the possible reservoir conditions, to the extent that the dam could be overtopped and/or the reservoir or upstream tributaries blocked.
- Whether reservoir operation could result in toe erosion adjacent to dormant or potential landslide areas.
- Whether any of the reservoir surrounds in the proximity of the spillway and/or low level outlet facilities may fail and block the facilities or impair their functions.
- What management regime should be implemented to prevent sediment or debris from affecting the performance of spillway and/or low level outlet facilities.
- What operational requirements should be implemented to ensure the stability of dormant and potential landslide areas are not adversely affected by reservoir drawdown.
- What management regime should be implemented to monitor the performance of known landslides and any completed remedial works during dam commissioning and operation.

ICOLD Bulletin 124 provides guidelines for the investigation and management of reservoir landslides, comments on possible risk mitigation measures, and discusses requirements and methods for the ongoing monitoring of reservoir landslide performance.

4.5.2 Reservoir triggered seismicity

Reservoir Triggered Seismicity (RTS) is an increase in seismic activity following the formation of a reservoir. RTS is relatively uncommon but can occur (e.g. Benmore dam in New Zealand, 1965, and Oroville dam in California, 1975). Where it has occurred, the earthquake ground motions have been typically less than the SEE for the dam.

ICOLD Bulletin 137 notes that dams and appurtenant structures that have been correctly designed for seismic loads are protected against RTS; however, existing structures and facilities in the vicinity of a proposed reservoir could be susceptible to RTS as the resulting seismic loads could be larger than those assumed in their design.

4.5.3 Wind and waves

The effects of wind setup of the reservoir, adjacent to the upstream face of a dam, and wave runup on the upstream face of a dam are effects that should be considered in setting the freeboard requirements for a dam. Wind speed, wind direction and fetch length are the predominant factors in establishing wind setup. Wave height, wave length and the physical characteristics (slope, roughness) of the upstream slope of the dam are the predominant factors in establishing wave runup.

Embankment dams are the most critical dam type when considering freeboard allowances, because of the likelihood of their failure when overtopped, and for new dams these Guidelines have adopted the recommended freeboard provision included in Fell et al (2005) which is that the adopted freeboard should be the largest of the following three freeboard requirements:

- At maximum normal reservoir elevation the freeboard should be the wind set up and wave run up for the highest 10% of waves caused by a sustained wind speed, which is dependent on the fetch, with an AEP of greater than 1 in 100.
- At maximum reservoir elevation during the passage of the IDF the freeboard should be the greater of (a) 0.9m or (b) the sum of the wind set up and wave run up for the highest 10% of waves caused by a sustained wind speed, which is dependent on the fetch, with an AEP of 1 in 10; .
- At intermediate flood elevations the freeboard should be determined so that it has a remote probability of being exceeded by any combination of wind generated waves, wind set up and reservoir surface occurring simultaneously.

Methods for the determination of wave setup and wave runup are included in Fell et al (2005).

Concrete dams can usually accommodate some overtopping without serious damage and, as such, the freeboard provisions can be somewhat less than those detailed for embankment dams.

4.5.4 Reservoir seiches

Reservoir seiches, generated by strong ground motions and/or fault displacement, have the potential to overtop dams and affect dam safety. While concrete dams can usually accommodate some overtopping without serious damage, embankment dams have a limited ability to withstand overtopping and large reservoir seiches could result in sufficient overtopping to initiate a dam failure.

Significant reservoir seiches can occur if the natural frequency of the reservoir is at or close to resonance with the dominant frequency of the earthquake waves affecting the site. In most cases normal freeboard provisions should be sufficient to safely accommodate seiches generated by strong ground motions; however, where a Medium or High PIC dam is located close to an active fault, the potential for seiche waves to overtop the dam crest and initiate a dam failure should be assessed.

Reservoir seiches can also be generated by fault displacement beneath a reservoir (e.g. Webby et al 2007) and, if a sufficient volume of the reservoir is uplifted by the fault displacement, they can result in sufficient overtopping to initiate a dam failure. Where an active fault crosses the floor of a reservoir for a Medium or High PIC dam the potential for reservoir seiches to initiate a dam failure should be assessed. In some cases, if the estimated fault displacement is significant, it may be necessary to develop a hydrodynamic model for the reservoir to analyse the seiche effects and provide wave characteristics for evaluating wave run-up and the potential effects of any overtopping flows.

4.6 Threats and other hazards

Threats that can affect dam safety can be grouped under internal threats (e.g. errors/omissions in design, construction defects, inappropriate operation and lack of maintenance) and external threats (e.g. vandalism and terrorism). Other concerns, such as the safety of the public and the health and safety of personnel during construction and operation, do not usually affect dam safety.

Threats associated with errors/omissions in design, construction defects, inappropriate operation and the lack of maintenance can be minimised by identifying the threats, adopting appropriate quality assurance systems during design and construction, and preparing and implementing proper procedures for operation, maintenance and testing of the facilities. Quality assurance systems for design and construction are discussed in section 3 of this module and section 2.5 of Module 4. The preparation and implementation of proper procedures for operation, maintenance and testing are discussed in Module 5.

With recent trends in the adoption of automatic and remote systems for the normal operation of dam facilities, and the associated absence of on-site personnel, it is important that appropriate systems are put in place to minimise the potential for unauthorised operation of facilities that are critical to dam safety. This may never be an issue for a Low PIC dam located on private property and operated by the dam Owner. However, Medium and High PIC dams that are located in areas accessible to the public are prone to vandalism and appropriate security measures should be installed to minimise the potential for vandalism and the unauthorised operation of equipment that fulfils dam safety functions. Appropriate security measures can include the installation of barrier fences and security cameras, the enclosure of control systems critical to dam safety in secure buildings, the use of authorised access cards, and the installation of intruder alarm systems.

Dams and their associated facilities should incorporate appropriate systems to protect people from hazards associated with their operation. In some cases few protection systems may be necessary (e.g. a Low PIC dam located on private property and operated by the dam Owner) while in other cases, where a dam and its associated facilities are accessible by the public, a number of protection systems may be necessary for public safety. This is discussed in more detail in Module 7. Typical areas that warrant attention include:

- Reservoir areas immediately upstream of intake facilities (e.g. powerhouse, spillway and penstock intake structures).
- Gate and stoplog shafts.
- Gate or valve operation areas.
- Spillway channels and discharge areas.
- Steep and slippery canal side slopes.
- Tailings discharge facilities.

Proper protection can only be provided by identifying potential hazards, evaluating the risks, mitigating or controlling hazards through the installation of appropriate protection systems (e.g. warning signs, lake booms, fences, handrails, sirens), and ensuring that the operating personnel are aware of the hazards and their responsibilities for the proper management of the hazards.

5. Investigations and data assembly

5.1 Introduction

All investigations and data assembly for the design must be to a level which is appropriate to the complexity of the dam site, the contemplated dam design or rehabilitation works, and the commercial value of the dam. Areas normally requiring investigation or measurement relative to dam safety are:

- Topography.
- Flood hydrology.
- Regional and site-specific geology.
- Seismic hazards (ground motions and fault displacement).
- Foundation characteristics.
- Construction materials.

Section 4.2 of this module provides guidelines for the assessment of flood hazards and the selection of appropriate flood magnitudes for the design and analysis of flood management facilities for Low, Medium and High PIC dams. Similarly, section 4.3 of this module provides guidance for the assessment of seismic hazards and the selection of appropriate seismic design parameters for the design and analysis of Low, Medium and High PIC dams. The following subsections provide guidelines for planning and managing an investigation programme, and outline additional investigation activities which should be completed to support the design or rehabilitation of Low, Medium and High PIC dams.

Several of the references, particularly ICOLD Bulletins 129 and Fell et al (2005), listed at the end of this module provide detailed guidance on investigation techniques and many more references exist through technical books, papers and conference proceedings. As such, the following subsections include little comment on investigation techniques. In addition, as the focus of these Guidelines is on dam safety, the subsections include little comment on the scope of any social, community or environmental studies that may require inclusion in an investigation programme.

5.2 Planning and managing an investigation programme

Most investigation programmes are completed in a series of separate stages with the following objectives:

- A pre-feasibility investigation – to identify possible dam sites and dam types, or possible options for rehabilitation of the dam, and obtain sufficient information for the planning of a feasibility investigation.
- A feasibility investigation – to identify a preferred dam site and dam type, or a preferred option for rehabilitation of the dam, confirm the technical feasibility of the preferred solution, and estimate the cost of project development.
- A design investigation – to address any outstanding issues raised in the feasibility investigation, and any additional questions that are raised during the detailed design and construction of the dam or rehabilitation works.

Many historical dam failures can be attributed to a lack of understanding of how the dam site would react to the construction of the dam and the formation of the reservoir. It is therefore most important that investigation programmes are carefully resourced, planned and managed to address all unknowns that could affect dam safety. As outlined in section 3.1, important requirements for all investigation programmes are that appropriate personnel are utilised, and that sufficient funds and time are allocated for their completion. A team approach is essential and all personnel (project manager, engineering geologists, engineers and technical specialists) should be selected for their technical skills and willingness to work in a team environment. For success and the avoidance of rework it is also most important that the Design Leader, or a senior member of the design team, is responsible for planning and managing the investigation programme.

All investigation programmes should be completed in a progressive fashion to ensure all unknowns are properly identified and addressed. An appropriate process for the completion of an investigation programme is outlined in Figure 5.1. It includes:

- Definition of the investigation objectives. Clearly, the objectives will vary depending on the anticipated dam type, or the proposed rehabilitation, and the investigation stage.
- Collection and assessment of existing information and the identification of information gaps. For a new greenfield site there may be little existing information available and many information gaps will be identified. Alternatively, for the investigation of a site previously considered for development or a proposed rehabilitation project, the existing information may be comprehensive and few information gaps will be identified.
- Planning an investigation programme to address the identified information gaps. For a new dam regional studies are often necessary to identify features within close proximity of the site that could affect the feasibility of its development (e.g. major fault systems and landslides), and site-specific studies are necessary to characterise the foundation and identify potential sources of construction materials. While an investigation programme for a major rehabilitation project could require the completion of regional studies, a programme for a limited rehabilitation project would normally be dominated by targeted site-specific studies to establish existing conditions.
- Implementing the investigation programme, reviewing the results as they become available and, if necessary, initiating additional investigation work. While the scope of investigation work necessary to address uncertainties usually reduces with time, investigation activities are often necessary during construction and, in some cases, investigation activities are necessary following commissioning.

It is most important to document all investigation results, interpretations and conclusions during all stages of an investigation programme. Ideally, a report should be prepared at the completion of each stage of an investigation programme to record the objectives, the work completed, the interpretations of the work completed, and any uncertainties that should be addressed through the completion of further investigations.

Investigation methods such as test pits and drillholes are invasive by nature and have the potential to introduce dam safety defects if they are not properly completed or sealed/rehabilitated. For example, drilling in an embankment dam should only be carried out using dry drilling techniques, drilling in the cores of embankment dams should exclude the use of water and high pressure air, and foundation drilling beneath an operational dam should include protection systems to avoid hole blowout if a high pressure zone is encountered in the foundation. The locations of all test pits and drillholes should be accurately recorded and shown on plans, and they should be sealed/rehabilitated either as part of the investigation program or during construction.

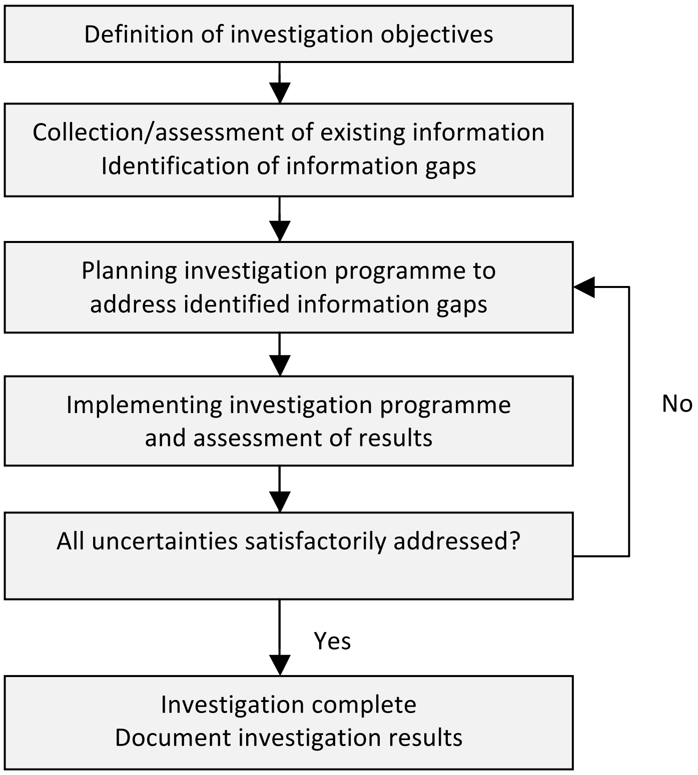


Figure 5.1: Progressive Investigation Programme

5.3 Topography

Topographical maps are an essential requirement for the investigation and design of any dam and usually include:

- Regional maps at a 1:50,000 scale and with a 20m contour interval, which are available from Land Information New Zealand (LINZ).
- Site-specific maps to suit the site conditions which are typically at scales between 1:2,000 and 1:500 and with 2m to 1m contour intervals. Site-specific topographical mapping should be produced during the initial stages of an investigation programme using ground survey, photogrammetry, or remote sensing technology that measures distance by illuminating a target with a laser and analysing the reflected light (e.g. LiDAR). The quality of maps produced by photogrammetry and remote sensing techniques can be affected by vegetation coverage and, in some instances, manual ground surveys will be necessary to give the required resolution.

All site-specific mapping should be completed in relation to a regional coordinate system and datum, and all features recorded during an investigation (e.g. geological features, drillholes) should be located and levelled to the same coordinate system and datum.

5.4 Geology and foundations

Regional and site-specific geological studies should be completed for all dams, regardless of their PICs. The extent of the studies necessary will vary according to the quality of the existing information that is available (e.g. regional geological maps, aerial photographs), the complexity of the site, composition of foundation, the type of dam and its PIC.

Dam design, and rehabilitation works when they are related to the foundation, are heavily influenced by the characteristics of the foundation materials. Therefore information on the stratigraphy and the extent to which the materials are weathered or erodible, the strength and stiffness of the materials, the permeability of the materials and whether they incorporate potential leakage paths, and the joints and whether they are oriented in a manner that could contribute to foundation instability is important.

Recommended minimum initial investigation requirements for the design of Low, Medium and High PIC dams are detailed below. In all cases, if the recommended minimum requirements identify any potential difficulties with the site (e.g. existing signs of slope instability, adversely orientated joints, weak or karstic foundation materials extending beyond the depths of the completed field work, the presence of volcanic ash or potentially liquefiable materials), additional investigation work should be completed.

Low PIC dams

Investigation activities should include examination of published geological maps, canvassing of local knowledge, inspection of the dam site and reservoir area for signs of surface instability, faults, dormant or ancient landslides (particularly if they form the abutments) and other adverse geological features, and the completion of hand auger holes and test pits over the dam footprint. Designers should determine whether some testing of the foundation materials should also be completed to determine their characteristics and the extent of any necessary foundation excavation. Depending on the nature of the materials, these could include water contents, in situ strengths, Atterburg limits, dispersivity tests, gradation and permeability.

Medium PIC dams

Geological and foundation investigation programmes should be sufficient to permit rational design of the dam and should include:

- All of the items listed above for Low PIC dams.
- Air photo interpretation and an appraisal of the regional geology.
- Engineering geological mapping and interpretation of geological structures and defects in the dam site area.
- Sufficient test pits and drillholes, with in-situ permeability testing, to characterise the foundation. Fell et al (2005) includes a discussion on the applicability and limitations of various site investigation methods.
- Additional in-situ and laboratory testing (e.g. shear strength, consolidation) to determine the characteristics of the foundation materials, as appropriate to the site conditions.

High PIC dams

Investigation activities should be similar to those outlined above for Medium PIC dams but should be more comprehensive and should be focussed on key issues identified by technical specialists. Additional investigation activities often include:

- Excavation and logging of shafts and drives.
- Drilling and monitoring of groundwater observation wells.
- Downhole electronic logging and core orientation.
- Geophysical logging of the subsurface foundation materials.
- Large scale in-situ tests (e.g. plate bearing tests, shear tests)
- Reactivity of concrete aggregates
- Reservoir slope stability investigations (e.g. drilling, groundwater observation, deformation surveys).

5.5 Construction materials

The identification and investigation of potential construction material sources is a key component of any investigation programme for a new dam and can be important for the rehabilitation of an existing dam. Haul distances between the borrow areas and dam site, the characteristics of the available materials (e.g. suitability for concrete or embankment construction, material quality, variability in the borrow area), and the scope of the completed investigation programme can all significantly affect the dam type and the final cost of a dam or rehabilitated dam.

The scope of any borrow material investigation will vary with the dam type, the characteristics of the rehabilitation project and the stage of the investigation. In comparison to a concrete dam and concrete appurtenant structures, which require durable, fine and coarse, non-reactive concrete aggregates, an embankment dam requires a wide range of materials including earthfill (core and shoulder materials), rockfill, transition, filter and drainage materials. The Designer should therefore be looking for materials that:

- Have sufficient strength when placed in the dam.
- Do not deteriorate during placement, unless this is a desired characteristic that can be achieved with an appropriate level of quality assurance.
- Do not have high rates of weathering where weathering could compromise their design performance or function.
- Do not have expansive properties (e.g. alkali-silica reactive properties in concrete aggregates).
- Do not have dispersive characteristics unsuitable for the cores of embankment dams.
- Have fines contents appropriate for their purpose (e.g. low permeability core, filter function, drainage function).
- Have good plasticity for use in the cores of embankment dams. Low plasticity materials can be used in dam cores but materials with good plasticity should be used if they are available.
- Lack plasticity and cannot hold an open crack for use as filter and drainage materials.
- Are not gap-graded.
- Are not prone to segregation.

A pre-feasibility investigation should include the completion of sufficient geological mapping to identify potential borrow material sources and enable the scoping of a later feasibility investigation. In comparison, a feasibility investigation for any dam project, including a dam rehabilitation project, should include sufficient work to:

- Identify preferred borrow areas.
- Prove that sufficient volumes of the material are available from the preferred borrow areas.
- Establish that the preferred materials are suitable for their intended design use.
- Ascertain what likely processing requirements and construction methods will be necessary during the construction of the dam or rehabilitation project.
- Select the appropriate dam type(s), or rehabilitation works, with respect to the foundation and available construction materials.
- Provide assurance that the materials will meet the design specification.

To satisfactorily address the above questions, a feasibility investigation normally includes:

- An exploration programme (test pits, shafts and/or boreholes) to log the available borrow materials, recover samples for laboratory testing, and enable the estimation of borrow area volumes.
- A laboratory testing programme to establish the characteristics of the materials and the suitability of the materials for their intended use. Laboratory testing requirements will vary according to the dam type and borrow material, but would typically include:
- Gradation, water content, Atterberg limit, compaction, permeability and strength tests for fine grained embankment materials. Dispersion tests may also be necessary in some instances.
- Gradation, permeability, soundness and durability tests for transition, filter and drainage materials.
- Gradation tests for rip-rap and rockfill materials.
- Gradation, specific gravity and absorption, abrasion, soundness, durability and alkali-aggregate tests for fine and coarse concrete aggregates.
- Petrographic analysis to assess the suitability of rip-rap, rockfill, transition, filter and drainage materials, and concrete aggregates.

It may also be appropriate, where geosynthetic materials are incorporated in an embankment design, to complete a series of laboratory tests on the proposed geosynthetic material (e.g. shear strength, peel strength, permeability, filtration compatibility, hydraulic transmissivity).

- Construction trials to demonstrate the applicability of materials or construction methods, for example:
- Concrete mix design.
- Embankment trials to determine appropriate fill placement, conditioning and compaction methods to determine the properties of the placed fill, and to confirm quality control methods.
- -Grout mix design tests.
- An assessment of the investigation results to confirm the suitability of the materials for dam construction, establish likely processing requirements, and estimate the costs of embankment or concrete placement.

6. Design Considerations

6.1 Introduction

Performance criteria to demonstrate that required levels of dam safety are met can be determined through a standards-based approach or a risk-based approach. An outline of the two approaches is as follows:

- Established design practice is based on the standards-based approach. It utilises design criteria largely based on deterministic concepts of reliability, typically because it is relatively straightforward and uses numerical measures of performance such as safety factors. The actual probability of failure cannot be explicitly evaluated using a deterministic approach, and the risks are managed implicitly through the adoption of a PIC for the dam, the selection of an appropriate Inflow Design Flood (IDF) and Safety Evaluation Earthquake (SEE) for the PIC of the dam, and the application of appropriate factors of safety or performance parameters (e.g. deformation) during the design process. It is common practice to select an IDF and SEE with lower annual exceedance probabilities for higher PIC dams to reduce the levels of risk where the consequences of failure are high.
- In a risk-based approach estimates of risk (probabilities and consequences of possible adverse events) can be used as indicators of dam safety levels achieved and may be compared with specific dam safety goals also expressed in probabilistic terms. While risk assessment can be a complex process, the risk-based approach can enhance the understanding of potential failure modes and adverse consequences, highlight the greatest contributors to risk, and provide insights into possible means for reducing risk and adding resilience. An introduction to risk assessment for dam safety management and an outline of the risk assessment process is included in ICOLD Bulletin 130. The Bulletin highlights that "the profession has yet to come to an accepted position on the role and usefulness of risk assessment as an aid to dam safety management". However, failure mode analysis and risk assessment have proven to be very valuable to a number of organisations in determining the necessity of, and most effective means of, rehabilitating existing dams.

While the standards-based approach does not directly account for uncertainties in loads and the ability of a dam to resist the loads, it acknowledges uncertainties through the use of factors of safety and the completion of parametric sensitivity studies. This approach has been very successful, is widely accepted by the dam engineering profession, and has been generally adopted in these Guidelines for the setting of dam design criteria and the evaluation of dam performance. While the standards-based approach is generally adopted by these Guidelines, a risk-based approach may be appropriate in some instances to validate the design and provide an enhanced understanding of residual risks where appropriate data is available. In addition, the adoption of a risk-based approach may be appropriate in some instances to achieve specific risk reductions or compare the relative merits of alternative design solutions for rehabilitation projects.

All designs should conform to established engineering principles for the safety of engineered systems, and be assessed for the recommended dam safety performance criteria included in these Guidelines. When the recommended design criteria in these Guidelines are not met, a potential deficiency may be present which requires evaluation and possibly rehabilitation to restore an appropriate level of dam safety. Risk assessment may be an appropriate and acceptable means to identify and communicate the dam condition, effective risk reduction measures, and an appropriate time frame for the implementation of the risk reduction measures.

Note that the consideration of the safety of a dam post-earthquake will likely require a detailed review of its design. Post-earthquake criteria provided in these Guidelines are only for the temporary condition, immediately post-earthquake, until satisfactory repairs have been completed and acceptable normal operating dam safety criteria have been restored. Any necessary interim risk reduction measures and the time to implement effective repairs should be agreed between the dam Owner, the Regional Authority and the affected stakeholders.

Much of dam design relates to achieving appropriate physical arrangements for the various components and careful detailing to account for the resulting hydraulic and seepage forces. Such details are included in recognised texts, technical papers and ICOLD bulletins and are beyond the scope of these Guidelines. However, all designs should give due attention to a number of important dam safety considerations including the following:

- Wherever it is practical and economic, secondary lines of defence should be incorporated within design arrangements.
- Possible changes in material characteristics or the inadequate performance of critical design elements within the expected life of the dam (e.g. physical degradation of materials, drain blockages).
- Shapes and dimensions to avoid excessive stresses and provide structural resilience to unexpected events.
- Ready access for future maintenance or repair.
- Health and safety during construction and operation.

While not directly related to the safety of a dam, all designs should also give due attention to control measures that minimise the risks to health and safety throughout the life of the structure. Design solutions should provide safe access for operational personnel and protect operational personnel and the public from hazards associated with the operation of the dam and its associated hydraulic structures.

The following three sections discuss a number of topics related to design methods, temporary works, and foundations and abutments that can affect the safety of any dam. The subsequent sections outline potential failure modes, loads and loading conditions, and recommended performance criteria for embankment dams, concrete dams, tailings dams, and appurtenant structures. The guidelines presented are applicable to the design of new dams, the evaluation of an existing dam, and the design of rehabilitation works for an existing dam. A number of important design issues that can affect dam safety are included for each dam type.

6.2 Design methods

6.2.1 Analysis techniques

A detailed discussion on design methods is beyond the scope of these Guidelines and Designers are referred to ICOLD bulletins and other references listed at the end of this module.

The available literature addresses a number of design methods that range from the more simple analysis techniques, such as a rigid body stability analysis, to more sophisticated finite element analysis techniques. The selection of the appropriate analysis method to adopt for the design of a dam, the analysis of an existing dam, or the rehabilitation of an existing dam should take into consideration the dam type and the PIC of the dam, and the ability of the analysis method to evaluate the safety of the dam against its potential failure modes. In many cases a simplified approach is adopted for the initial development of a design concept and later, more sophisticated techniques are utilised to obtain an improved understanding of dam behaviour. Ultimately the Designer must be able to demonstrate that the dam will meet appropriate performance criteria and that the strength and durability criteria of the Building Regulations will be satisfied.

General guidelines for the selection of design methods for embankment design, according to the PIC of the dam, are as follows:

- **Low PIC dams**
  Precedent or empirically based design methods may be acceptable where the dam is less than 10m in height and the dam type and foundation incorporate no unusual characteristics. Otherwise, rational design methods based on material properties and currently accepted factors of safety in the dam engineering profession should be adopted.
- **Medium PIC dams**
  Precedent or empirically based design methods may be acceptable where the dam is less than 10m in height and the dam type and foundation incorporate no unusual characteristics. In addition, if precedent or empirically based design methods are adopted, the proportions and details for the dam should be conservative. Otherwise, rational design methods based on material properties and currently accepted factors of safety in the dam engineering profession should be adopted.

- **High PIC dams**
  Rational design methods based on material properties and currently accepted factors of safety in the dam engineering profession should be adopted for all dams. Design methods should be comprehensive and reflect nationally and internationally accepted practice. The Designer should develop the design progressing from simplified analysis techniques to more sophisticated analysis techniques, using the preceding steps as validation of each following stage. Independent check analyses may be required to validate the design.

  For Low PIC dams where empirical or semi-empirical methods are utilised for the design of the dam, the design should be suitably conservative in recognition of the uncertainties inherent in empirical design. In addition, for a Low PIC dam where full time on-site supervision is not in place during construction, the design should be suitably conservative in areas where the potential for poor construction and associated adverse effects are the greatest (e.g. selection, placement and compaction of embankment materials adjacent to concrete structures).

6.2.2 Potential failure modes

The identification and assessment of potential failure modes for a dam (new or existing) can be achieved through the completion of a Failure Modes and Effects Analysis (FMEA). FMEA's are common in the petrochemical and power industries and are utilised internationally to identify inherent dam-specific and site-specific credible potential failure modes (and therefore key dam vulnerabilities) for a dam. Using the findings and understandings developed from the completion of FMEAs, dam designs can then be refined to address the identified potential failure modes and minimise the potential for failure mode development through the addition of risk reduction resilience. The design phase can also utilise the potential failure modes to establish the surveillance and monitoring procedures for the dam.

An FMEA is best completed in a facilitated workshop environment, attended by representatives of the Owner and Designer, and peer reviewers with relevant knowledge of the dam site characteristics and the proposed design. The workshop should result in an enhanced understanding of the key vulnerabilities of the dam and surveillance requirements to provide early warnings of the development of the potential failure modes. The process and outcomes of the FMEA should be fully documented and include a summary of other failure modes identified but not considered credible, with reasons for their rejection as credible failure modes.

Potential failure modes for a dam can often be difficult to identify and evaluate. Subtle geological features that can have an important influence on the safety of a dam can be difficult to identify (e.g. isolated lenses of openwork gravels beneath the core of a dam). However, historical dam failures (ICOLD 1974 and USSD 1994) and an analysis of historical embankment dam failures by internal erosion and piping (Fell et al 2005) do provide useful information.

FMEAs should be completed during the design of any new Medium or High PIC dam and the design of any rehabilitation works for an existing Medium or High PIC dam. Later comprehensive safety reviews (refer Module 5) for Medium and High PIC dams should include a review of the FMEA report and incorporate any necessary recommendations to update the FMEA report to better reflect actual dam performance. Additional guidelines for the completion of FMEAs and their consideration during comprehensive safety reviews are provided in section 3.4 of Module 5 (Dam Safety Management).

6.3 Temporary works

For a dam constructed under contract, the design of temporary works is usually the Contractor's responsibility. However, the Designer should have key decision making authority for the following temporary works:

- The diversion works during the construction of a new dam or the rehabilitation of an existing dam.
- Diversion arrangements during construction should be carefully considered in relation to the potential for floods to outflank the diversion facilities and the consequences that such an event could have on dam construction and people, property and the environment downstream of the dam. As discussed in section 4.2.2, the potential for overtopping the dam during construction may be high while the dam is low but the consequences may only be minor. Conversely, the consequences may be significant as the dam reaches full height, but the potential for dam overtopping may be low due to the short time exposure and the upstream storage available for routing of the flood event.
- Any other temporary works which could affect the permanent works.

The Designer should specify the parameters for diversion during construction (i.e. diversion facilities, their capacity and their associated cofferdams) taking into account the Owner's risk tolerance, the recommendations included in section 4.2.2, and public safety. The Contractor should propose final diversion details for approval by the Designer, based on risk allocation set out in the contract documents. The design for any cofferdams should reflect their PIC.

Any temporary works which in any way affect the permanent works, as designed and specified, must be reviewed and approved by the Designer.

6.4 Foundations and abutments

6.4.1 Foundation defects

Foundation defects can affect the integrity and stability of any dam type and untreated foundation defects have contributed to many dam failures around the world. Clearly the foundation for any dam must fulfil the following five functions:

- It must provide stability.
- It must provide sufficient stiffness to ensure deformations are within acceptable limits.
- It must control and limit seepage flows and uplift/piezometric pressures beneath the dam.
- It must prevent the transportation of dam materials through the foundation.
- It must not degrade over time.

If any one of the above functions is only marginally satisfied, the safety of the dam may be less than envisaged. Any concerns that arise in relation to the above functions should be addressed by appropriate foundation engineering.

At some dam sites geological conditions are reasonably straight forward and all of the above functions are readily satisfied. At other dam sites geological conditions are complex and many defects may not become apparent until foundation excavation gets underway. The challenge is to keep the uncertainties within acceptable limits; however, there are some geological environments that require more care during investigation, design and construction. They include:

- Clean coarse sands, gravels and cobbles (open work deposits) which could provide a pathway for foundation piping or the piping of embankment materials into the foundation.
- Loose silt or sand deposits that are potentially liquefiable.
- Infilled joints that could be eroded out and provide the potential for high seepage flows or the piping of embankment materials.
- Interbedded soil deposits (fine against coarse) that could provide the potential for foundation piping.
- Weak strata, interbeds and seams with low strengths which could result in potential sliding failure surfaces within the foundation.

- Highly compressible and/or dispersive soils which could result in collapse and differential settlements, and cracking or foundation piping.
- Volcanic deposits whose engineering properties can vary enormously over short distances. Lava flows can be underlain by beds of breccia, scoria or sand with high permeabilities and low resistance to erosion. Sites where tuffs, lahar deposits and agglomerates are present often incorporate low density and low strength materials.
- Karst features (caves, sinkholes) which can result in high seepage losses and further sinkholes following impoundment by the washing out of infilling or overlying materials.
- Persistent sub-horizontal joint sets that control the shear strength at the dam/foundation interface or within the dam foundation.
- Faults and other major discontinuities which can incorporate low strength materials and, if unfavourably orientated, can affect dam stability.
- Active faults (primary and secondary) that can result in displacements beneath a dam and the initiation of internal erosion, increased uplift pressures and reductions in dam stability.
- Landslides or unstable rock abutments that may require substantial remedial works to protect the long-term integrity of the abutments.

6.4.2 Foundation treatments

Foundations for dams require some treatment to satisfy the requirements of stability, deformation and water tightness. Generally the scope of any foundation treatment depends on the type of dam, the PIC of the dam, and the characteristics of the foundation materials. For a Low PIC embankment dam on a soil foundation it may only be necessary to remove all overlying organic materials; however, for a Medium or High PIC concrete gravity dam on a rock foundation it will be necessary to remove all overlying materials to a suitable rock quality, treat particular rock defects, and it may be necessary to complete a programme of consolidation and curtain grouting.

ICOLD Bulletin 129 provides a detailed account of foundation treatment methods which are grouped into excavation and surface treatment, treatment by sealing measures, treatment by drainage measures, and treatment by strengthening measures. In addition, ICOLD Bulletin 88 provides a detailed account of the investigation, design and treatment of rock foundations.

Excavation and surface treatment involves the removal of all undesirable materials necessary to achieve a foundation that satisfies or can be treated to achieve the requirements of stability, deformation and water tightness. This necessitates the following for particular dam types:

Zoned embankment dam

The removal of all erodible, weak, unstable or liquefiable, compressible or loose materials, and the treatment of any rock defects to achieve a uniformly varying foundation and abutment profile, to enable a tight bond between the core material and its foundation, and to provide an adequate defence against the development of a preferential seepage erosion pathway capable of transporting embankment materials along the foundation and abutment contacts.

Foundation shaping to remove steps or prominent features that could result in areas of low stress and initiate settlement cracking in the core.

If it is uneconomic to remove liquefiable materials they must be stabilised by special ground improvement works. Impervious foundation materials beneath the dam's drainage features which would prevent proper functioning of the feature must be removed. If necessary, graded filters should be installed to prevent the erosion of shoulder materials into the foundation and foundation materials into the embankment.

Concrete faced rockfill dam

Seepage paths beneath the plinths (upstream toe slabs) are short and hydraulic gradients are high so it is most important that excavation and surface treatments minimise the potential for erosion or piping in the foundation beneath the plinth. Excavation methods should be selected to minimise the potential for foundation damage and foundation clean up should be completed to a standard that ensures a well bonded contact between the concrete and foundation rock.

Apart from a short distance downstream of the plinth, where soil and soft weathered rock should be removed if filter and transition materials are installed between the face slab and downstream rockfill, the foundation beneath the downstream rockfill often only requires the removal of surface deposits to expose the points of hard in situ rock. If the foundations are weathered then the section downstream of the concrete plinth could be founded on material which is more prone to erosion and piping. In this case filters will need to be more extensive. Gravel deposits are often left in place as they frequently have a higher modulus of compressibility than well compacted rockfill.

Concrete gravity dam

Apart from low head structures which may be built on suitable overburden materials but require special treatments for the control of seepage flows, all concrete gravity dam foundations should be cleaned down to reasonably uniform surfaces of competent rock.

Foundation defects such as weathered zones, fault zones and weak seams should be excavated to appropriate depths and backfilled with concrete. In some cases, where prominent defect zones containing erodible material are present, it may be necessary to excavate upstream and downstream cutoff shafts and backfill them with concrete. In other cases, where the global stability of concrete monoliths is adversely affected by unfavourably orientated weak foundation seams (e.g. bedding surfaces, joints, fault and shear surfaces) that form blocks or wedges, it may be necessary to remove additional material or construct shear keys to achieve adequate margins of stability. Foundation treatment by drainage of discontinuities associated with foundation blocks and wedges is recognised as one of the most effective procedures available, as drainage can reduce or remove both hydraulic driving pressures and uplift pressures on resisting planes.

Concrete arch dam

Excavation and surface treatment requirements are more demanding than for a concrete gravity dam. The requirements for a stable, symmetrical and uniform foundation often necessitate deep excavations, particularly in the abutments, and extensive foundation treatment works.

Sealing measures are often specified at dam sites to reduce seepage flows through dam foundations (to reduce water loss), to prevent foundation erosion and, in conjunction with drainage systems, to reduce uplift pressures beneath dams. The treatment method commonly varies according to the nature of the foundation material and can include:

- The excavation of a shallow cutoff trench to a lower impermeable layer, directly beneath the core of a zoned embankment dam, and backfilling the cutoff trench with core material.
- Curtain grouting or consolidation grouting to form a curtain or blanket of grouted rock.
- Grout curtains should be designed for the site-specific geological conditions. Only stable (low bleed) grouts should be used. Triple row grout curtains are preferred with holes oriented to intersect prominent joint sets (e.g. vertical holes are inappropriate when treating vertical defects). Designers should specify the spacing and orientation of grout holes, the grout curtain depth, the grout mix parameters, the target permeability measured in Lugeons, and the quality control requirements.
- Grouting techniques should be appropriate for the geological conditions and the specified grouting performance requirements.
- The excavation and construction of a deep cutoff wall to a lower impermeable layer directly beneath the dam or in the abutments. Available cutoff walls include diaphragm walls and slurry walls which are excavated and backfilled with various materials (e.g. plastic concrete, cement/bentonite slurry), walls constructed from contiguous and interlocking concrete-filled piles (secant pile walls), and relatively thin walls formed by a descending vibrating beam and then backfilled with mortar during its withdrawal. Cutoff walls can be constructed through overburden and through rock foundations.

- The in-place mixing of overburden materials with a cementitious binder.
- The construction of a blanket of impermeable material immediately upstream of the dam.

Drainage measures are provided for the control of seepage through and beneath dams, and the reduction of uplift pressures beneath dams. In rock foundations these objectives are often achieved by the construction of an upstream grout curtain and the later drilling of a fan of drainage holes from one or more galleries or the foundation surfaces immediately downstream of the dam. In overburden materials they are usually achieved through the construction of drainage blankets, toe drains, and/or relief wells.

Strengthening measures can sometimes be necessary to improve the characteristics of a dam foundation. The strengthening of a rock foundation to provide a more homogeneous material and minimise deformations under dam loadings can be achieved through the grouting of discontinuities, and the excavation, concrete backfilling and grouting of weak zones of foundation material. Where a dam is founded directly on overburden materials the important structural design consideration is bearing capacity. For cohesive materials, the bearing capacity can be improved by drainage measures to enhance the consolidation process. For cohesionless materials a number of ground improvement techniques are available that include static (pre-loading) or dynamic compaction from the ground surface, vibrocompaction, blasting through a grid of boreholes, compaction grouting using a low fluidity grout to displace the borehole walls into the overburden material, and deep mixing and jet grouting to provide a series of column inclusions within the overburden material. Methods such as stone columns that provide densification through the addition of materials (especially porous materials), or direct compaction (with drainage provisions) such as dynamic compaction with wick drains, have proven to be more effective than soil replacement methods.

Detailed descriptions of the above foundation treatment methods and their applications are included in ICOLD Bulletins 88 and 129. Bruce (2013) provides a compilation of current practice in the wide range of techniques for dam foundation engineering. Weaver and Bruce (2007) provide considerable detail on contemporary drilling and grouting for dam foundation grouting.

The design of foundation engineering works must account for performance criteria, constructability, health and safety and quality assurance needs to demonstrate that the feature will perform its function and provide adequate service life.

6.5 Embankment dams

6.5.1 Introduction

Embankment dams are grouped according to the types of material used in their construction. They commonly include:

- Homogeneous earthfill dams which are constructed from a single material except for a pervious zone which is placed beneath the downstream shoulder or at the downstream toe.
- Homogeneous earthfill dams which incorporate additional features such as:
  - an upstream geomembrane liner as an impermeable barrier, or
  - a concrete core wall as an impermeable barrier.
  - filter and drainage materials (such as a chimney drain linked to a pervious downstream blanket at the foundation contact) to maintain the downstream shoulder in a dry condition and to control and discharge seepage flows.
- Zoned earthfill dams which normally incorporate a low permeability core material, higher permeability shoulder materials, and filter and drainage materials for the control and discharge of seepage flows.
- Zoned earth and rockfill dams which normally incorporate a low permeability core material, rockfill shoulder materials, and filter and drainage materials for the control and discharge of seepage flows.
- Concrete-faced rockfill dams with an upstream concrete facing and a rockfill or gravel embankment.
- Rockfill dams with a central impervious core of earth, asphalt or concrete.

The following subsections discuss potential failure modes for embankment dams, loading conditions which must be taken into account during their design, evaluation and rehabilitation, and recommended performance criteria for embankment dams. A number of defensive design details that are important to dam safety are also discussed. Concrete- faced rockfill dams and geomembrane–lined embankment dams are discussed in Sections 6.6 and 6.7.

6.5.2 Potential failure modes

It is not possible to provide a complete listing of potential failure modes for embankment dams as each dam is unique – it incorporates different materials, different foundation conditions, different design configurations, and different design details. It is therefore most important that the identification of potential failure modes for a dam is based on site-specific conditions and the specific characteristics of the dam.

The examination of potential failure modes should be carried out for dam safety evaluations to assist in the determination of any necessary rehabilitation works. They are also a valuable tool for use during the design of new dams and the rehabilitation of existing dams to ensure that potential dam vulnerabilities are addressed and risk reduction measures are incorporated as appropriate.

Embankment dams can be vulnerable to and should therefore be designed against:

- Deformation and consequent loss of freeboard and/or increase in seepage.
- Internal deterioration through internal erosion and piping from one of the following processes:
  - Concentrated leak erosion – Occurs in soils which are capable of sustaining an open crack or gap, or in the interconnecting voids in a continuous permeable zone. Erosion occurs along the sides of the crack or gap, or in the voids, where the shear stress of the seepage flow exceeds the critical shear stress of the soil particles.
  - Backward erosion – The detachment of soil particles when seepage exits to a free unfiltered surface such as the ground surface downstream of a soil foundation, the downstream face of a homogeneous dam, or a coarse rockfill zone immediately downstream of a fine grained core material. Erosion starts at the exit point and a continuous passage is developed by backward erosion when the seepage gradient exceeds the 'flotation gradient' of the soil.
  - Suffusion – Selective erosion of finer particles from the matrix of coarser particles, in such a manner that the finer particles are removed through the voids between the larger particles by seepage flow, leaving behind a soil skeleton of coarse material. A potentially suffusive soil is a gap-graded soil which has a deficiency of medium sized particles to fill the voids between the coarser particles. This process can occur via seepage through the main body of a dam which is not protected by an adequate filter. Suffusion is also experienced at the toe of embankment dams where foundation seepage under artesian pressures emerges through the overburden.
  - Contact erosion – Selective erosion of fine particles along a contact surface between a fine soil and a coarse soil, caused by flow passing through the coarse soil (e.g. flow occurring along a contact surface between silt and gravel sized materials). It relates only to conditions where the flow in the coarser layer is parallel to the interface between the coarse and fine layer.

In the backward erosion process, detached particles are carried away by the seepage flow and the process gradually works its way towards the upstream side of the embankment or its foundation until a continuous pipe is formed. There are three forms of backward erosion:

- Backward erosion piping, in which the roof of the pipe is formed by a cohesive soil layer within the embankment and the pipe is essentially horizontal.
- Global backward erosion, where the pipe formation is nearly vertical within a broadly graded silt/sand/gravel embankment.
- Stoping (as in mining) backward erosion, where the pipe is formed vertically with the materials falling by gravity and being carried away by a horizontal seepage or leakage flow through the dam or foundation. The susceptible materials are non-plastic silts, sands and rock flour.

Flaws in an embankment dam that would be considered vulnerabilities in an FMEA include:

- Cracks caused by settlement or hydraulic fracture.
- Irregularities or steps in the abutment or foundation profile.
- Desiccation cracks near the crest – drying shrinkage or freeze-thaw effects.
- Gaps or cracking adjacent to spillway walls or conduits.
- Poorly graded materials or segregation, giving rise to coarse zones susceptible to high seepage flows and the migration of fines.
- Poorly compacted layers which can give rise to interconnected voids or a gap wetting induced collapse.
- Poor compaction at interfaces between separate zones of a dam.
- The lack of sealing or inadequate protection of joints in the core/foundation or core/abutment contact areas.
- The lack of filters.
- Inadequate drainage provisions.
- Relic defects in soil foundations.
- In-filled defects in rock foundations.
- Dam or foundation soils susceptible to liquefaction.
- High foundation permeabilities that enable the development of artesian pressures and potential blowouts at the dam toe.

Potential cracks in an embankment dam that would be considered vulnerabilities are shown in Figure 6.1 and the influence of a number of factors on the likelihood of cracking occurring are listed in Table 6.1. Transverse cracks are especially hazardous to water-retaining embankments because they present an open pathway across the embankment that can potentially quickly erode and downcut, leading to a breach. Fong and Bennett (1995) report transverse cracks are more prone to occur near the abutments of embankment dams. Swaisgood (1998) reports that they particularly tend to occur where abutments are steeply sloping and stiffer than the embankment. Transverse cracking in embankment dams is also possible where differential settlements occur across steps in foundations or rigid structures.

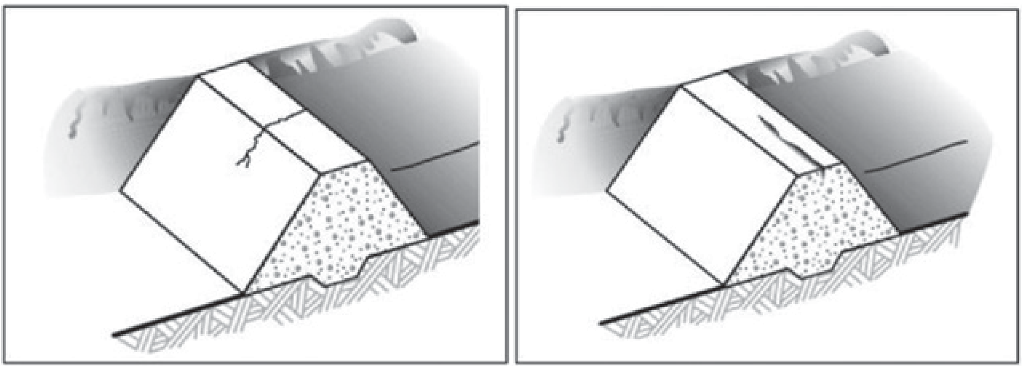


Figure 6.1: Longitudinal and Transverse Cracking (from USFWS 2008).

Table 6.1: Influence of Factors on the Likelihood of Cracking or Hydraulic Fracturing (from Foster and Fell, 2000).

Factor	Influence on Likelhood of Cracking or Hydraulic Fracturing		
	More Likely	**Neutral**	**Less Likely**
Overall abutment profile	Deep and narrow valley. Abrupt changes in abutment profile, continuous across core. Near vertical abutment slopes.	Reasonably uniform slopes and moderate steepness (e.g. 0.25H:1V to 0.5H:1V	Uniform abutment profile, or large scale slope modification. Flat abutment slopes (>0.5H:1V)
Small scale irregularities in abutment profile	Steps, benches, depressions in rock foundation, particularly if continuous across width of core (e.g. haul road, grouting platform during construction, river channel).	Irregularities present, but not continuous across width of the core.	Careful slope modification or smooth profile.
Differential foundation settlement	Deep soil foundation adjacent to rock abutments. Variable depth of foundation soils. Variation in compressibility of foundation soils.	Soil foundation, gradual variation in depth.	Low compressible soil foundation. No soil in foundation.
Core characteristics	Narrow core, H/W>2, particularly core with vertical sides. Core material less stiff than shell material. Central core.	Average core width, 2<H/W<1 Core and shell materials equivalent stiffness.	Wide core, H/W<1 Core material stiffer than shell material. Upstream sloping core.
Closure section (during construction)	River diversion through closure section in dam, or new fill placed a long time after original construction.		No closure section (river diversion through outlet conduit or tunnel).

Cracking, creating an opening and/or loose materials and a resulting preferential seepage erosion pathway, can also occur at the interfaces between embankments and spillway walls, conduits and other rigid structures that are located adjacent to, beneath, or pass through embankment dams. Inappropriate details at embankment/structure interfaces, the lack of filter and drainage protection, and low stresses associated with arching of embankment fills across the tops of conduits, can initiate cracking and the erosion of embankment materials. Many embankment dam failures have been influenced by inappropriate design details, and inadequate filter and drainage protection adjacent to conduits.

As indicated previously, the identification of potential failure modes for a dam should be based on site-specific conditions and the specific characteristics of the dam. However, as an aid, the more common potential failure modes identified for embankment dams, which are related to the dam and its foundation, are outlined in Table 6.2.

Table 6.2: Potential Failure Modes for Embankment Dams

Potential Failure Mode	Common Causes
Overtopping	Insufficient freeboard to accommodate storms and flood events
Internal erosion of embankment materials	Presence of defect or crack, cohesionless core material or core material with a Plasticity Index less than 7, dispersive soils, lack of adequate filter protection
Suffusion of embankment materials	Cohesionless core material or core material with a Plasticity Index less than 7, gap graded embankment materials
Internal erosion of embankment materials into foundation materials	Open joints at interfaces, lack of adequate filter protection, lack of or inappropriate foundation treatment
Internal erosion of foundation materials	Foundation material has a Plasticity Index less than 7, dispersive foundation materials, lack of or inappropriate foundation treatment
Instability of downstream shoulder	Weak foundation, weak shallow seam in foundation, poor conditioning and compaction, lack of effective drainage and saturation of downstream shoulder, insufficient shear strength, strong earthquake shaking
Instability of upstream shoulder	Weak foundation, poor conditioning and compaction, rapid drawdown of reservoir, insufficient shear strength, strong earthquake shaking
Loss of freeboard, overtopping and subsequent erosion	Insufficient freeboard to accommodate foundation and embankment settlement, settlement following seismic loading, liquefaction of embankment and/or foundation materials, seiches generated by earthquakes, uplift of the reservoir due to fault displacement, reservoir landslides
Erosion along embankment/structure interfaces	Inappropriate design details, lack of filter and drainage protection, poor compaction adjacent to structure

6.5.3 Loading conditions

Loading conditions for the design and rehabilitation of embankment dams are presented and discussed in various ANCOLD guidelines, Canadian Dam Association (2007), and various USACE and USBR engineering manuals.

Loading conditions that should be considered in the design or rehabilitation of an embankment dam are:

- Normal loading conditions.
- Unusual loading conditions.
- Extreme loading conditions.

Normal loading conditions are those which the dam is expected to continuously withstand during normal operation. Examples include steady state seepage and embankment stability with normal maximum reservoir elevation, and embankment stability with no reservoir for a flood detention dam.

Unusual loading conditions occur on an infrequent basis. Examples include the end of construction condition where high pore water pressures can exist in core and foundation materials, severe wave action, rapid drawdown of the reservoir, and the OBE. Minor damage, such as crest settlement and minor shallow or surface cracking, is acceptable; however, the dam should continue to behave in a satisfactory and safe manner.

Extreme loads are those associated with low probability events which, if they were to occur, would be considered severe tests of a dam's performance and would require diligent visual inspection and observation, and a readiness to respond to a dam safety emergency. Examples include floods at or above the IDF, earthquakes at or near the SEE, and the post-SEE loading condition. Significant damage to the structure is possible and major repairs may be required; however, the damage must not result in an uncontrolled loss of the reservoir.

6.5.4 Stability and deformation performance criteria

Potential stability failures for embankment dams under different loading conditions should be assessed in terms of minimum factors of safety.

Static Assessment

For embankment dams, the dam, foundation and abutments must be stable during construction and under all operating conditions, including full or partial drawdown. Recommended minimum factors of safety for limit equilibrium stability studies, for static loading conditions, are listed in Table 6.3. The recommended factors of safety reflect those adopted by the Canadian Dam Association. In addition, for static loading conditions, they are similar to those adopted by the US Bureau of Reclamation and the US Corps of Engineers, and those recommended by Fell et al (2005).

Table 6.3: Recommended Minimum Factors of Safety for Slope Stability – Static Assessment

Loading Condition	Slope	Minimum Factor of Safety1,2,4
End of construction before reservoir filling	Upstream and downstream	1.3
Long-term (steady state seepage, normal reservoir level)	Downstream	1.5
Full or partial rapid drawdown	Upstream	1.2 to 1.3[3]

Notes:

1. The factor of safety is a representation of the factor required to reduce operational shear strength parameters, or increase the loading, in order to bring a potential sliding mass into a state of limit equilibrium, using generally accepted methods of analysis.
2. Higher factors of safety may be necessary if there are high levels of uncertainty in the inputs to the stability analysis.
3. Higher factors of safety may be required if drawdown occurs relatively frequently during normal operation.
4. The above factors of safety are appropriate for the design of new dams on high strength foundations with low permeability zones constructed of soil which is not strain weakening, using reasonable conservative shear strengths and pore pressures developed from extensive geotechnical investigations of borrow areas, laboratory testing and analysis of the results. Fell et al (2005) provides guidance for adjusting the above minimum factors of safety for other conditions such as an existing dam, soil or weak rock foundation materials, strain weakening soils, and limited strength investigation and testing.

Seismic Assessment

A dam may be damaged during an earthquake but it must be able to safely contain the reservoir contents in its post-earthquake condition. Earthquake damage could include crest settlement and lateral spreading, longitudinal or transverse cracking, separation or cracking at the boundary of embankment and concrete structures, and/or slope movements on the upstream or downstream face of a dam. Crest settlement must not result in the reservoir overtopping the crest of the dam, and slope movements must not result in the loss of freeboard or the loss of support to the core or upstream water retaining membrane. Cracking or separation should be limited to the depth above the full supply level and, if not, immediate intervention is necessary to protect against a seepage erosion induced breach of the dam.

A wide variety of methods are available to evaluate the seismic stability of embankment dams which include pseudo-static methods, simplified methods of deformation analysis, and numerical modelling techniques.

The use of simplified stability analyses using a pseudo-static approach should only be used as a screening tool. Yield acceleration is the analytically calculated acceleration applied to a potential slide mass that indicates an instantaneous factor of safety against sliding of 1.0. If the peak acceleration for the SEE loading condition (taking into account structural amplification response) is greater than the calculated yield acceleration, the implication is that at each time during the earthquake when the yield acceleration is exceeded some displacement will occur. The Designer should then establish the extent of predicted cumulative displacement and determine whether the dam will continue to retain its contents in its damaged state.

Simplified methods exist for evaluating embankment seismic response and are appropriate for most applications. Linear and non-linear dynamic analysis methods are normally only utilised for High PIC dams where stability and deformation studies indicate marginal safety or material degradation, or where the dynamic response of the dam is not readily estimated. Recommended minimum requirements for seismic stability are listed in Table 6.4. The recommended factors of safety for the pseudo-static and post-earthquake loading conditions reflect those adopted by the Canadian Dam Association (2007).

Table 6.4: Recommended Minimum Requirements for Slope Stability– Seismic Assessment

Loading Condition	Slope	Minimum Factor of Safety or Acceptable Deformation
Extreme (applied as pseudo-static load)	Upstream and downstream	1.0
OBE (consider embankment response)	Upstream and downstream	Generally 1.0. Minor deformations are acceptable provided the dam remains functional and the resulting damage is easily repairable
SEE (consider embankment response)	Upstream and downstream	Deformations are acceptable provided they do not lead to an uncontrolled release of the impounded contents
Post-earthquake	Upstream and downstream	1.2 to 1.3

Empirical methods can be used to estimate earthquake induced embankment crest settlements. These are generally based on historical data and offer reasonably coarse estimates.

Embankments with short natural periods in the order of 0.1 second (e.g. low height and stiff cross sections), are likely to experience near resonant response and high spectral accelerations at the embankment crest. Longitudinal cracking will likely occur along the crest and upper faces of the embankment. There is limited case history knowledge of transverse cracking on embankment dams, but the examples identified tend to occur at higher accelerations or are directly related to foundation shape discontinuities. Most documented cases of embankment dams subjected to earthquakes with a Moment Magnitude (Mw) >6.75 and a peak ground acceleration (PGA) >0.3g report transverse cracking in addition to longitudinal cracking.

Clearly the assessed damage (cracking and settlement) for the SEE should incorporate some margin to provide assurance that an uncontrolled release of the reservoir cannot be initiated. The Designer should consider the dam fundamental period in response to ground motions and case studies of dam performance. Some examples of useful methodologies that Designers can consider are outlined below.

- Fell et al (2005) describe a simplified methodology for estimating settlement and cracking in embankment dams subjected to seismic shaking. The methodology uses research by Pells & Fell (2002) and Swaisgood (1998), developed from the historical seismic performance of embankment dams, and includes plots of damage contours versus earthquake magnitude and peak ground acceleration for earthfill and rockfill dams. Pells and Fell (2002) plot embankment dam cases for which both longitudinal and transverse cracking occurred, along with cases where only longitudinal cracks were reported.
- Fong and Bennett (1995) provide plots of normalised settlement versus crack depth which can be used to estimate crack depths.
- Bray and Travasarou (2007) provide a simplified method for estimating deformation that accounts for embankment properties, such as shear strength and geometry, by considering yield acceleration. The method is based on 688 ground motion records and provides a means for estimating the seismic settlement of embankments. It can also be used to estimate embankment settlements for very high PGAs.
- ICOLD Bulletin 141 also includes simplified methodologies for assessing likely deformations in rockfill embankments subjected to strong earthquake ground motions.

The above methodologies are empirically based and utilise the limited database of dams that have been damaged by earthquakes. With advances in research these sources may be revised, or new methodologies developed, and it is therefore important that the Designer maintains an awareness of new techniques and methodologies developed for the estimation of seismic induced deformation in embankments.

For detailed numerical analyses, the Designer should utilise the above simplified methodologies as validation checks.

The Designer should analyse the post-SEE condition of the dam to obtain an understanding of the state of the dam before analysing the aftershock loading condition. Damage may result in pore pressure changes within the embankment that have an adverse effect on material properties and dam stability. Estimates of any strength reductions that result from the main shock should be incorporated in the aftershock analysis and again in the final post-earthquake analysis. If it is envisaged that the reservoir will not be drawn down immediately following the SEE, then the aftershock loading conditions should be analysed with the dam in a medium to long term post-earthquake seepage (pore pressure) condition. As stated in section 6.1, the post-earthquake criteria are only applicable for the temporary condition, immediately post-earthquake, until satisfactory repairs have been completed and acceptable normal operating dam safety criteria have been restored. During this period interim risk reduction measures may be necessary to provide an acceptable level of dam safety until satisfactory repairs have been completed.

If cracking is so extensive that subsequent leakage saturates the embankment, it could exit the downstream slope leading to destabilising forces at the face, with resultant slope instability or unravelling of the shoulder material. Embankment resistance to leakage instability is predominantly a function of the downstream slope angle, the mean particle diameter of the shoulder material, and the leakage discharge exiting the downstream face and toe.

In assessing the capability of an embankment dam or foundation to resist earthquake motions, the potential for liquefaction must also be addressed. Where possible, liquefiable materials should be avoided or removed. If liquefaction is possible the post-liquefaction static and aftershock stability of the dam will need to be evaluated, using the estimated residual strength of the liquefied soil, with and without remedial measures to ensure dam failure does not occur.

6.5.5 Design details

In addition to meeting the above performance criteria, successful embankment dam design relies on the adoption of good defensive design details. These are addressed in a number of ICOLD bulletins and include:

- Providing ample freeboard and appropriate crest details.
- Using the best available materials in the more critical areas of the embankment.
- Providing well designed and constructed filter and transition zones to ensure compatibility between adjacent materials.
- Providing ample drainage zones for the interception and control of seepage flows.
- Providing good design details (e.g. flaring or widening the filter and transition zones) at all interfaces between the embankment and its foundation, and at all interfaces between the embankment and concrete structures (e.g. spillways and diversion culverts).
- Providing adequate protection against erosion by wave action and runoff.

Freeboard and Crest Details

ICOLD Bulletin 142 states that the most common cause of failure for any dam type is overtopping of an earthfill embankment and that overtopping should not be accepted as a design criterion for any embankment dam. While the bulletin provides detailed information on the safe passage of floods, it includes no recommendations for the determination of minimum freeboard allowances. These Guidelines have adopted the minimum freeboard provisions included in Fell et al (2005), as detailed in section 4.5.3.

In addition to overtopping by wind generated waves, the freeboard provision should be sufficient to protect the dam against overtopping caused by abnormal events such as an earthquake (ground motions and/or fault displacement), a seiche and a landslide into the reservoir.

The recommended freeboard allowances included in section 4.5.3 are appropriate for the design of new embankment dams and the evaluation of existing embankment dams where the cost of providing additional freeboard is small. For existing embankment dams where the cost of providing additional freeboard is high and the maximum water surface elevation is so close to the dam crest that wind generated waves and setup would overtop the crest, or the maximum water surface elevation is higher than the existing crest, the potential of the overtopping to initiate a dam failure should be evaluated. The resulting evaluation may indicate that the existing freeboard provision is sufficient, or that additional freeboard should be provided to reduce the potential for an overtopping failure.

At existing dams the crest may be irregular with low spots due to excessive settlement, variations in settlement, or the provision of camber that can leave the upstream and downstream abutment contacts at lower elevations than the central portion of the dam. Thus, the available freeboard should be established by a survey of the crest profile.

Crest details for an embankment dam should be designed to:

- Provide a suitable width for construction and, if appropriate, a suitable width for a permanent access road. Unless a permanent access road is needed, a crest width of 6m should be sufficient for most dams. To enable access for maintenance, crest widths should never be less than 4m.
- Provide a suitable level of protection against internal erosion and piping. During extreme flood conditions the reservoir level, excluding waves, should not exceed the top of the impervious core. In addition, any filter and transition materials should extend to the top of the core material.
- Contain the reservoir without inducing seepage erosion on the downstream face during extreme floods. For new dams and major rehabilitations to existing dams, the core and protective filters should extend to the peak reservoir level during the discharge of the adopted IDF. For existing dams where the reservoir surface rises above the core during an extreme flood event, a risk assessment should be completed to determine the time for the seepage front to reach the downstream face, the head loss that would be expected between the upstream and downstream faces, and the resulting erosion potential of the crest material on the downstream face. The risk assessment should also consider the potential for seepage through cracks in the core where it is unprotected by filters above normal operating level.

Embankment Materials
At many sites there is a shortage of good quality, naturally occurring materials and in many cases processing is necessary to obtain suitable materials for construction. At the outset it is important to establish the characteristics of the naturally occurring materials and where they could be best utilised in the construction of the embankment. For example:

- There may be insufficient plastic core material for the construction of the dam core and, as such, it may be prudent to utilise the plastic material in the more critical areas (e.g. adjacent to the core/foundation interface and all core/concrete interfaces).
- The scarcity of a suitable plastic core material may necessitate the use of a core material with little plasticity (e.g. a silty sandy gravel) and the adoption of a wider core and enhanced filter protection than envisaged during the initial design.
- The naturally occurring material may be abundant but variable and it may be appropriate to utilise the material with less fines and more variability in the downstream shoulder of the dam.
- The available rockfill breaks down during compaction and it may be necessary to install additional filter and drainage materials to achieve a drained downstream shoulder.
- The naturally occurring alluvial materials require a significant amount of processing to produce the specified filter and drainage materials, and it may be more economical to import suitable materials to the site.

The construction specification should include material grading envelopes, filter compatibility requirements, target moisture contents, compaction requirements, quality control tests and quality assurance requirements. Trial processing and embankment trials are recommended to establish final specification parameters. Strict adherence to the compaction specification is necessary to avoid the presence of crushed layers, that adversely affect permeability contrasts, and uncompacted layers that encourage embankment settlement and cracking. Cores susceptible to desiccation cracking should be protected from drying out during any construction shutdown and capped at their crests to minimise the potential for desiccation cracking during their operational lives.

Filter, Transition and Drainage Zones
Seepage through embankment dams must be managed to prevent erosion and degradation of dam components. Filters and drainage zones should be provided where the shoulder material is coarse in relation to the core, should be considered essential where the core incorporates dispersive soils, and should be provided around culverts, conduits and any penetrations through the dam. Filter, transition and drainage zones must be designed to ensure compatibility between adjacent materials, and provide sufficient drainage capacity to safely accommodate the anticipated seepage flows under all loading conditions, including the post-earthquake condition.

Filters can be divided into critical and non-critical filters. Critical filters are those that are critical to the control of internal erosion in a dam and, as such, they should be designed and constructed to meet stringent, no-erosion filter criteria. Non-critical filters are those that can be readily repaired if erosion occurs. Examples of critical filters in Figure 6.2 are 'g' and 'h' (if there is potential for the erosion of embankment material into the foundation), and examples of non-critical filters are 'a' and 'c'. Although not shown in Figure 6.2, filters just downstream of the core around conduits passing through a dam and around any other penetrations through a dam are also critical filters.

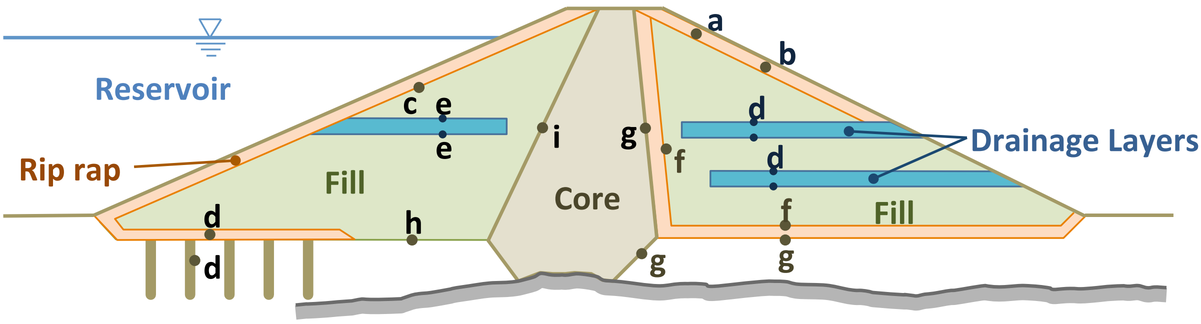


Figure 6.2: Critical and Non-Critical Filters (Redrafted from Fell et al 2005).

Critical Filters

A properly designed filter will block the movement of soils eroded from a crack and prevent subsequent erosion. Figure 6.3 schematically demonstrates how an eroded fine material is caught at the filter face, and how high hydraulic gradients between the water in the crack and the adjacent filter can result in a widening of the eroded material on the filter until the gradient is reduced. Upstream filters can also have a function of "crack stopping" to fill an open crack and prevent further erosion.

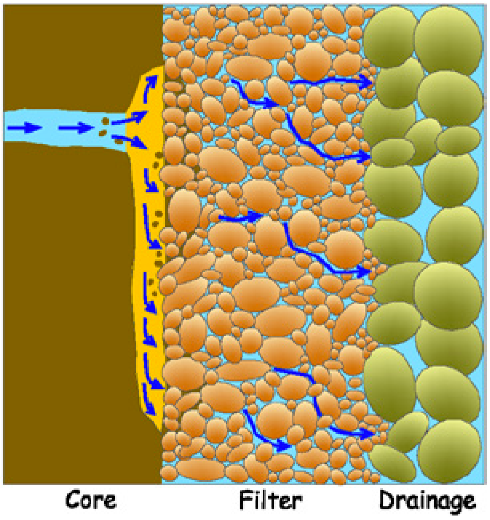


Figure 6.3: Schematic of an Effective Filter

Fell et al (2005) assesses alternative methods for the design of filters, reviews a number of factors that affect filter design and performance, and recommends methods for the design of critical filters. ICOLD (2013) includes a detailed account of internal erosion processes and provides guidelines for the engineering assessment of the vulnerability of a dam to failure or damage by internal erosion. It also includes a discussion on design methods for critical filters and a number of comments on the appropriateness of the methods. The recommended method included in Fell et al (2005) should be adopted for the design of any filter, transition or drainage zones.

The following general criteria apply to filters:

- The granular filter should be non-plastic and highly unlikely to hold an open crack.
- The filter should be designed to meet 'no-erosion' criteria as described in Fell et al (2005).
- The filter should be sufficiently permeable for the seepage flow to pass through it without significant build up in pressure. The grading of the filter should have ≤2% (or at most 5%) fines passing the 0.075mm sieve.
- Gap graded filters, and gradings prone to segregation or degradation, should be avoided.
- Filter and drainage zones must be sufficiently wide to adequately perform their filtering and drainage functions, to minimise the potential for the introduction of construction related defects (e.g. horizontal offsets, segregation), and to remain effective following any differential movements during construction or displacements following an earthquake.
  - For filters upstream and downstream of a dam core the specified width should reflect the proposed construction method (e.g. end dumping from a truck, the use of a spreader box).
  - For horizontal filters the specified thickness should be sufficient to minimise the potential for continuous coarse zones through the filter material. Fell et al (2005) recommend that the specified thickness should be no less than 20 times the maximum particle size of the filter material.
- To ensure the full height of the core is protected against internal erosion, critical filters downstream of the core should extend over the full height of the core.
- Filter placement methods should minimize the potential for segregation and contamination.
- Filter compaction levels should be dense enough to be dilative but not so dense as to become brittle and crack prone.

Horizontal drains also need to be filter compatible. If large discharges are expected then a coarse drain, protected by filters above and below the drain (i.e. three layers), is recommended.

To assess the internal stability of a filter, Kenney and Lau (1986) recommend limits based on sandy gravel tests. Burenkova (1993) considers the slopes of the grading curves which is the basis for the recommendations by Wan and Fell (2008) and Fell and Fry (2013) for silty sandy gravels. Each method should only be used for soil types that are the same as the soil type tested.

Non-Critical Filters

Non-critical filters such as those upstream of the core of a dam where the filter is not subject to the risk of high exit gradients if the core cracks, and beneath upstream rip rap protection where some damage may be acceptable, are sometimes designed to lesser standards than critical filters. However, if proper protection is required, the filters should be designed as critical filters.

Fell et al (2005) includes recommendations for the design of non-critical filters and highlights specific applications where it is appropriate to adopt the design philosophy recommended for critical filters. In many cases a well graded gravelly sand, with a maximum particle size of 75mm and less than 5% fines, should be suitable.

Assessing Filters in Existing Dams

ICOLD (2013) and Fell et al (2005) provide guidelines for the engineering assessment of the vulnerability of an existing dam to internal erosion. The guidelines include the identification of potential internal erosion failure modes, screening of the potential failure modes according to particular dam, foundation and concrete structure characteristics, identification of those potential failure modes that are more likely to occur, and analysis of the more likely potential failure modes to determine whether internal erosion could initiate, continue and progress. Figure 6.4 provides examples of possible locations where internal erosion can be initiated in embankment dams.

In addition to the locations illustrated in Figure 6.4, it is noted that abutment steps or irregularities are locations where internal erosion (seepage erosion) can be initiated in an embankment dam.

In addition, it is noted that the pressures along a foundation seepage path (6 in Figure 6.4) can be significantly greater than the pore pressures in the dam, especially beneath and downstream of the core. In such instances the gradient is from the foundation into the dam and the potential for the erosion of foundation materials into the downstream shell or a drainage blanket should be considered.

It is also important to recognize the dominant internal erosion mechanism as either (1) **seepage erosion** (also known as scour or tractive force erosion) where the seepage flow path is open (e.g. a crack or separation along a wall or conduit) or (2) **backward erosion piping** where the seepage flow path is opened by erosion of particles starting from the downstream exit and progressing by pipe formation to the reservoir. Once the pipe and flow pathway is fully developed the erosion mechanism becomes seepage erosion along the sidewalls of the pipe. In Figure 6.4 pathways 1 to 3 are typically seepage erosion pathways while pathways 4 to7 are typically backward erosion piping pathways. However, the two processes can sometimes operate in tandem.

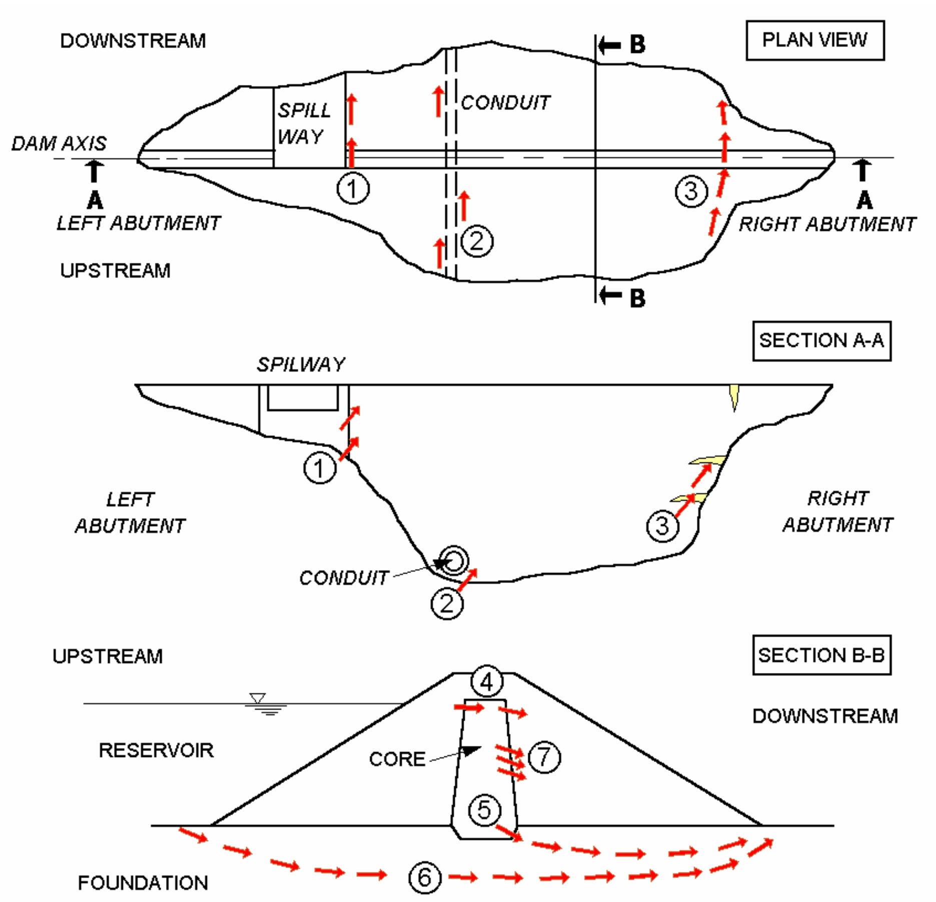


Figure 6.4: Possible Locations for the Initiation of Internal Erosion (from Fell and Fry 2007)

Analysis of the seepage erosion and backward erosion piping related potential failure modes should include a review of the following:

- Initiation: Will erosion of the material (considering its relative erodibility) be initiated under the existing seepage gradients? Is there a design or construction flaw, or a reason for erosion to commence (e.g. flood level above the top of the core)?
- Continuation: Is there an unfiltered or poorly filtered exit? Will the filters, transition zones or downstream zones prevent erosion continuing? Assess the grading against criteria for no-erosion, some erosion, excessive erosion, and continuing erosion.
- Progression: Is the seepage path open or will a developing pipe stay open and will the upstream material fill the crack or limit the seepage flow? Will the critical gradient or velocity be reached for erosion to progress?
- Intervention: Will there be sufficient warning to intervene? Can the reservoir be drawn down in sufficient time to prevent a failure? Do we have ready access to suitable technical specialists, materials and equipment to avert a failure?

If the filter protection systems within an existing dam are insufficient to resist the more likely potential failure modes, it will be necessary to consider the need for remedial works to reduce the potential for failure to occur. 'No-erosion' filters are clearly acceptable, but filters that fit the 'continuing erosion' category will probably necessitate the completion of remedial works. For filters that fit the 'some erosion' or 'excessive erosion' categories, a qualitative assessment of the risk should be completed to establish whether remedial works are necessary. A quantitative risk assessment of internal erosion is complex and should only be carried out by technical specialists experienced in the technique.

Geotextiles in lieu of Granular Filters

ICOLD Bulletins 55 and 95, and Fell et al (2005), provide guidelines for the use of geotextile fabrics in embankment dams. The following recommendations generally reflect the guidelines:

- Geotextiles should primarily be used where they can be readily exposed, repaired or replaced, or where they can provide temporary control of seepage flows that have the potential to transport materials. For example, geotextiles installed beneath wave protection layers and within toe drains can be inspected, repaired or replaced if required.
- Geotextiles should not be used in a configuration where they serve as the sole defence against dam failure. As such, they should not be used in lieu of sand/gravel filters for the control of internal erosion in the body of or beneath an embankment dam.

Giroud (1997) includes comments on geotextile filter design and installation.

Protection around Conduits

A conduit or pipe through an embankment dam is a common location for the initiation of internal erosion, particularly for existing dams that do not include good filter protection. Inappropriate conduit details, the lack of filter and drainage protection, and low stresses associated with arching of embankment fills across the tops of conduits can initiate the erosion of embankment materials. Erosion can progress through the loss of material into the conduit, erosion along the outside of the conduit, and water losses from the conduit. Many embankment dams have failed through inappropriate conduit design, and inadequate filter and drainage protection adjacent to conduits. FEMA L-266 (2006) and Fell et al (2005) provide recommended practices, which include:

- Where practicable, avoid placing conduits through the dam, or on soil and erodible rock foundations, by the use of tunnels in the abutments (for larger dams) or placing the conduit in a trench excavated into non-erodible rock and backfilled with concrete to the dam foundation surface.
- Where conduits or other penetrations pass through existing dams or where they must be designed to pass through embankments, as will be the case for most smaller dams and many larger dams on soil foundations, filters should be provided immediately downstream of the core and completely surround the conduit. Alternatively for Low PIC dams where filters are not provided immediately downstream of the core as part of the design cross section, a filter diaphragm should be placed around the conduit and suitable drainage should be provided for the controlled discharge of seepage flows from the filter diaphragm to the toe of the dam.

- Conduits should be continuously supported on a concrete bedding which extends, as a minimum, up to the centreline of the conduit and has outside slopes no steeper than 1 (horizontal) to 8 (vertical).
- To enable good compaction adjacent to the conduit, cutoff collars should not be used and the soil being compacted adjacent to the conduit should be wet of optimum moisture content.
- Cast in situ conduits should have sides no steeper than 1 (horizontal) to 8 (vertical), and should be constructed in trenches sufficiently wide to enable proper compaction of the backfill material and with side slopes no steeper than 1 (horizontal) to 1 (vertical) to minimise the potential for arching across the top of the culvert.
- Care should be taken to ensure no desiccation cracking is left in place at the base or adjacent to the sides of a trench excavated for a conduit.
- Care should be taken to ensure the conduit joint details will prevent the erosion of backfill materials into the conduit and the leakage of water out of the conduit.
- No un-encased metal conduits should be used unless they are separated from the embankment fill by an air space (e.g. within a larger conduit that provides ready access for maintenance and repairs). Metal conduits which are concrete encased and are not separated from the embankment fill by an air space should be continuously welded, and the encasement should be reinforced to carry all static and dynamic loads without any contribution from the metal conduit.

Where any of the above recommended practices have not been followed, the completion of a risk assessment may assist in establishing whether a potential deficiency needs to be addressed.

Interfaces between Embankments and Concrete Structures or Abutments
Interfaces between embankment dams and concrete structures are potential sources of internal erosion. All concrete surfaces adjacent to embankment materials, particularly core materials, should be smooth and free of construction defects (e.g. horizontal offsets along construction joints), and should incorporate slopes no steeper than 1 (horizontal) in 8 (vertical) to encourage positive contact pressures along the interface.

Filter and drainage materials should always be provided for the control of seepage flows along such interfaces and, where filter and drainage materials are included within embankments, some consideration should be given to flaring the core material and widening the downstream filters in the vicinity of the interfaces.

Many of the features outlined above for interfaces between embankment dams and concrete structures are also applicable to dam abutment contact surfaces.

Drainage Pipes
Drainage pipes should only be utilised in areas where they are readily accessible for maintenance or replacement (e.g. in toe drains).

The Designer should specify corrugated smooth wall pipe rated for the embankment loads with the perforation size based on the filter grading.

Toe Drainage Capacity
High drainage capacity at the downstream toe can be provided by a toe drain system or by a zone of materials with a suitable grading to withstand the predicted flow. This might be achieved through coarse free draining fill at the dam toe or a partial height toe buttress (often referred to as a Swedish berm). Scandinavian researchers developed empirical methods for the design of drainage buttresses to prevent toe unravelling based on large scale tests. Bartsch and Nilsson (2007) provide an empirical relationship between the mean rock particle size (D50), the downstream slope of the rockfill and the unit discharge flow based on these test results.

Surface Erosion

The upstream slopes of embankment dams and their abutments require protection against erosion by wave action.

ICOLD Bulletin 91 provides a detailed discussion on loads that need to be considered and design criteria that should be adopted for the design of upstream slope protection systems including dumped rip-rap , hand placed rip-rap, soil cement facings, concrete paving and precast concrete blocks, bituminous concrete linings, gabions and reno-mattresses, steel and timber facings and roller compacted concrete facings. The design methodologies included in ICOLD Bulletin 91 should be adopted for the design of upstream slope protection systems.

Quarried, angular and dumped rip-rap, where it can be economically obtained, is the preferred material for the protection of upstream slopes because of its flexibility and its thickness. The integrity of other materials such as rounded river cobbles and boulders can be affected by wave action and embankment settlement, particularly if they are placed over a geosynthetic fabric. Such materials should only be used where quarried rockfill cannot be economically obtained and where the materials can be readily inspected, repaired or replaced.

To ensure the protection of underlying materials rip-rap should be well graded and durable, and should extend a sufficient distance down slope to protect the underlying material from wave action at the minimum reservoir operation level. Additional protection may be necessary below the level of the rip-rap if there is the potential for initial reservoir filling to erode the embankment material and undercut the rip-rap.

Downstream slopes should also be protected from erosion where they are constructed from materials other than rockfill. Design details to minimise the potential for surface erosion on the downstream slopes of dams includes:

- The placement of a protective layer of rockfill, or topsoil and grass.
- The provision of berms to limit the distance over which runoff can concentrate.
- The provision of berm drains for the interception and controlled discharge of runoff to the dam toe.
- The provision of lined open drains along the abutment contacts.

6.6 Concrete-faced rockfill dams

6.6.1 Introduction

Concrete-faced rockfill dams (CFRDs) are a form of embankment dam that rely on the upstream concrete face slab for water retention. Asphaltic concrete has been used as a variant to conventional concrete in some dams in the world.

Typical CFRD design will have a concrete plinth, founded on competent rock at the upstream toe of the dam, to connect the face slab to the foundation. This is a critical element of the dam.

The following subsections discuss potential failure modes for CFRD dams, loading conditions which must be taken into account during their design, evaluation and rehabilitation, and recommended performance criteria for CFRD dams. A number of defensive design details that are important to dam safety are also discussed.

ICOLD Bulletin 141 and Fell et al (2005) provide detailed accounts of the design and construction features of CFRDs and their performance.

6.6.2 Potential failure modes

As stated previously, the identification of potential failure modes for a dam should be based on site-specific conditions and the specific characteristics of the dam. However, as an aid, the more common potential failure modes for CFRD dams, which are related to the dam and its foundation, are outlined in Table 6.5.

Table 6.5: Potential Failure Modes for Concrete Faced Rockfill Dams

Potential Failure Mode	Common Causes
Overtopping	Insufficient freeboard to accommodate storms and flood events
Excessive leakage and unravelling of downstream shoulder	Settlement, defect or crack in facing slab or plinth, shoulder material not coarse enough to withstand leakage discharge
Internal erosion of embankment materials	Defect or crack in the facing slab, lack of adequate filter protection, high fines content in embankment fill
Internal erosion of foundation materials	Foundation material has a Plasticity Index less than 7, dispersive foundation materials, lack of or inappropriate foundation treatment, high gradient around plinth
Instability of downstream shoulder	Defect or crack in facing slab, weak shallow seam in foundation, lack of effective drainage and saturation of downstream shoulder, insufficient shear strength, strong earthquake shaking
Instability of upstream shoulder (sliding failure involving/ disrupting the face slab)	Rapid drawdown of reservoir, insufficient drainage, strong earthquake shaking
Loss of freeboard, overtopping and subsequent erosion	Insufficient freeboard to accommodate foundation and embankment settlement, settlement following seismic loading and/or foundation materials, seiches generated by earthquakes, uplift of the reservoir due to fault displacement, reservoir landslides
Loss of freeboard, overtopping and subsequent erosion	Insufficient freeboard to accommodate foundation and embankment settlement, settlement following seismic loading, liquefaction of embankment and/or foundation materials, seiches generated by earthquakes, uplift of the reservoir due to fault displacement, reservoir landslides

Fell et al (2005) outlines a framework for assessing potential failure modes for a CFRD.

Rogers et al (2010) describes the failure of the Taum Sauk reservoir in the USA and the combination of factors leading to this failure. Pinto et al (1998) discusses incidents of cracked upstream face slabs due to high stresses attributed, in part, to the valley shape. Wieland (2009) provides descriptions of damage to CFRDs from earthquakes but notes that there are few observations of dam responses to strong earthquakes.

6.6.3 Loading conditions

The loading conditions that should be considered in the design or rehabilitation of a CFRD are as stated for an embankment dam in section 6.5.3.

6.6.4 Stability and deformation performance criteria

The dam, foundation and abutments must be stable during construction and under all operating conditions, including full or partial drawdown. Recommended minimum factors of safety for limit equilibrium stability studies, for static and seismic loading conditions, are the same as for embankment dams and are listed in Tables 6.3 and 6.4. The comments and guidelines relating to embankment stability, deformation and post-earthquake performance in section 6.5.4 are also applicable to CFRDs.

Settlement may occur under static conditions or as a result of earthquake shaking. The potential for settlement should be assessed and consequent effects that should be addressed during the design include:

- The loss of freeboard and the risk of overtopping.
- The extent of damage to the upstream face slab.

The performance of the upstream face slab is critical to dam performance as extensive cracking could result in sufficient leakage to threaten the stability of the dam. In addition, a stable well founded plinth and a stable supporting backfill are critical to the performance of the face slab. An inadequate transition between the concrete face slab and rockfill can restrict flow into the rockfill if cracking or joint opening occurs in the slab, and poorly graded materials with the potential for internal instability could result in increased leakage and unraveling or instability of the downstream shoulder. The design process should include an assessment of the potential settlement of the dam, and the potential cracking or joint opening in the concrete face slab, and sufficient seepage and stability analyses to demonstrate that the embankment has adequate reserves of stability.

6.6.5 Design Details

In addition to meeting the above performance criteria, successful CFRD design relies on the adoption of good defensive design details, such as:

- Adopting an appropriate location and orientation for the dam to reduce the risk of foundation displacement damaging the plinth.
- Founding the plinth on competent rock.
- Providing an adequate filter zone behind the plinth.
- Providing sufficient slab thickness for the anticipated loads.
- Providing ample freeboard and appropriate crest details.
- Providing appropriate material zoning and well-designed filter and drainage zones behind the face slab, using the best available materials, to ensure compatibility between adjacent materials and enable free drainage of leakage through the concrete facing.
- Adopting stringent compaction standards to minimise potential embankment settlements.
- Locating facing slab joints to account for non-uniform deformations of the supporting rockfill, providing good joint and waterstop design details to lower the risk of a major leakage through a joint, and selecting a slab width and a jointing system that accommodates the reversible nature of seismic responses to strong ground shaking and temperature variations.
- Shaping the foundation beneath the plinth to avoid high stress concentrations.

Location and Orientation of the Dam

If the concrete plinth crosses or rests on any foundation features that could displace under reservoir loading or in an earthquake, the dam should be oriented to minimise the offset implications for the plinth. In the vicinity of such foundation features, specific details to reduce damage to the plinth should be assessed and filters with dimensions at least 1.5 times the expected offset should be placed behind the perimetric joint between the face slab and the plinth.

An upstream impermeable blanket, with appropriate filter layers, should also be considered to cover the plinth and perimetric joint in the location of the foundation feature.

Slab Thickness

The upstream face slab is a stiff element that relies on rockfill support, and any loss of support will result in slab cracking and leakage.

The slab thickness must be sufficient to accommodate robust joint details. Consideration should also be given to situations where the valley shape could introduce high compressive stresses in the face slab. Problems have occurred with high CFRDs in narrow canyons, where the dam height and crest length have had roughly equal dimensions.

The face slab will develop high in-plane stresses from the cross-valley component of earthquake ground motions, and the potential for shear failure and spalling needs to be addressed in the slab design.

Freeboard and Crest Details

The recommendations included in section 6.5.5 are also applicable for CFRDs.

Crest structures, including wave walls, require careful detailing to accommodate:

- The predicted settlement without compromising the watertightness of the joints.
- The different response characteristics, in comparison to those experienced by the main rockfill embankment, during strong earthquake shaking.

Material Zoning

Filters are required beneath the face slab and immediately downstream of the plinth to restrict flow into the rockfill, if cracking or joint openings occur in the face slab, and to limit deformation of the slab at the perimetric joint and restrict flow into the embankment or foundation if the perimetric joint opens.

The gradations of the embankment materials must be internally stable and the embankment zones should increase in coarseness towards the downstream face and toe. Where embankment materials break down under compaction and result in materials with high proportions of sand and silt, the resulting fill may not be free draining. In such cases filter and drainage layers must be provided beneath the face slab and along the foundation contact to ensure the controlled collection and drainage of leakage to the dam toe.

Compaction Standards

Earlier CFRDs were constructed of dumped rockfill. This is no longer recommended due to the effects of excessive settlement on the concrete face slab and other rigid structures.

The long-term settlements of well compacted rockfill can be expected to be in the range of 0.1 to 0.2% of the embankment height. Strong ground motions during earthquakes will produce greater settlements.

Facing Slab Joints

The spacing of vertical joints in the face slab should consider the predicted embankment settlement under all loading conditions. Generally, more joints and narrower slab widths are recommended to provide more articulation of the slab. Joints should also be located and detailed above features likely to initiate differential settlement (e.g. steps in the foundation).

Shear keys and durable water stops that can sustain some movement are recommended details at the perimetric joint and at all vertical joints. The joint dimensions need to account for the reversible nature of the embankment dam response to earthquake ground motions.

Foundation and Abutment Shaping

Prominent features (steps or irregularities) in the foundation or abutments should be removed to reduce the likelihood of differential settlement.

As stated earlier, narrow valleys can result in high compressive forces in the upstream face slab.

6.7 Geomembrane-lined embankment dams

6.7.1 Introduction

Impermeable geomembrane liners are often used as the watertight barrier for small embankment dams. Many of the design requirements for embankment dams and CFRDs and their foundations apply, particularly with respect to settlement, slope deformation and withstanding leakage.

There have been a number of different geomembrane materials that have been used as impervious layers in dams and canals. ICOLD Bulletin 135 lists 10 different polymers used as geomembranes in more than 240 large dams around the world (refer Table 6.6), and provides guidelines for the design of geomembrane sealing systems for embankment dams.

The use of polyvinyl chloride (PVC) membranes accounts for 65% of the installations cited. Of these roughly equal numbers are installed as covered and exposed membranes. By contrast the other two popular membranes (linear low density polyethylene – LLDPE and high density polyethylene – HDPE) are typically installed in covered arrangements to provide protection against environmental conditions and mechanical damage or vandalism.

It is noteworthy, however, that there are many applications of exposed, particularly HDPE, linings.

Table 6.6: Use of Geomembranes in Dams (from ICOLD Bulletin 135)

Material	Abbreviation	Total No. of Dams			Total
		Exposed	Covered	Unknown	
Polyvinyl Chloride – Plasticised	PVC-P	80	73	3	156
Linear Low Density Polyethylene	LLDPE	0	29	1	30
High Density Polyethylene	HDPE	3	12	1	16
Butyl rubber	IIR	5	4	2	11
Polyisobutylene	PIB				
Ethylene-propylene-diene monomer	EPDM				
Chlorosulfonated polyethylene	CSPE	3	5	1	9
Geotextiles impregnated with polymers	In situ membrane	2	7	0	9
Polyolefin	PP	3	3	0	6
Chlorinated polyethylene	CPE	0	3	0	3

The following subsections discuss potential failure modes for geomembrane-lined embankment dams, loading conditions which must be taken into account during their design, evaluation and rehabilitation, and recommended performance criteria for geomembrane-lined embankment dams. A number of defensive design details that are important to dam safety are also discussed.

6.7.2 Potential failure modes

As stated previously, the identification of potential failure modes for a dam should be based on site-specific conditions and the specific characteristics of the dam.

The more common potential failure modes for geomembrane-lined embankment dams are quite similar to those for CFRDs and the potential failure modes listed in Table 6.5 are applicable. However, additional potential failure modes for new and existing dams include:

- The potential for deterioration that has occurred or could occur over time.
- The potential for poor construction practice in placement, interconnections and sealing.

6.7.3 Loading conditions

The loading conditions that should be considered in the design, evaluation or rehabilitation of a geomembrane-lined embankment dam are as stated for an embankment dam in section 6.5.3.

6.7.4 Stability and deformation performance criteria

The dam, foundation and abutments must be stable during construction and under all operating conditions, including full or partial drawdown. Recommended minimum factors of safety for limit equilibrium stability studies, for static and seismic loading conditions, are the same as for embankment dams (the membrane provides no resistance) and are listed in Tables 6.3 and 6.4. The comments and guidelines relating to embankment stability, deformation and post-earthquake performance in section 6.5.4 are also applicable to geomembrane-lined embankment dams. However, the membrane does provide a potential failure surface and could create a location for pressure build up greater than that for a geometrically similar dam with no membrane.

Settlement may occur under static conditions or as a result of earthquake shaking. The potential for settlement should be assessed and consequent effects that should be addressed during the design include:

- The loss of freeboard and the potential for overtopping.
- The extent of any embankment cracking and whether the geomembrane can continue to function as a water retaining element.

The installation and resulting performance of the geomembrane is critical to the performance of the dam as openings, tears or joint failures could result in sufficient leakage to threaten the stability of the dam. Inadequate supporting and drainage layers between the geomembrane and embankment fill may lead to saturation and instability of the embankment. Furthermore, poorly graded embankment materials with the potential for internal instability could result in increased leakage and unraveling or instability of the downstream shoulder. The design process should include an assessment of the potential for damage to the geomembrane lining, and sufficient seepage evaluations, internal erosion assessments and stability analyses to demonstrate that the embankment has adequate reserves of stability.

6.7.5 Design details

In addition to meeting the above performance criteria, successful design relies on the adoption of good defensive design details, such as:

- Specifying a geomembrane suitable for the environmental conditions and the required life expectancy.
- Specifying appropriate subgrade preparation for the geomembrane.
- Specifying requirements for joint performance and leakage testing for the chosen geomembrane.
- Providing suitable anchorage and fastenings for the geomembrane.
- Providing robust and effective connections and seals at all structure penetrations.
- Providing ballast where needed to counteract excess groundwater pressures during operation or dewatering.
- Preventing wind uplift damage during construction and at low reservoir levels.
- Providing appropriate protection against waves, and protection against UV light damage and vandalism.
- Providing ample freeboard and appropriate crest details.
- Adopting stringent compaction standards to minimise potential embankment settlements.
- Providing appropriate material zoning and well-designed filter and drainage zones to ensure compatibility between adjacent materials and to allow the free drainage of leakage through the geomembrane.
- Considering secondary lines of defence at areas vulnerable to cracking.

Selection of Geomembrane

ICOLD Bulletin 135 provides a detailed account of geomembrane materials, their behavior and ageing characteristics, and recommended quality control systems that should be adopted during their manufacture and installation. Table 6.7 has been prepared from information included in the bulletin and provides a summary of the oldest geomembrane installations at dams by geomembrane type, as at 2010.

Table 6.7: Geomembrane Longevity in Dams (from ICOLD Bulletin 135)

Material	Abbreviation	Oldest Installation (Years)	
		Exposed	Covered
Polyvinylchloride – Plasticised	PVC-P	1974	1960
Linear Low Density Polyethylene	LLDPE	-	1970
High Density Polyethylene	HDPE	1994	1978
Butyl rubber	IIR	1982	1959
Polyisobutylene	PIB		
Ethylene-propylene-diene monomer	EPDM		
Chlorosulfonated polyethylene	CSPE	1981	1986
Geotextiles impregnated with polymers	In situ membrane	-	-
Polyolefin	PP	1995	2000
Chlorinated polyethylene	CPE	-	1970

Fourie et al (2010) comments on the advantages and disadvantages of the three most commonly used geomembranes – HDPE, LLDPE and PVC. It should be noted however that, because the PVC formulation can be enhanced with additives such as plasticisers, stabilisers and ageing retardants, it can be specifically formulated to meet different service conditions such as resistance to UV, specific contaminants and very low temperature environments.

The following physical/mechanical properties should be considered during the selection of a geomembrane for a particular application:

- Its burst strength.
- Its stress/strain characteristic.
- Its puncture resistance.
- Its tear strength.
- The interface shear strength between the geomembrane system and the embankment slope.
- Its elongation/expansion and contraction characteristics.
- The jointing system.
- Its durability.
- Its permeability.

The ability of a liner to span a transverse crack is the primary defence against embankment failure due to transverse cracking. Giroud et al (2013) includes an approach to determine the behaviour of a geomembrane liner if a crack develops in the subgrade. The approach takes into account the pressure applied by the reservoir, the tensile stress-strain behaviour of the geomembrane, and the interface friction between the geomembrane and supporting material, and shows that the tension in the geomembrane is the result of two mechanisms – the shear stresses applied to the lower face of the geomembrane by the supporting material during the opening of the crack, and the strain of the geomembrane as it deflects over the open crack. The Designer needs to understand the uncertainty related to estimation of the crack width and, as a minimum, should apply a factor of 1.5 to the estimated crack width when determining an appropriate geomembrane solution.

Geomembranes may require reinforcing to provide sufficient strength to span cracks. Geotextiles may also be necessary to protect geomembranes from damage.

Subgrade Preparation

All surfaces supporting the geomembrane should be smooth and free of angular rocks, roots and debris. The embankment surface should be proof rolled to identify inappropriate subgrade conditions, and voids created from the removal of soft materials, angular rocks and debris should be filled with fine material and proof rolled a second time.

The construction specification should define key subgrade quality requirements such as the maximum acceptable undulation, the maximum rock fragment size and the avoidance of puddles.

Joint Performance and Leakage Testing

The integrity of the joints between geomembrane panels is critical to the watertightness of the geomembrane. There are various jointing methods available and each is dependent on the properties of the geomembrane and the requirement for quality assured integrity. All three common geomembranes (HDPE, LLDPE and PVC) are usually joined using double track automatic welding. Single track manual welding is usually only applied in areas that are inaccessible by the automatic welding machine.

Leakage testing of joints should be included in the construction specification to provide quality assurance.

Anchorage and fastenings.

Geomembranes require anchorage at the top of embankments, and within or at foundation and abutment contacts. Frequently used anchorages at the top of an embankment slope have included a simple run-out length of geomembrane beneath a soil cover, and embedment of the geomembrane in a trench which is backfilled with an appropriate material.

Stainless steel fixings should be used for fastenings where geomembranes abut pipes, embankment penetrations and concrete structures.

Groundwater Pressures

The potential for groundwater pressures beneath geomembranes to exceed reservoir pressures should be assessed. If excess groundwater pressures are possible during operation or dewatering, ballast should be provided to prevent uplift of the geomembrane. A geomembrane-lined canal that passes through cuts where high groundwater levels are present is an example where ballast may be necessary to prevent the uplift of the geomembrane.

Wind Uplift

Ballast and fixings should be provided if large areas of a geomembrane lining are exposed to wind uplift. This can occur during construction and during operation with low reservoir levels.

Wave Protection and Protection from UV Light Damage and Vandalism.

Wave action can repeatedly deform an exposed geomembrane and can result in fatigue effects, on particular material properties, and uplift tensile stresses through suction. Waves may also move cover materials, loosen anchorages and damage the supporting layer beneath the geomembrane.

The Designer needs to assess the vulnerability of the proposed geomembrane solution to wave action and, if necessary, provide an appropriate protection layer and improved geomembrane anchorages.

Some geomembranes may require cover to prevent degradation by UV sunlight and damage by vandalism. The temperature effects on any exposed membrane should be assessed.

Freeboard and Crest Details

The recommendations included in section 6.5.5 are also applicable for geomembrane-lined embankment dams.

The crest width and crest details should be designed to accommodate any necessary anchorage zones and provide ready access to the geomembrane system for maintenance and repair.

Compaction Standards

Compaction standards are important for all embankment dams. For geomembrane-lined embankment dams, excessive settlement from inadequate compaction will result in tensions within the geomembrane lining system.

Material Zoning
The gradations of the embankment materials must be internally stable and the embankment zones should increase in coarseness towards the downstream face and toe.

The subgrade material beneath the geomembrane should provide good support and restrict flow into the embankment if tears or leakages develop in the geomembrane. Filter and drainage zones should be designed to ensure compatibility between adjacent materials and controlled drainage of any leakage flows through the embankment

Secondary Lines of Defence at Areas Vulnerable to Cracking.
A geomembrane should be designed to span estimated crack widths. However, given the uncertainties associated with the estimation of crack widths, a defensive design approach should be adopted in areas where cracking could occur and/or be more extensive than envisaged. For example:

- A thicker geomembrane layer, a reinforcing layer or a double layer of geomembrane could be installed at critical locations.
- A leakage buttress could be installed at critical locations for the management of discharges from a damaged geomembrane.

6.8 Concrete gravity and buttress dams

6.8.1 Introduction

Concrete gravity and buttress dams are grouped according to the types of material used in their construction and how they achieve their strength and stability. They commonly include:

- Conventional concrete gravity dams (refer Figure 6.5) which are constructed from conventional concrete and rely on the shearing resistance developed at their base, as a result of their weight (hence the name gravity) less uplift under the dam, and the integrity of the foundation to resist the imposed load from the reservoir. Guidelines for the design of concrete gravity dams are provided in FERC (1993) and USACE (1995).

Figure 6.5: Concrete Gravity Dam – Clyde Dam (provided by Contact Energy)

- Roller compacted concrete (RCC) dams (refer Figure 6.6) which are constructed from zero slump concrete using traditional earth placing methods and similarly rely on the shearing resistance developed at their base, as a result of their weight less uplift under the dam, and the integrity of the foundation to resist the imposed reservoir load. Hansen and Reinhardt (1991) provide an overview of design considerations for RCC dams.

Figure 6.6: RCC Dam – Horseshoe Bend Dam (provided by Pioneer Generation)

- Hardfill dams (refer Figure 6.7) which are constructed from a cemented sand and gravel, and incorporate a facing of concrete for water tightness and erosion protection. As for the above gravity dams, they rely on their weight and the integrity of the foundation to resist the imposed reservoir load. Japanese Dam Engineering Center (2007) provides guidelines for the design and construction of cement sand and gravel (CSG) dams.

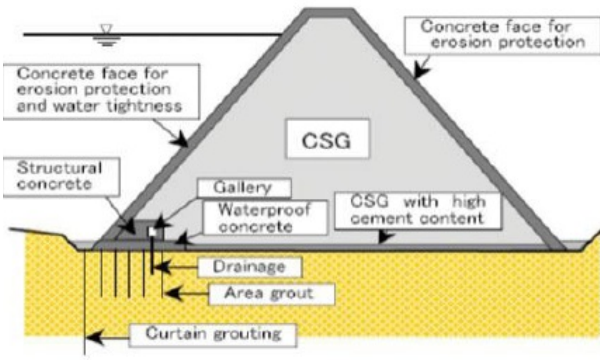


Figure 6.7: Hardfill Dam (CSG is Cement, Sand and Gravel)

- Concrete buttress dams (refer Figure 6.8) which incorporate an upstream concrete face supported at intervals by a series of support buttresses. They rely on their weight, the structural strength of face and foundation slabs, and the integrity of the foundation to resist the imposed reservoir load. The shearing resistance to resist the reservoir load is developed primarily along the buttresses, as opposed to beneath the entire base for concrete gravity dams.

Figure 6.8: Concrete Buttress Dam – Branch Dam (provided by TrustPower)

- Multiple arch buttress dams which incorporate a series of concrete arches supported by, and constructed integrally with, equally spaced triangular shaped buttresses. They have much in common with concrete buttress and concrete arch dams; however, no multiple arch buttress dams are believed to be in service in New Zealand.

The following subsections discuss potential failure modes for concrete gravity and buttress dams, loads and loading conditions which must be taken into account during their design, evaluation and rehabilitation, and recommended performance criteria for concrete gravity and buttress dams. A number of defensive design details that are important to dam safety are also discussed.

6.8.2 Potential failure modes

The general comments on the identification and evaluation of potential failure modes included in section 6.5.2 for embankment dams are also relevant to concrete gravity and buttress dams.

Fell et al (2005) includes some statistics on dam failures which highlight that failure rates between 1900 and 1975 for concrete gravity and concrete buttress dams were 0.3% and 2.6% respectively of dams built. These figures can be compared with the failure rate quoted for embankment dams, over the same time period, which was 1.2% of dams built. The available information demonstrates that the safety of concrete buttress dams between 1900 and 1975 was significantly less favourable than the safety of all other dam types over the same time period.

With respect to the relatively high failure rate of buttress dams, in comparison to that for concrete gravity dams, it is noted that concrete gravity dams are far more robust than the relatively thin slabs and narrow buttresses that support buttress dams. Furthermore, a localized flaw in the dam or foundation of one of the slab and buttress elements could produce a failure while a flaw of similar magnitude under or within a concrete gravity dam would barely be noticed and/or the load that could not be taken by that area of the dam would easily be transferred to adjacent monoliths.

It is also well recognized that most concrete gravity dam failures relate to foundation issues (Douglas, Spannagle and Fell 1998). Douglas, Spannagle and Fell reported that for 10 concrete gravity dam failures 6 were related to foundation issues, one was related to a structural issue, one was related to an appurtenance structure, and 2 were classified as unknown. Following the publication of their report the Camara Dam in Brazil, which was an RCC gravity dam, failed due to foundation problems. Thus, the available evidence shows that seven of eleven concrete gravity dam failures were foundation related.

Hansen and Nuss (2011) summarise the seismic performance of concrete gravity and buttress dams that have experienced earthquakes with peak ground accelerations greater than 0.3g. Observations from the research indicated that:

- Well-constructed RCC dams performed no differently in earthquakes to dams built of conventionally placed mass concrete.
- Seismic ground motions can be amplified significantly at the dam crest, with in excess of 2g being recorded at some dams. Damage to equipment and buildings from high accelerations at the dam crests was evident and highlighted the need for careful consideration of amplified ground motions during design.
- Rockslope failures from abutments and onto access roads caused significant damage and delayed access to some sites.
- Cracking in dams occurred at changes in geometry, highlighting the importance of avoiding the inclusion of such features wherever possible.
- Concrete buttress dams developed horizontal cracks at high elevations where there were significant changes in structure stiffness.
- Foundation fault displacement can result in severe damage if fault movement mitigation features have not been included in the design. Hansen and Nuss (2011) noted that in the one example of a foundation fault displacement, the discharge from the reservoir was limited by the size of the gap created by the block displacement.

Hansen and Nuss (2011) note that a number of features contributed to the lack of complete failures at concrete gravity and buttress dams subjected to large earthquake loads. The features included insufficient durations of strong ground motions, the natural frequency of the dam not matching the frequency of the earthquake, load redistribution in the structure, three dimensional effects and increases in the tensile strength of the concrete during dynamic loading. These Guidelines therefore promote the adoption of dam design features that provide increased resilience.

The more common potential failure modes for concrete gravity and buttress dams, which are related to the dam and its foundation, are outlined in Table 6.8.

Table 6.8: Potential Failure Modes for Concrete Gravity and Buttress Dams

Potential Failure Mode	Common Causes
Sliding along concrete lift joints in the dam, or cracked surfaces in the dam	Poor lift joint bonding, high uplift pressures, insufficient shear strength
Structural failure	Deterioration in concrete quality, overstressing of buttresses during cross valley seismic loads
Sliding along the concrete/foundation interface, or planes of weakness in the dam foundation	High uplift pressures, insufficient shear strength, inappropriate foundation treatment
Piping of foundation materials	High gradients through foundation, lack of or inappropriate foundation treatment

6.8.3 Loading conditions

Loading conditions for the design and rehabilitation of concrete dams are presented and discussed in various ANCOLD guidelines, Canadian Dam Association (2007), and various USACE and USBR engineering manuals.

Loading conditions that should be considered in the design, evaluation or rehabilitation of concrete gravity and buttress dams, and the general performance criteria for concrete gravity and buttress dams for each loading condition, are similar to those outlined in section 6.5.3 for an embankment dam. Comments on each loading condition and examples of each loading condition for concrete gravity and buttress dams are provided below.

- During normal loading conditions the behaviour of the dam should remain in the linearly elastic range. In a rigid body analysis the normal loading condition should include the consideration of dead loads, hydrostatic loads (headwater and tailwater), loads imposed by silt deposition upstream of the dam and backfill materials adjacent to the dam, internal and external uplift pressures and temperature effects.
- During unusual loading conditions minor non-linear behaviour of the dam is acceptable; however, any necessary repairs should be minor. Any rigid body or cracked base analysis should include the consideration of all the loads outlined above for the normal loading condition in combination with the OBE, including hydrodynamic loads, and in combination with an appropriate reduction in the efficiency of underdrains (if present).
- During extreme loading conditions non-linear behaviour of the dam is acceptable provided the overall performance criterion of safely retaining the reservoir is met. Any rigid body or cracked base analysis should include the consideration of all the loads outlined above for the normal loading condition in combination with the IDF and in combination with the SEE including hydrodynamic loads. The analysis should also address the post-SEE condition, taking into account an appropriate reduction in the efficiency of underdrains (if present), the loss of any cohesion at the dam/foundation interface, an appropriate reduction in the friction angle at the dam/foundation interface, and any increase in the horizontal load that could result from liquefaction of silts deposited immediately upstream of the dam.

6.8.4 Stability and structural performance criteria

As for embankment dams, potential stability failures for concrete gravity and buttress dams under different loading conditions are usually assessed in terms of minimum factors of safety. The factors of safety generally relate to sliding stability and compressive stresses at the dam toe.

The primary performance indicator for concrete gravity and buttress dams is their stability against a sliding failure, either along the dam/foundation contact or along a plane of weakness in the dam or dam foundation. Recommended minimum sliding factors of safety (defined as the available shear strength divided by the net driving force) for limited equilibrium stability analysis of concrete gravity and buttress dams are provided in Table 6.9. The tabulated figures and accompanying notes generally reflect the material included in ANCOLD (2013) and are similar to those included in Canadian Dam Association (2007). ANCOLD (2013) should be referred to for additional information relating to failure surfaces, concrete strengths, dam/foundation interface strengths, and dam foundation strengths. Note that the recommended factors of safety relate to sliding failures along the dam/foundation contact, along a plane of weakness in the dam, or along a joint set or other plane of weakness in the dam foundation.

Table 6.9: Recommended Minimum Sliding Factors of Safety for Concrete Gravity and Buttress Dams

Loading Condition	Minimum Sliding Factor of Safety		
	Friction and Cohesion Present		Friction Only Present
	Not Well Defined1,2,6	Well Defined1,2,6	Well Defined2,6,9
Normal	3.04	2.04	1.53
Unusual	2.04	1.54	1.33
Extreme - Flood	1.54	1.34	1.13
Extreme – Earthquake	(note 10)		
Post-earthquake		1.2 (note 11)	

Notes:

1. Given the significant impact a very small amount of cohesion can have on shear resistance, the recommended minimum sliding factors of safety for friction and cohesion should be used with extreme caution.

For stability within the body of the dam and at the dam/foundation interface:

2. 'Well defined' means that a sufficient number of tests have been completed to define the strength parameters with reasonable certainty (i.e. the assumed strength parameters should be exceeded by 80% of the test results from a test regime involving an appropriate number of tests).
3. In some cases Ø for concrete could be significantly lower than 45o (e.g. cracked surfaces, open joints, lift joints incorporating a cement slurry bond layer). In such cases and in all cases where friction alone controls the stability of the dam, Ø should be determined from laboratory tests.
4. The minimum sliding factors for friction and cohesion assume that the sliding surface will pass through intact concrete or well-prepared construction joints.
5. In assessing the strength of the dam/foundation interface consideration needs to be given to the thoroughness of the foundation clean-up and whether the strengths of parts of the foundation below the interface may control the stability. For the 'well defined' case for existing dams, strength tests should be carried out on core samples taken from the interface zone (typically a few metres below the interface surface).

For stability within the foundation of the dam:

6. 'Well defined' means that there is good exposure of the foundation material at the dam site and that there is sufficient reliable data to establish the existence and persistence of foundation discontinuities (e.g. faults, joints, bedding plane shears) and define the foundation strength parameters with reasonable certainty (i.e. the assumed strength parameters should be exceeded by 80% of the test results from a test regime involving an appropriate number of tests).
7. Recommended shear strength parameters for foundation discontinuities, for incorporation in stability assessments, are listed in the following table:

Discontinuity Type	Typical Feature	Strength Parameters (Refer Note A)
Clean discontinuity (no previous displacement)	Clean joint Bedding plane	f(ǿ$_b$, i) c'=0
Thick infilled discontinuity (no previous displacement)	Infilled joint Infilled bedding plane	f(ǿ) of infill material (note b) c'=0
Discontinuity with previous displacement	Shears Faults	f(ǿ$_r$) of infilling and f(i) of wall rock c'=0
Multiple discontinuity	Highly jointed rock mass	m_b, s, a, σ_c

Notes:

a) Strength parameters:

- f — function of
- c' — cohesion (at zero normal stress)
- ǿ$_b$ — basic friction angle (for wet surfaces)
- ǿ$_r$ — "effective" residual friction angle
- i — average roughness angle
- m_b, s, a — Hoek-Brown Criterion (1995) parameters
- σ_c — uniaxial compressive strength of intact rock

b) Test to be carried out on remoulded samples; ǿ to be based on peak strength under drained conditions; c' to be neglected.

8. The minimum sliding factors assume the adoption of reasonably conservative strengths. For the friction only condition the adopted strength should be at or near the lower bound of good quality test data.

9. Where weak surfaces (e.g. bedding plane shears) are present in the foundation, the actual strength will usually be the frictional strength. In such situations the criteria should be met using the frictional strength.

For stability within the body of the dam, at the dam/foundation interface, and within the foundation:

10.The earthquake load case is used to determine the post-earthquake condition of the dam. In line with US recommendations (e.g. FERC, 2002) a minimum Factor of Safety is not given. If sliding assessments indicate displacement, then the Designer needs to consider the amount of displacement that has occurred along the surface analysed whether it is at the dam/foundation contact, in the dam or in the foundation.

11.For the post-earthquake load case the minimum sliding factor should not be less than 1.2 for the friction only 'well defined' case. If the sliding factor falls below 1.1 there is a high likelihood of failure given that the friction only strength condition has been reached. In such a case the dam should be remediated as a matter of urgency to meet the minimum sliding factor recommended for the 'normal' loading condition.

If a cracked base analysis indicates unacceptable results then the stability analysis can be completed assuming that the base cracks all the way through to determine if the dam is stable under the limit case of complete cracking.

Other performance indicators include the position of the resultant force, tensile stresses at the dam heel and compressive stresses at the dam toe. Recommended criteria for the position of the resultant force and maximum compressive stresses for rigid body analysis of concrete gravity and buttress dams are provided in Tables 6.10 and 6.11. The recommended criteria reflect those included in Canadian Dam Association (2007) and USACE (1995).

Table 6.10: Recommended Position of the Force Resultant for Concrete Gravity and Buttress Dams

Loading Condition	Position of the Force Resultant
Normal	Preferably within the middle third of the base (i.e. 100% compression). For existing dams it may be acceptable to allow a small percentage of the base to be under zero compression if all other performance criteria are met (note 1).
Unusual	75% of the base should be in compression and all other performance criteria should be met.
Extreme	Within the base and all other performance criteria should be met.

Notes:

1. It is important that all possible failure modes are addressed under a potential cracked base scenario wherever tensile stresses are present at the dam/foundation contact or along a plane of weakness in the dam foundation.
2. Rocking may occur under extreme earthquake loads and some permanent displacement could result. The Designer needs to determine whether this occurs and, if it does, demonstrate that the reservoir is not released and that post-earthquake stability is adequate.

Table 6.11: Recommended Maximum Stresses for Concrete Gravity and Buttress Dams

Loading Condition	Normal Compressive Stress
Normal	$<0.3xf'_c$
Unusual	$<0.5xf'_c$
Extreme - Flood	$<0.5xf'_c$
Extreme – Earthquake	$<0.9xf'_c$
Post-earthquake	$<0.5xf'_c$

Note:

1. In addition to the above, the maximum foundation bearing pressure should be less than the allowable bearing pressure, as determined by an appropriately qualified technical specialist, for normal and unusual loads, and less than 1.33 times the allowable bearing pressure for extreme loads.
2. Within the body of a dam, tensile stresses during normal loading conditions may be acceptable so long as the limits of 0.1xf'c and 0.05xf'c (where f'c is the compressive strength of concrete) within the concrete mass and at lift joints, respectively, are not exceeded and all other performance criteria are met. Tensile stresses during earthquake loading conditions may be acceptable so long as they do not exceed 1.5 times the above limits and all other performance criteria are met.
3. In the absence of specific testing, tensile strengths at the dam/foundation interface, and along defects in the foundation, should be assumed to be zero.

Relatively long and straight concrete gravity and buttress dams can be analysed as idealised two-dimensional elements. Concrete gravity dams which are built in a narrow canyon, or which are curved in plan and rely on abutments to transfer loads when cantilever capacities are exceeded, should be analysed in three dimensions. Likewise, blocks or wedges in the foundations or beneath the abutments of concrete gravity dams should be analysed in three dimensions.

As stated for embankment dams, higher sliding factors of safety and lower compressive stresses than those listed in the above tables may be necessary if there are high levels of uncertainty in the inputs to the rigid body analyses, particularly in the strength of foundation materials.

At large seismic loads, rigid body stability analyses are likely to result in factors of safety <1.0, indicating that the applied loads exceed the resisting loads. In such cases, analyses that allow the determination of the amount of displacement that occurs during the earthquake loading should be completed. The Designer should then use the resulting information to assess whether or not the dam can safely retain the reservoir during and immediately following the earthquake event, and determine its post-earthquake condition for incorporation in an analysis of its stability during an aftershock.

Dam block displacements may occur during a large earthquake. If linear elastic analyses indicate that little or no displacements occur, then those analyses can be considered appropriate. However, if the displacements are large enough to result in material property changes, non-linear analyses should be completed. Both analyses should be completed using a number of time history records to effectively analyse dam performance. The results of non-linear analysis models should be validated against the results of alternative analyses, including those for pseudo-static and linear elastic analyses, and the sensitivity of the results to variations in the assumed model parameters should be assessed.

As stated in section 6.1, the post-earthquake criteria are only applicable for the temporary condition, immediately post-earthquake, until satisfactory repairs have been completed and acceptable normal operating dam safety criteria have been restored. During this period interim risk reduction measures may be necessary to provide an acceptable level of dam safety until satisfactory repairs have been completed.

6.8.5 Design details

There are a number of design details for concrete gravity and buttress dams that can affect dam safety. They include:

- The geometry of the dam.
- The treatment of foundation defects.
- Shear transfer between dam blocks.
- The design of the upstream face to reduce the likelihood of tensile cracking and seepage.
- Providing suitable drainage facilities for the control of uplift pressures.
- Providing sufficient freeboard and appropriate crest details.
- Horizontal lift joints.
- Construction, contraction, expansion and isolation joints.
- The design of surfaces for high velocity flow.
- The concrete mix design including the compressive strength, tensile strength and modulus of elasticity of the concrete.
- The use of post-tensioned anchors to enhance the stability of dams.

Dam Geometry

Concrete gravity dams are usually constructed in discrete dam blocks. While there may be construction expediencies that make this advantageous, the primary reason for discrete blocks is to provide contraction joints for thermal expansion and contraction during construction and long term operation. In conventional mass concrete gravity dams the transverse joints are constructed at formed faces; however, in RCC dams the joints are typically created as the RCC is placed. Experience gained from RCC dams constructed without transverse joints demonstrates that transverse cracking will occur, often induced at undesirable locations due to foundation or other irregularities. In uniform RCC dams, where there are no irregularities, transverse joints have been observed to form at about 15m intervals. When joint control is exercised, joints are typically constructed at 20m to 30m intervals; however, a thermal assessment of the structure should be completed to determine the ideal spacing.

Sliding stability requirements and the available shear strength at the foundation interface are likely to dominate the base dimensions. High tensile stress zones should be avoided wherever possible and, if they are unable to be avoided, the dam shape should be adjusted to reduce the tensile stresses as much as reasonably practicable. Cracks should be expected to propagate from high tensile stress zones and, as such, the following should be considered carefully during dam design:

- Geometrical modification of the heel of a dam to reduce tensile stresses, or the incorporation of higher strength concrete in the heel of a dam to increase the tensile capacity of the concrete. Higher strength conventional concrete may be appropriate in the heels of RCC dams to increase the tensile capacity of the concrete.
- The avoidance of prominent changes of slope and sharp discontinuities in the foundation profile to reduce the likelihood of high tensile stress zones.

- The avoidance of sharp changes in the upstream or downstream face geometry to reduce the likelihood of high tensile stress zones. High tensile stress zones often result from changing the face geometry to achieve a wider dam crest for a road across the top of a dam. Koyna Dam in India cracked at a change in slope on its downstream face during an M6.5 earthquake in 1967.
- The seismic design of concrete buttress dams. Changes in cross-sections within face slabs and floor slabs are particularly vulnerable to cracking if not detailed for high seismic loads, and slender monoliths have poor seismic resistance to cross valley seismic ground motions. Sefid Rud dam in Iran suffered cracking at the top of its buttress monoliths during an M7.3 earthquake in 1990.

Foundation Defects and Discontinuities

The identification and appropriate treatment of foundation defects is discussed in section 6.4 of these Guidelines. In addition to the measures required for the control of seepage flows, the design challenges for concrete gravity and buttress dams include the identification of all defects and discontinuities that could affect dam stability, the determination of their shear strengths, and the design of any necessary strengthening works to ensure adequate reserves of stability. The assessment of the foundation is one of the most important aspects of the design and safety evaluation of concrete dams as most historical concrete dam failures have resulted from foundation weaknesses (e.g. Sheffield Dam and Morris Shepherd Dam in the USA).

The design of new dams, the safety evaluation of existing dams, and the design of rehabilitation works for existing dams should consider the sliding resistance along any identified joint or shear plane with an orientation that could influence the development of a sliding failure. The Designer should also consider the stability of any combinations of joint or shear planes that form unstable wedges of rock and could result in dam block displacements.

The determination of foundation shear strengths can be difficult and, while the adoption of conservative values from published information may be sufficient for Low PIC dams, foundation shear strengths for Medium and High PIC dams should be based on the results of laboratory tests. Fell at al (2005) includes recommended practices for the assessment of shear strengths in clean discontinuities, infilled joints and seams showing evidence of previous displacement, thick infilled joints, seams or extremely weathered beds with no evidence of previous displacement, and jointed rock masses with no persistent discontinuities.

Shear Transfer

Shear keys are resilient features that can provide some load transfer between dam blocks.

For new designs the stability of straight gravity dam blocks, designed by 2-D analysis, should not be reliant on load transfer with their neighbouring dam blocks. However, for existing dams constructed with shear keys, it is appropriate to assess and consider the load transfer that can be accomplished during extreme seismic loads or high flood conditions. It is quite likely that load transfer between monoliths and/or the interlocking of monoliths upon initiation of any sliding movements have contributed to the good stability record of concrete gravity dams.

Upstream Face

The concrete specification for the upstream face of a concrete gravity or buttress dam should encourage long term durability, crack control and water tightness. Higher strength conventional concrete is commonly used in the upstream face of a mass concrete or buttress dam. For an RCC dam, conventional concrete or grout enriched RCC is often used at the upstream face.

The concrete specification at the upstream heel of a dam should reflect the size and extent of any tensile stresses that develop during unusual or extreme loading conditions. This is particularly important at sites that are located in areas of high seismic risk. For RCC dams located in areas of high seismic risk, conventional concrete should be used in the upstream heel rather than grout enriched RCC.

Waste water dams, or water supply dams in dry regions, may require upstream membranes to achieve very low specified seepage requirements.

The durability of the upstream face also needs to be considered if the reservoir is highly acidic. The treatment of water flowing into the reservoir may be an option at a mine site. However, if such a system is unavailable, not applicable, or unreliable, the Designer must demonstrate that the structure meets durability criteria. Sulphate-resisting cements or upstream membranes may provide sufficient resistance. The design life of the solution and the practicality of repair or replacement during the life of the dam should be considered.

Drainage Facilities

Drainage facilities are frequently installed in concrete dams for the control of uplift pressures at the foundation contact, along a plane of weakness in the dam foundation, and along concrete lift joints. Guidelines for the estimation of uplift pressures are included in the literature (e.g. Canadian Dam Association (2007), Fell et al (2005)). Such guidelines are appropriate for the design of new dams; however, stability assessments for existing dams can be based on measured uplift pressures with appropriate allowances for seepage trends.

Points that should be considered during the design of a drainage system include:

- The location and depth of the foundation drains. Ideally they should be located in a gallery, drilled to intersect defects, and extend beneath any potential failure surface. They should also be oriented to intersect foundation defects, installed downstream of any grout curtain, and drilled following the completion of any foundation grouting.
- The spacing and diameter of the foundation drains. Drain spacing will be somewhat dependent on the foundation geology; however, for an efficient drainage system, the spacing should not exceed 3m. The diameter of the drains should be a minimum of 75mm to enable drain maintenance.
- The potential for erosion of foundation materials into the drillholes. If any drillhole intersects foundation materials considered likely to erode into the hole, then a suitable filter and screen standpipe should be installed. The filter should be removable for maintenance and replacement.
- The location, spacing and diameter of internal drains. Ideally they should be located close to the upstream face of the dam and drain into a drainage gallery. Their spacing should be sufficient to ensure they don't encourage longitudinal cracking and their diameter should be at least 150mm to minimise the potential for leakage to bypass the drains and to facilitate future cleaning.
- The watertightness of drainage galleries. Drainage galleries should preferably be located within the dam body and not in an area where high tensile stresses could result in the development of a crack between the upstream face and the gallery. Unless suitable mitigating measures can be reliably installed, the watertightness of a gallery located external from the dam body, at the heel of the dam, could be affected by dam block displacement.
- The reliability of any installed dewatering facilities necessary to pump water from drainage galleries to the tailwater. If the post-earthquake stability of the dam relies on the effective control of uplift pressures, any pump facilities and their associated pipelines should be designed to remain operational following the SEE.
- The future maintenance of the drainage system. Without ready access to the drainage system, for inspection and maintenance, its long-term effectiveness cannot be assured and uplift pressures should be assumed to vary linearly between full headwater pressure at the heel of the dam and full tailwater pressure at the toe of the dam.

Freeboard and Crest Details

Concrete gravity and buttress dams can usually accommodate some overtopping without serious damage and, as such, the freeboard provisions can be somewhat less than those detailed for embankment dams in section 6.5.5 of this module. However, from a dam safety perspective it is important that sufficient freeboard is provided to ensure the safety of the dam, its abutments and appurtenant structures are not compromised during the IDF, and to enable the continued operation of appurtenant structures (e.g. spillways) during the IDF. In some cases, additional freeboard provisions may be required by the Owner to meet asset management objectives.

The crest width for the non-overflow section of a concrete gravity or buttress dam is usually set by stability considerations and any access requirements for the maintenance and repair of appurtenant structures (e.g. spillway gates).

Horizontal Lift Joints

Concrete gravity dams and buttress monoliths are generally constructed in horizontal layers. RCC dams may also be constructed using sloping layers, but the resulting lift joints are essentially the same as horizontal lift joints. The bond at horizontal lift joints is critical to:

- Prevent the development of potential sliding failure modes in the dam body.
- To provide adequate tensile resistance between the concrete layers.
- To prevent the development of potential horizontal seepage paths that could result in high uplift pressures within the dam body.

Lift joint preparation is a key factor in achieving adequate bond between concrete layers. Lift joint surfaces should be clean and free of loose material and dirt. High pressure water cleaning to ensure the removal of concrete laitance and green cutting of previously placed layers can be used to provide better bond conditions. For RCC dams the Designer must specify the parameters for the following joint preparation options:

- Fresh RCC directly on a compacted RCC layer. Time limits and temperature parameters before initial set are required and, during this time window, a new layer may be placed over a compacted layer of RCC. After initial set, a cold joint develops which requires treatment with a mortar bedding layer. The time and temperature parameters should be developed and demonstrated during an RCC construction trial.
- Mortar bedding on a cold joint immediately before fresh RCC. The Designer may chose this procedure for all lift joints.

The bond at horizontal lift joints should be confirmed by obtaining cores from a trial RCC embankment and testing them in a laboratory. Bond quality checks, by obtaining cores and testing them in a laboratory, should also be part of the construction quality assurance process.

Construction, Contraction, Expansion and Isolation Joints

Joints are provided in concrete gravity and buttress dams to minimise cracking and the effects of cracking on relative movement. They include inclined or vertical construction joints for practical concrete construction, contraction joints to regulate the locations of cracks, expansion joints to accommodate volumetric changes in adjacent concrete blocks, and vertical isolation joints to enable movements at specific locations (e.g. directly above a fault in the dam foundation).

All joints require seals to limit joint leakage. The seals must be strong enough to withstand rough treatment during construction and the water pressure, flexible enough to accommodate relative movements between adjacent concrete sections, and durable enough to remain effective during the design life of the dam. A wide range of sealing materials is available and a successful joint system is heavily reliant on the selection of the most appropriate seal and the design detail for the joint. ICOLD Bulletin 57 provides guidelines for the selection of the most appropriate material and its installation in vertical and horizontal joints.

High Velocity Flow

Surfaces exposed to high velocity flows require considerable attention to detail by the Designer and strong quality assurance requirements during construction. Hydraulic flow characteristics need to be carefully modelled and negative pressures should be avoided to reduce the risk of cavitation. High quality surface finishes are often required to avoid cavitation type erosion.

Conventional concrete should be the minimum specification for high velocity flow surfaces, including spillway surfaces on RCC dams.

A relatively small amount of bed load can be highly abrasive to concrete surfaces. Silica fume in the concrete mix provides a more durable surface and steel plates are sometimes installed around gates and abrupt transitions to minimise the potential for erosion.

While numerical hydraulic modelling can be used, the limitations of these techniques must be understood. Physical models may be necessary to ensure hydraulically efficient spillway geometry; however, they should only be undertaken by experienced modellers.

Concrete Mix Design
Concrete mix design requires care to ensure the concrete is a reliable construction material and that it delivers the specified strength and durability objectives. In many cases on-site concrete manufacture will be required. The batching plant for conventional concrete and any plant for the manufacture of RCC must be appropriate for the mix designed and have a production rate that exceeds the maximum required delivery rate at critical times in the construction programme. The Designer should record the results of concrete mix trials, to demonstrate the suitability of the selected mixes, and should receive concrete plant acceptance testing quality control records as evidence that the concrete mixes meet the design requirements.

The control of temperature rise is important in mass concrete and RCC construction. The Designer must specify the mix design, acceptable cement properties, acceptable pozzolanic materials (non-cementitious materials that can replace cement but achieve the specified strength and durability requirements) and acceptable temperature parameters. Methods for determining mass concrete mix proportions are provided in ACI (1989) report 211.1 and methods for determining RCC mix proportions are provided in ACI (1988) report 207.5R.

Many concrete gravity dams, including RCC dams, often require cooling and insulating systems for the management of thermal effects during construction. ANCOLD (2013), ACI (1998) and ICOLD Bulletins 107, 126 and 136 include guidelines for assessing the need for temperature control, and outline alternative construction practices for the prevention of uncontrolled cracking.

Consideration should be given to the following during the design and production of concrete mixes for concrete gravity and buttress dams:

- The need for low heat cements.
- The need for low alkali cements to reduce the risk of alkali silica reactions.
- Sulphate resisting cements if there is a risk of exposure to highly acidic water.
- The benefits of pozzolan replacements (Class F (low lime) fly ash is preferred).
- The necessity for silica fume or other additives to meet durability requirements (e.g. for high velocity water surfaces).
- Maximum placing temperatures.
- Minimum placing temperatures.
- Target slumps.
- Quality control test target ranges and acceptance levels.

Production quality control tests should include:

- Consistency tests such as slump tests for mass concrete and Vebe test times for RCC.
- Compressive strength cylinders.
- Tensile tests of cores through lift joints.

Post-tensioned Anchors
Post-tensioned anchors should not be included as a primary stability means in the design of new concrete dams, especially for normal operating loads. However, anchors are often utilised to raise or improve the stability of existing concrete dams. McInerney et al (2007) includes a detailed account of present day practice in North America and provides a benchmark for the design and assessment of stressed anchors for dam projects in New Zealand. Recognising the conclusions reached in the study completed by McInerney et al, these Guidelines recommend that:

- Without clear evidence that an existing post-tensioned anchor installation is performing as intended, it should be assumed to have no value. Techniques available at the time of preparing these revised Guidelines, utilising indirect methods of non-destructive testing, are unlikely to provide sufficient evidence that anchors are performing as intended.

- New and replacement anchors should be re-stressable post-tensioned anchors incorporating double corrosion protection or an encapsulated tendon. Such a protection system (Class I protection) encases the prestressing steel inside a plastic encapsulation filled with grout or a corrosion inhibiting compound. An epoxy coated strand tendon grouted into a drillhole that successfully passes a specified water pressure test (refer Post-Tensioning Institute 2004) also satisfies the requirements for a Class I protection system.
- All post-tensioned anchor installations should be designed in a manner which enables future regular inspection of the anchor heads and load testing of the anchors. Inspection and load testing frequencies, and sample numbers, for anchor installations should reflect the consequences of anchor failure. For a Low PIC dam it may be appropriate to only inspect and test 10% of the anchors at a frequency of 5 years, while at a High PIC dam it may be appropriate to inspect and test 33% of the cables at a frequency of 5 years.

6.9 Concrete arch dams

6.9.1 Introduction

Arch dams (refer Figure 6.9) are usually built as independent cantilever blocks separated by vertical contraction joints. The vertical contraction joints are then grouted, at an optimal ambient temperature, so that the structure will act as a monolithic system to distribute loads from the shell to the abutments. Hence the details of construction and the integrity of the abutments are critical to the safety of the dam.

Arch dams are often classified on the basis of their thickness and geometry (e.g. variable thickness, double curvature, etc). Gravity arch dams (gravity dams curved in plan) that rely on their curvature to distribute loads into the abutments through arch action require the consideration of both gravity dam and arch dam actions.

Figure 6.9: Concrete Arch Dam – Moawhango Dam (provided by Genesis Energy)

Many early arch dams were designed assuming all horizontal water loads were transferred horizontally to the abutments by arch action and all vertical loads (self weight and water loads on sloping upstream faces) were carried vertically to the foundations by cantilever action. In some cases arch thicknesses were determined using the thin cylinder formula while, in other cases, the thicknesses were determined by elastic arch analyses.

Present day arch dam analysis assumes that the horizontal water load is divided between the arches and cantilevers so that the calculated arch and cantilever deflections are equal at all conjugate points in all parts of the dam. The distribution of stresses in an arch dam varies with the horizontal curvature, the shape of the vertical cross-sections, the general dimensions of the structure, and the uniformity of the foundation and abutment profile. For arch dam sites that do not include pronounced irregularities:

- Maximum cantilever stresses usually occur at the base of the highest cantilever. Maximum compressive stresses usually occur in the downstream face at the base of the dam, and tensile stresses often occur in the upstream face at the base of the dam and in the downstream face towards the centre and top of the dam.

- Arch stresses are usually higher towards the centre and top of the dam, and maximum arch stresses usually occur at the crown and abutment sections. At the crown section, high compressive stresses usually occur in the upstream face of the dam and relatively low compressive or tensile stresses in the downstream face. At the abutment sections stress conditions are usually reversed.

While the design and analysis of arch dams is reasonably straightforward, they do demand higher than normal analytical skills and a sound understanding of the variables that can affect the performance of the dam (e.g. foundation strength and deformation properties, foundation defects and discontinuities, concrete strength and deformation properties, the effects of temperature variations, etc).

The following subsections discuss potential failure modes for arch dams, loads and loading conditions which must be taken into account during their design, evaluation and rehabilitation, and recommended performance criteria for arch dams. A number of defensive design details that are important to dam safety are also discussed.

6.9.2 Potential failure modes

The general comments on the identification and evaluation of potential failure modes included in section 6.5.2 for embankment dams are also relevant to concrete arch dams.

Fell et al (2005) includes some statistics on dam failures which highlight that failure rates between 1900 and 1975 for concrete arch dams were 0.7% of dams built. This figure can be compared with the failure rate quoted for embankment dams, over the same time period, which was 1.2% of dams built.

Hansen and Nuss (2011) summarise the seismic performance of 7 arch dams experiencing earthquakes with peak ground accelerations greater than 0.3g. Ghanaat (2004) discusses evidence of failure mode development at Pacoima Dam after the 1971 San Fernando earthquake and the 1994 Northridge earthquake. Observations from the research indicated that:

- Contraction joints have the lowest tensile capacity and should be expected to open and close during extreme earthquake shaking.
- Seismic ground motions can be amplified significantly at the dam crest. Damage to equipment and buildings from high accelerations at the dam crests was evident and highlighted the need for careful consideration of amplified ground motions during design.
- Rock mass security in the abutments is vitally important. Ghanaat (2004) noted that rock anchors installed in the abutment at Pacoima Dam after the 1971 earthquake limited the movement of a key rock mass supporting the thrust block during the 1994 earthquake.
- Rockslope failures from abutments and onto access roads caused significant damage and delayed access to some sites.

Hansen and Nuss (2011) note that a number of features contributed to the lack of complete failures at concrete dams subjected to large earthquake loads. The features included insufficient durations of strong ground motions, the natural frequency of the dam not matching the frequency of the earthquake, load redistribution in the structure, three dimensional effects and increases in the tensile strength of the concrete during dynamic loading. These Guidelines therefore promote the adoption of dam design features that provide increased resilience.

As with concrete gravity dams, known arch dam failures are primarily related to foundation issues. The more common potential failure modes for arch dams, which are related to the dam and its foundation, are outlined in Table 6.12.

Table 6.12: Potential Failure Modes for Arch Dams

Potential Failure Mode	Common Causes
Structural failure along cracked surfaces in the dam	Insufficient shell thickness for applied loads, defects in concrete, deterioration in concrete quality
Structural failure of a cantilever	Excessive opening of vertical contraction joints accompanied by cantilever tensile cracking (e.g. along horizontal lift joints)
Loss of abutment support	Movement of abutment rock wedges formed by discontinuities
Sliding along the concrete/foundation interface, or planes of weakness in the dam foundation	High uplift pressures, insufficient shear strength, inappropriate foundation treatment
Piping of foundation materials	High gradients through foundation, lack of or inappropriate foundation treatment

6.9.3 Loading conditions

Loading conditions that should be considered in the design, evaluation or rehabilitation of concrete arch dams, and the general performance criteria, are similar to those outlined in section 6.8.3 for a concrete gravity or buttress dam. Comments on each loading condition and examples of each loading condition for a concrete arch dam are provided below.

- During normal loading conditions the behaviour of the dam should remain in the linearly elastic range. The normal loading condition should include the consideration of dead loads, hydrostatic loads (headwater and tailwater), loads imposed by silt deposition upstream of the dam and backfill materials adjacent to the dam, and temperature effects (normal, maximum and minimum concrete temperatures).
- During unusual loading conditions minor non-linear behaviour of the dam is acceptable; however, any necessary repairs should be minor. Analysis should include the consideration of all the loads outlined above for the normal loading condition in combination with the OBE, including hydrodynamic loads, and in combination with an appropriate reduction in the efficiency of underdrains (if present).
- During extreme loading conditions non-linear behaviour of the dam is acceptable. Analysis should include the consideration of all the loads outlined above for the normal loading condition in combination with the IDF and in combination with the SEE including hydrodynamic loads. The analysis should also address the post-SEE condition, taking into account the possibility of open joints, the possibility of movement in the abutments, the loss of any cohesion at the dam/foundation interfaces, an appropriate reduction in the friction angle at the dam/foundation interfaces, and any increase in the horizontal load that could result from liquefaction of silts deposited immediately upstream of the dam.

6.9.4 Stability and deformation performance criteria

Sliding stability is important for concrete arch dams, not along the foundation contact but at abutment areas where foundation wedges formed by combinations of faults, shears and/or joint sets can affect the overall functionality of the dam by reducing the ability of the abutments to accept the arch thrusts. Compared to concrete gravity and buttress dams, the design and assessment of concrete arch dams is usually more dependent on allowable deflections and concrete stresses.

Arch dams rely on abutments remaining intact to carry the significant thrust forces. Non-linear behaviour may occur in the dam or abutment during extreme earthquakes but the over-riding performance criteria of safely retaining the reservoir applies.

A full design or safety evaluation for an arch dam will require a three dimensional analysis. Simplified structural theory may be possible for initial assessments of single curvature structures, but a more complex analysis should be completed for final design. Potential abutment wedges need to be identified and analysed for stability using the resultant forces from dam analyses. Guidelines for the design and evaluation of concrete arch dams are included in USACE (1994) and FERC (1993).

Recommended criteria for the design and evaluation of concrete arch dams are provided in Table 6.13. The recommended criteria have been developed from those included in USACE (1994) and FERC (1993).

Table 6.13: Recommended Performance Criteria for Concrete Arch Dams

Loading Condition	Performance Criteria		
	Maximum Compressive Stress	Maximum Tensile Stress	Minimum Factor of Safety Against Sliding
Normal	0.25xf'_c	f'_t	2.0
Unusual - Flood	0.4xf'_c	f'_t	1.3
Unusual - Earthquake	0.4xf'_{cd}	f'_{td}	1.3
Extreme - Flood	0.67xf'_c	f'_t	1.1
Extreme – Earthquake	0.67xf'_{cd}	f'_{td}	1.1[3]
Post-earthquake	0.25xf'_c	f'_t	2.0
Construction (before grouting)	For all cantilevers the resultant should be located within the base and the maximum tensile stress should be f'_t		

Notes:

1. 1.f'_c is the 28 day compressive strength of the concrete and should be >28MPa, and f'_t is the tensile strength of the concrete. For Low PIC dams f't can be assumed to be 10% of f'c. For Medium and High PIC dams f'_t should be determined from the results of splitting tensile tests.
2. 2.f'_{cd} and f'_{td} are the dynamic compressive and tensile strengths based on the results of laboratory tests for the appropriate rate of loading as determined from the dynamic analysis.
3. 3.For Medium and High PIC dams subjected to extreme seismic loading, time history response analyses should be completed to determine abutment and foundation stability. The factor of safety against sliding will vary with time and may be less than 1.0 for one or more cycles if the resulting cumulative displacement is very small and tolerable.

6.9.5 Design details

There are a number of design details for arch dams that can affect dam safety. They include:

- The geometry of the dam.
- The treatment of foundation defects.
- Providing suitable drainage facilities for the control of uplift pressures.
- Providing sufficient freeboard and appropriate crest details.
- The details of the contraction joints between the individual cantilever sections.
- The concrete mix design.

Dam Geometry

Arch dams are usually constructed in discrete cantilever blocks with vertical contraction joints which are grouted on completion. A thermal assessment, that addresses cooling requirements and construction considerations, should be carried out to determine the desired spacing of the contraction joints.

The cantilever blocks need to be designed for construction conditions until the contraction joints are grouted. The cantilever blocks also need to be checked for excessive tensile stresses if analysis shows contraction joint openings during earthquake loading conditions.

Load distribution into the abutments is most important for arch dams and consideration must be given to the integrity of the abutments, the orientations of the arch thrusts into the abutments, and the stability and deformation of the abutments in response to the arch loads. In addition, it is important to define arch thrust loads on any wedges or blocks formed by discontinuities in the foundation or abutments that could displace under the combination of gravity loads, reservoir water pressure loads in the discontinuities, and arch thrusts.

Foundation Defects

The identification and appropriate treatment of foundation defects is discussed in section 6.4 of these Guidelines. In addition to the measures required for the control of seepage flows, the design challenges for arch dams include the identification of all defects and discontinuities that could affect dam stability, the determination of their shear strengths, and the design of any necessary strengthening works to ensure adequate reserves of stability.

The design should consider the sliding resistance along any identified joint or shear plane with an orientation that could encourage the development of a sliding failure. The Designer should also consider the stability of any combinations of joint or shear planes that form unstable wedges of rock and could result in the loss of support for the dam. The foundation immediately downstream of the dam is the critical zone for an arch dam and every care must be taken to ensure that it is not damaged during the construction process.

The determination of foundation shear strengths can be difficult and the guidelines included in section 6.8.5 for concrete gravity and buttress dams are also applicable to concrete arch dams.

Drainage Facilities

While uplift is not usually important in thin arch dams, it can be significant in thick arch dams and in the stability of any blocks or wedges that are formed by discontinuities in the foundation and abutments. The guidelines included in section 6.8.5 for drainage facilities in concrete gravity and buttress dams are appropriate for arch dams; however, additional drainage facilities in the abutments are a common requirement for arch dams.

High pressures can occur in the foundations and abutments of arch dams and drainage can be necessary for the control of foundation and abutment stability. In such cases drainage is often provided by angled drain holes along the foundation contact and adits, driven into the abutments at appropriate locations which recognise the stresses within the rockmass, with curtains of drilled holes connecting the adits.

Freeboard and Crest Details

Concrete arch dams can usually accommodate some overtopping without serious damage and, as such, the freeboard provisions can be somewhat less than those detailed for embankment dams in section 6.5.5 of this module.

The quality of the rock at the impact point for the overtopping flow, downstream of the dam, is the key consideration in establishing the amount of overtopping flow that can be safely discharged without undermining the arch dam foundation. From a dam safety perspective it is important that the foundation material downstream of the dam is able to be inspected and evaluated and, if there is concern over the potential for erosion undermining the dam foundation, that sufficient freeboard is provided to ensure the safety of the dam and its abutments are not compromised during the IDF.

Many arch dams incorporate free overflow spillways along their crests and consideration must be given to the loads that spillway operation may place on the dam, the dissipation of energy and the control of erosion immediately downstream of the dam, and the accessibility to both abutments for ongoing surveillance, monitoring and maintenance.

Contraction Joints

Radial contraction joints are usually provided between the cantilever blocks at approximately 15m centres, although an appropriate spacing is often determined from temperature studies.

The joints usually incorporate shear keys to provide shearing resistance between the cantilever blocks, waterstops to prevent seepage flows from migrating through the joints, grout stops to confine grouting within specified areas of the joints, and grout pipes for grouting of the joints. Grouting operations should be closely monitored to ensure they don't result in harmful overstress in the dam structure.

Concrete Mix Design

Concrete mix design requirements are similar to those for concrete gravity and buttress dams, and the guidelines provided in section 6.8.5 are appropriate.

6.10 Tailings dams

6.10.1 Introduction

All tailings dams should be designed in accordance with sound dam engineering practice. As such, the large majority of the design recommendations included in these Guidelines are applicable to the design of tailings dams.

While many of the design recommendations included in these Guidelines apply to tailings dams, tailings dams differ from other dams in a number of ways. One of the primary differences is that the construction (deposition) phase of a tailings dam continues throughout its operational life. As such, many of the original design parameters can change during the operational life of a tailings dam and technical support from design consultants and peer reviewers is typically required on a more frequent basis than for conventional water storage dams.

The following subsections provide a brief overview of issues that are particular to the design of tailings dams and, because the design process normally continues throughout their operational lives, the overview includes a discussion on construction methods, operational issues and closure systems. Any recommendations which replace those included in other sections of the Guidelines are highlighted. The material has been largely obtained from ICOLD bulletins listed in the references.

6.10.2 Corporate and management support

Because the construction (deposition) phase for a tailings storage facility can extend over many years and because the tailings must remain safely stored until their toxicity has reduced to environmentally acceptable levels, corporate and management support is critical to the ongoing safety of tailings dams.

There is normally no direct financial return from the construction and operation of a tailings dam and the natural temptations are to limit capital expenditure, reduce operating costs, and minimise financial contributions to the closure of a tailings storage facility. Dam safety and environmental standards for tailings dams can only be assured through the ongoing support of corporate and managerial personnel to tailings disposal operations.

6.10.3 Characterisation and behaviour of tailings

Different industrial operations can result in the production of tailings with widely different characteristics. For example the tailings from a mining operation usually comprise finely ground rock and water that can be used, at least in part, to construct the tailings dams for their retention. Alternatively, tailings produced by most industrial and chemical operations are usually fine grained, fluid or semi-fluid, and are unsuitable for the construction of tailings dams. As such, the retention of tailings from most industrial and chemical operations is achieved by the construction of conventional water storage dams.

The grain size of mine tailings depends upon the characteristics of the ore and the mill processes used to concentrate and extract the metal values, and can vary from fine sands to clay sized materials. As such, mine tailings are normally transported to the storage facility as slurries, with concentrations varying between 30% and 60% by weight of solids to liquids. Typical physical characteristics for various types of tailings are listed in Table 6.14.

Table 6.14: Typical Physical Characteristics of Tailings (Source: Fell et al (2005))

Type of Tailings	General Characteristics
Ultra-fine tailings, aluminium red mud	Clay and silt, high plasticity, very low density (3) and permeability
Washery tailings, coal, bauxite, some iron and nickel ores	Clay and silt, medium to high plasticity, medium to low density and permeability
Oxidised (1) mineral tailings, gold, copper, lead, zinc, etc	Silt and clay, some sand, low to medium plasticity, medium density and permeability
Hard rock (2) mineral tailings, gold, copper, lead, zinc, etc	Silt and some sand, non-plastic, high density, medium to high permeability
Notes: 1. Ore is completely or highly weathered, or altered rock 2. Ore is slightly weathered to fresh rock 3. Assuming no desiccation	

The potential pollution hazards associated with the storage of tailings slurries vary with the industrial operation. Mining processes that merely grind up an inert ore without the addition of toxic chemicals usually result in no pollution hazard. However, an industrial operation that includes the use of toxic chemicals can result in short-term or long-term pollution hazards. Guidelines for the effective control of pollution hazards are included in the references listed at the end of this module.

6.10.4 Tailings storage methods and deposition

The construction materials and construction methods for tailings dams vary widely to accommodate the particular needs of the selected site, the available materials for tailings dam construction, and the financial and operating policies for the industrial operation. The construction methods usually adopted include:

- The construction of a conventional embankment dam where the structure is required to store water which will be replaced, in part, by tailings during the deposition period, or where the impoundment includes a natural inflow and water storage is required for its control. The embankment can either be constructed to its full height at the commencement of the project, or in stages to spread its construction cost over the planned period of deposition.
- The construction of a tailings dam by the upstream method, where increased tailings storage is provided by constructing additional embankments on the tailings immediately upstream of the starter dam. The additional embankments can be constructed from tailings which have been processed through cyclones and are discharged on the upstream side of the delivery pipeline and, as a result, the crest of the embankment moves upstream as the dam height increases. The additional embankments can also be constructed from waste rock where mining is by open pit.
- The construction of a tailings dam by the downstream method, where increased tailings storage is provided by constructing additional embankments against the downstream shoulder of the starter dam. The additional embankments can be constructed from the coarse fraction of the tailings which have been processed through cyclones and are discharged downstream to form the embankment, with the fine fraction being discharged into the impoundment. As a result the crest of the embankment moves downstream as the dam height increases. The additional embankments can also be constructed from waste rock.
- The construction of a tailings dam by the centreline method, where increased tailings storage is provided by constructing additional embankments against the downstream shoulder of the starter dam and on the tailings immediately upstream of the crest of the starter dam. The raises can be constructed from the coarse fraction of the tailings which have been processed through cyclones and are discharged downstream and, when the delivery pipeline and cyclone are raised, discharged upstream. The crest of the final embankment is built directly above the crest of the starter dam. The additional embankments can also be constructed from waste rock.

The three tailings dam construction methods are shown diagrammatically in Figure 6.10. The upstream construction method only shows the use of tailings for construction of the additional embankments.

The particular construction method adopted generally reflects the characteristics of the mine operation (e.g. type of tailings, tailings production rate, site foundation conditions, local seismicity, etc). However, one important factor that should be considered in the selection of the construction method is the importance of seepage control to the stability of the downstream slope of the embankment. Downstream construction and, to a lesser extent, centreline construction provide more opportunities for the effective control of seepage flows than upstream construction. Downstream construction is also recommended in seismic environments. Upstream construction should only be used in seismic environments where the tailings can be demonstrated by monitoring to be drained, the rate of rise will not result in the generation of excess pore pressures, and the design is supported by rigorous analysis.

The disposal arrangement at the tailings storage facility is largely dictated by the embankment construction method. Where a conventional embankment dam and water storage is utilised the disposal system may be a single point pipeline discharge into the impoundment. Where tailings are used for the construction of the embankments the disposal system usually incorporates a delivery pipeline and a bank of cyclones for the controlled discharge and use of the tailings. In all cases the adoption of a more controlled deposition system that takes into account the slopes formed by the deposited tailings above and below the water level in the storage facility, and the different densities of the deposited materials achieved by different deposition methods, can provide significant economic benefits. For example, the consideration of deposition angles can increase the volume of material stored for a given embankment height, and beach deposition can result in higher material densities.

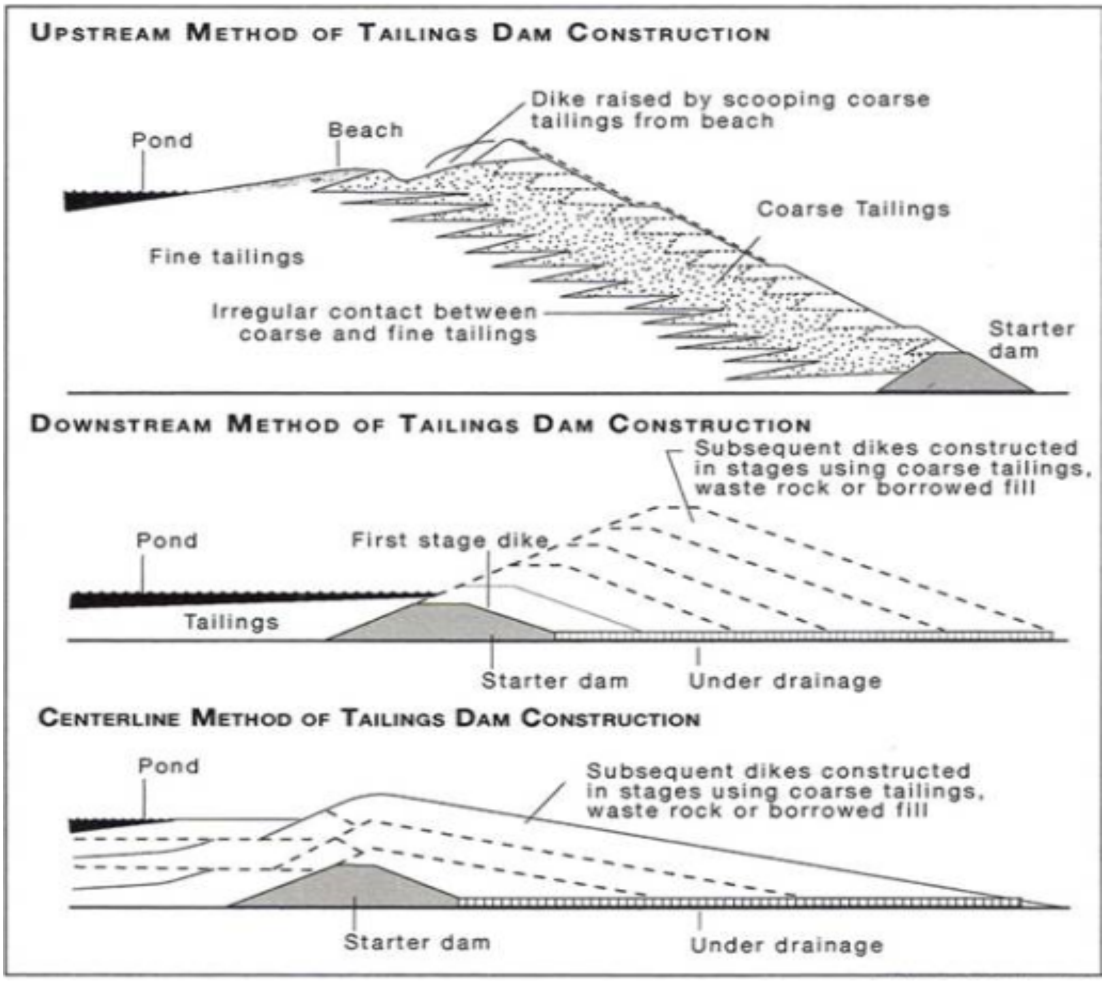


Figure 6.10: Tailings Dam Construction Methods

In most impoundments the solids settle out of suspension on discharge and the resulting stored material comprises settled solids of variable consistency and a supernatant fluid, usually water, which can be supplemented by runoff and/or direct rainfall. The supernatant fluid may be returned to the processing plant for reuse, stored in the impoundment for future use or for removal by evaporation, or, if sufficiently innocuous, discharged into the downstream catchment.

The main requirement for successful removal of the supernatant is the provision of an outlet facility which can be adjusted as the level of the impoundment increases. The outlet facility (or decanting system) usually incorporates an extendible intake and a conduit to convey the discharge away from the embankment; however, pump barges are sometimes used to reduce the risks associated with raising the level of an outlet facility and to provide more flexibility in the location of the outlet facility within the impoundment.

6.10.5 Design overview

Procedures for the design of tailings dams are, in many areas, quite different from those for conventional water storage dams and they are not as widely known nor as well understood as those for conventional water storage dams. A detailed discussion on the design of tailings dams is beyond the scope of these Guidelines and Designers are referred to the relevant ICOLD bulletins, the ANCOLD Guidelines on Tailings Dams (2012) and other relevant references listed at the end of this module.

One advantage inherent in the design of tailings dams is that most are built slowly and a design-as-you-go approach, using information obtained from the monitoring of dam performance, can often be adopted.

The following material highlights important issues that are particular to the design, construction and operation, evaluation and closure of tailings dams.

6.10.6 Potential failure modes

ICOLD Bulletin 121 provides an overview of reported failures for tailings dams, and concludes that the main causes of tailings dam failures during operation have been slope instability, overtopping and earthquakes. For tailings dams following closure the main causes of failure have been overtopping and earthquakes.

The identification of potential failure modes for a tailings dam should be based on consideration of the construction method, the materials used in its construction and the site specific characteristics for the dam. However, the information included in ICOLD Bulletin 121 indicates that the more common potential failure modes are as outlined in Table 6.15.

Table 6.15: Potential Failure Modes for Tailings Dams

Potential Failure Mode	Common Causes
Instability of downstream shoulder	Saturation of downstream shoulder, perched phreatic surfaces, insufficient shear strength, liquefaction of embankment or foundation materials
Overtopping	Insufficient freeboard to accommodate storms and flood events, inappropriate management of the water balance during operation
Internal erosion	Inadequate control of seepage, bad filter and drain design, poor design and construction control resulting in cracking and leakage paths

The historical information also indicates that tailings dams constructed by the upstream method are more prone to failure than those constructed by the downstream or centreline methods. While this may merely reflect that the upstream method is the oldest and most commonly used method of tailings dam construction, the downstream and centreline methods do provide more opportunities for the effective control of seepage.

6.10.7 Loading conditions

Loading conditions that should be considered in the design of a tailings dam are similar to those outlined in section 6.5.3 for embankment dams. However, there are a number of additional external and internal loads that should be considered in the design of tailings dams. They include:

- The elevation of the pool water level. The design of conventional water storage dams always includes the consideration of water loads; however, they can be overlooked in the design of tailings dams. Where the pool is located close to the crest of the dam, the direct load of the water should be included in the stability analyses. Where the pool is located away from the crest of the dam, long periods of high water level resulting from continuous rainfall or incorrect operation can result in significant increases in the level of the phreatic surface.
- The rate of rise in the level of the impoundment and its influence on pore pressures. If the rate of rise is greater than the rate of pore pressure dissipation, liquefaction of loose tailings can occur. Several observed cases of liquefaction have been initiated by trigger events such as vibrations from passing equipment and an increase in the degree of saturation following heavy rainfall.
- The mass of the tailings and their consolidation can impose a 'downdrag' force on the upstream face of the dam and may result in increased pore pressures. Such forces can be significant for the design of membrane faced dams and decanting facilities.

6.10.8 Stability and deformation performance criteria

As for embankment dams, potential stability failures for tailings dams under different loading conditions are usually assessed in terms of minimum factors of safety. Recommended minimum factors of safety for limit equilibrium stability studies, for static loading conditions, are listed in Table 6.16.

Table 6.16: Recommended Minimum Factors of Safety for Slope Stability – Static Assessment

Loading Condition	Slope	Minimum Factor Of Safety1,2
End of construction of starter dam	Upstream and downstream	1.3
Normal during operation (steady state seepage, normal pool level)	Downstream	1.5
Long term post-closure (steady state seepage)	Downstream	1.5

Notes:

1. The factor of safety is the factor required to reduce operational shear strength parameters in order to bring a potential sliding mass into a state of limiting equilibrium, using generally accepted methods of analysis.
2. Higher factors of safety may be necessary if there are high levels of uncertainty in the inputs to the stability analysis.

For seismic loading the same criteria summarised for embankment dams in Table 6.4 apply.

The above recommended factors of safety are similar to those recommended for embankment dams; however, for tailings dams, careful consideration needs to be given to the following:

- The stability of the tailings dam, during all stages of construction, to its maximum height. This is particularly important for a clay foundation where the increase in strength resulting from consolidation under the increasing weight of tailings may be insufficient to maintain stability as the height of the dam increases.
- The form of construction. For upstream construction the failure surface usually includes a large mass of fine tailings materials. For downstream and centreline construction, with good drainage, the failure surface is predominantly located within the constructed embankment.
- The variability in the density of the tailings materials and hence their shear strength.
- The variability in the permeability of the coarse and fine tailings and its effect on the dissipation of pore pressures.

- The potential for chemical reactions to modify the physical properties of the tailings and foundation materials.
- The potential for liquefaction of the tailings materials and the consequent reduction in their shear strength (particularly for upstream construction).

As stated in section 6.5.4 for embankment dams, the use of simplified stability and deformation methods is appropriate for most applications. Numerical methods should be utilised for High PIC dams where stability and deformation studies indicate marginal safety, or where necessary to prove acceptable performance (e.g. upstream construction in a seismic environment).

6.10.9 Design details

From a dam safety perspective there are a number of design details for tailings dams that are additional to those outlined in section 6.5.5 for embankment dams and warrant careful attention during the design process. The details are addressed in a number of ICOLD bulletins and are discussed below.

The Tailings Storage Site

The site for a conventional water storage dam is largely dictated by available water sources, topographical conditions and foundation conditions. This is not always the case for tailings dams which, for ease of tailings disposal, are usually sited within close proximity of the mining or industrial operation. In addition, a tailings dam site must provide security for the long-term storage of the tailings following closure.

The Deposition Method

The selection of an appropriate deposition method is critical to the design process, particularly for dams constructed from tailings. Many factors need to be taken into consideration in selecting the deposition technique including the topography of the site, the physical and chemical characteristics of the tailings materials, the supply rate and slurry concentration of the tailings, and the rate of rise in the level of the tailings impoundment. The selected deposition method will largely govern the form of the tailings dam, including its geometry and any internal drainage facilities necessary for the control of seepage flows.

The Water Balance

Inadequate management of the water balance is one of the primary causes of tailings dam failure, and it is most important that the available water storage and the installed capacities of the decanting and spillway structures can safely accommodate all inflows to the tailings storage facility. Normal inflows include the tailings transport water, direct rainfall into the impoundment, runoff from upstream catchments, and seepage discharges captured and returned to the storage facility. Abnormal inflows, which must be allowed for in the design, can include water or effluents delivered from extraneous sources and extreme storm events not allowed for in the design. Often tailings dams are designed for no discharge with excess water re-cycled for use in the process plant or pumped for water treatment prior to release. The water balance may rely on diversion drains to divert runoff from upslope. A water balance model should be established using realistic assumptions and should be regularly reviewed and updated during operation to account for actual operating experience and changes in basic assumptions (e.g. quantity of tailings produced, volume of water pumped from tailings dam, catchment area).

Freeboard

In comparison to a conventional water storage dam, the crest of a tailings dam is usually under continual construction and it is most important that the freeboard, between the supernatant pool and the dam crest, can always safely accommodate the design flood event. In cases where the dam is being formed using the tailings being deposited, the freeboard may only be provided by the slope and length of the tailings exposed beach. A minimum freeboard of 1m above the design flood level is recommended.

Seepage Control
Seepage control is particularly important for maintaining stability where upstream and centreline construction is used. Drainage zones may need to be incorporated at foundation level upstream of the starter dam and in the tailings. Seepage interception facilities and collection drains must be filter compatible with the tailings and foundation materials. Geosynthetic fabrics can become blocked and can tear, and should not be used in lieu of sand/gravel filters for the control of internal erosion in the body of or beneath a tailings dam. They should only be used where they can be readily exposed, repaired or replaced.

Beach Length
For upstream and centreline construction the stability of the embankment is largely governed by the position of the phreatic surface. To maintain the phreatic surface at the design distance from the downstream face, and therefore maintain an adequate level of embankment stability, a minimum beach length should be specified.

Decanting and Spillway Facilities
The sizing and operation of decanting and spillway facilities are critical to the safety of a tailings storage facility. Under sizing or inappropriate operation of the decanting and spillway facilities can result in a rise in the pool level with consequential effects on freeboard and dam stability.

Designing for Closure
The planning and provision for closure should be incorporated within the initial design to ensure the long term environmental safety of a tailings storage facility.

6.10.10 Construction and operation

The recommendations included in Module 4 (Construction and Commissioning) and Module 5 (Dam Safety Assurance) relating to construction personnel, construction contracts, construction planning, quality management, construction records and dam safety assurance are relevant to the construction and operation of tailings dams. However, there are a number of significant differences in the construction and operation of tailings dams which can affect dam safety:

- Often the construction of a tailings dam is undertaken by a mining company as a component of a mining operation. In such a case it is natural that the primary focus will be on production and the efficiency of the mining operation, and that the construction of the tailings dam will be of secondary importance. From a dam safety perspective, it is most important that the construction of a tailings dam is appropriately resourced and managed to ensure the design intent is achieved. Dam safety can only be assured through the appointment of a construction team with an appropriate level of experience in tailings dam construction, the implementation of appropriate quality control procedures, and the ongoing support of the design consultant and corporate and management personnel throughout the tailings disposal operation.
- As outlined earlier, the construction of a tailings dam continues throughout the operational life of the tailings storage facility and ongoing design support is essential to ensure the design intent is met during all stages of construction. Regular monitoring of the dam's performance (e.g. piezometric pressures, seepage flows) and testing of the deposited tailings materials (e.g. water content, density, permeability, shear strength) will be necessary to confirm design assumptions and support the 'design-as-you-go' approach.
- It is not uncommon for the rate of mining, and therefore the quantities of tailings, and processing and operational procedures to change during the life of a tailings dam. It is important that the implications of such changes on the design are considered and appropriate amendments made where necessary. Regular reviews are recommended.
- The construction and operation process will vary according to the physical and chemical properties of the tailings materials and the rate at which they are delivered to the storage facility. Unlike a conventional water storage dam, the construction of a tailings dam must reflect the requirements of the mining process and the operation of the dam will commence shortly after the onset of its construction.

- The operation process should be supported by a formal, detailed Operation, Maintenance and Surveillance Manual. Unlike a conventional water storage dam, where such a manual is often prepared towards the end of dam construction, an Operation, Maintenance and Surveillance Manual for a tailings dam should be prepared ahead of dam construction. The manual should be similar to that outlined in Module 5 (Dam Safety Assurance) but it should also include activities related to the operation, maintenance and surveillance of the tailings disposal system, such as:
  - Operation and maintenance of the tailings delivery system.
  - Ensuring that the deposition process achieves adequate particle size segregation on the beaches.
  - Maintenance of the beach length, slope and freeboard.
  - Water balance operating procedures.
  - Operation and maintenance of the decanting facility.
  - Regular testing of the deposited tailings.
- An Emergency Action Plan should be in place throughout the operational life of the tailings storage facility. Guidelines for the preparation of an Emergency Action Plan are included in Module 6 (Emergency Preparedness).

6.10.11 Closure

A tailings impoundment will generally remain in existence long after the associated mine or processing plant has ceased operation and it is important that the impoundment, tailings dam and associated structures remain safe in the long term. It is therefore important that the closure of a tailings storage facility is given early consideration during the design process. ICOLD Bulletin 153 (2013) provides advice on design for closure. The international trend is towards a design life of in excess of 1,000 years.

While environmental controls are important to ensure the long-term environmental safety of a tailings storage facility, their design and management are beyond the scope of these Guidelines. From a dam engineering perspective, important issues that should be addressed in the design of a tailings dam closure include:

- The long-term stability of the tailings dam. This is not normally a cause for concern if the embankment was stable during its operational life.
- The protection of the outer embankment slopes against the effects of erosion.
- The ongoing effectiveness of the seepage control facilities to effectively manage the residual moisture in the tailings and any springs identified beneath the impoundment.
- The long-term ability of the facility to safely manage and discharge catchment rainfall and runoff. Long-term safety may necessitate the management and discharge of larger rainfall and runoff events than those that were adopted for the operation of the tailings storage facility. This can arise because often runoff from upstream will be diverted past the tailings dam during operation, but will run through the tailings dam after closure.
- Ongoing surveillance and monitoring, and reviews of the surveillance and monitoring results, to identify any adverse trends which could affect the safety of the tailings facility.

6.11 Appurtenant structures

6.11.1 Introduction

The Building Act defines an appurtenant structure, in relation to a dam, as "a structure that is integral to the safe functioning of the dam as a structure for retaining water or other fluid". This is interpreted to be primarily about the safe containment of the reservoir and, as such, appurtenant structures are those structures at the dam site, other than the dam itself, that are designed and are required for the safe containment and control of the reservoir under all loading conditions.

Figure 6.11 provides a framework for determining whether a structure is an appurtenant structure.

Typical appurtenant structures include spillways, penstock intake structures, water intake structures, canal inlet structures, and low level outlet structures. Pipelines and penstocks downstream of intake structures should also be considered appurtenant structures if there is no gate or valve designed to isolate them from the reservoir contents. Appurtenant structures often incorporate mechanical and electrical equipment (e.g. gates, valves, gate and valve operating equipment, standby generators) for the controlled discharge or release of the reservoir contents.

The following subsections discuss potential failure modes for appurtenant structures, loads and loading conditions which must be taken into account during their design, evaluation and rehabilitation, and recommended performance criteria for appurtenant structures. Gate and valves installed in appurtenant structures that fulfil dam safety functions, and a number of defensive design details that are important to dam safety are also discussed.

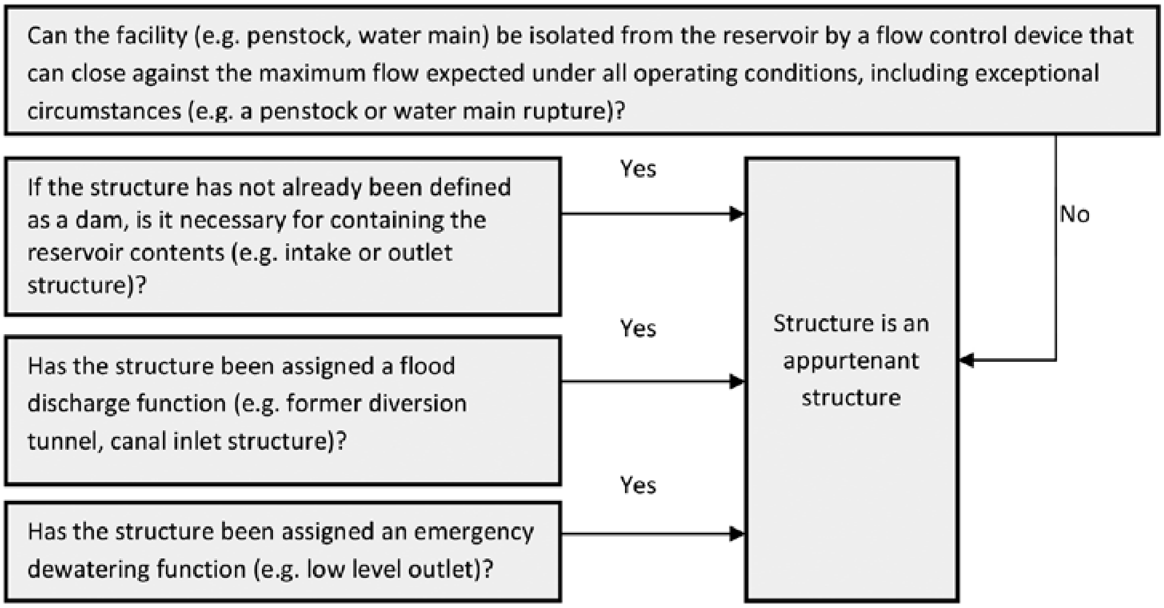


Figure 6.11: Determining Whether a Structure is an Appurtenant Structure

6.11.2 Potential failure Modes

The general comments on the identification and evaluation of potential failure modes included in section 6.5.2 for embankment dams are also relevant to appurtenant structures.

Inadequate design and/or inappropriate operation of appurtenant structures can significantly affect the safety of a dam, particularly an embankment dam. In addition, many appurtenant structures are located in prominent positions on dams or abutments and are therefore vulnerable to large ground motions during earthquakes. Various reviews of earthquake related damage to dams (Fell et al (2005), Wieland (2012) and Hansen and Nuss (2011)) note earthquake damage to elevated equipment for the operation of appurtenant structures.

The more common potential failure modes for dams, which are related to the design and operation of appurtenant structures, are outlined in Table 6.17.

Table 6.17: Potential Failure Modes related to Appurtenant Structures

Potential Failure Mode	Common Causes
Overtopping	Insufficient spillway capacity, inappropriate operation of spillway facilities, inability to operate spillway facilities (spillway blockage, gate jamming through pier deformation, equipment malfunction, control systems failure, power supply failure, lack of access for manual operation, no operator for manual operation), inappropriate management of water balance in a tailings storage facility
Erosion	Cavitation damage, erosion by abrasion or uplift of stilling basin leads to loss of spillway chute followed by backward erosion to reservoir
Erosion of embankment materials	Inadequate detailing of embankment/structure interfaces (e.g. spillway, intake and conduit interfaces), inadequate filter protection systems adjacent to appurtenant structures, rupture of pipeline through embankment
Structural gate failure	Overstressing of gate arms, gate bearing seizure

6.11.3 Loading conditions

Loads and loading conditions that should be considered in the design or rehabilitation of an appurtenant structure are similar to those outlined in section 6.8.3 for a concrete dam.

It is also frequently necessary to analyse the performance of the structure, or a component of the structure, under various gate/valve and hydraulic operating conditions. Examples for each loading condition include the following:

- Normal loading conditions – All gates/valves open, all gates/valves closed, adjacent gates/valves open and closed. These operating conditions are common in canal inlet, penstock intake and spillway gate structures, and bottom outlet gate/valve structures.
- Unusual loading conditions – All maintenance bulkheads in place, adjacent maintenance bulkheads in place and not in place, and normal gate/valve configurations with the OBE. These operating conditions occur in canal inlet, penstock intake and spillway gate structures, and bottom outlet gate/valve structures. An additional operating condition is the dewatering of stilling basins for inspection or the completion of remedial works.
- Extreme loading conditions – All gates/valves open during the IDF, adjacent gates/valves open and closed during the IDF, and normal gate/valve configurations with the SEE. These operating conditions occur in spillway, canal inlet and penstock intake structures, and bottom outlet gate/valve structures. Other operating conditions relevant to spillways and their stilling basins include discharges during the IDF and rapid reductions in discharge following the IDF.

Design loads for an appurtenant structure relate to the function it performs, the asset it protects and the potential consequences if the structure fails. If a gate is required to operate post-SEE, then the gate, its operating equipment and the structure supporting the gate must be designed for the same level of ground shaking as the dam it is protecting (allowing for ground motion amplification effects as discussed in section 6.11.4). If the appurtenant structure is a structure required to contain the reservoir (possible examples might be a penstock or a surge chamber) then the design loads should reflect the consequences of its failure.

6.11.4 Stability and structural performance criteria

Performance criteria for appurtenant structures are similar to those outlined in section 6.8.4 for concrete dams and the recommendations relating to sliding factors of safety, the position of the force resultant, and normal compressive stresses are applicable.

In addition to the above performance criteria, appurtenant structures should have adequate reserves of weight to ensure flotation does not occur during all loading conditions. Factors of safety recommended in USACE (2005) are 1.3 for normal loading conditions, 1.2 for unusual loading conditions and 1.1 for extreme loading conditions.

Appurtenant structures and installed mechanical equipment that fulfils a dam safety function should be operational after the SEE. Accordingly, they should be designed to accommodate the amplified loads relevant to their locations during the SEE for the dam. Ground motion accelerations at elevations above the floor of a valley will be amplified by the dam height and abutment topography, and appurtenant structures located close to dam crests or high on dam abutments will experience ground motions that exceed the peak ground acceleration for the SEE at ground level. Elevated gantries on dam crests for lifting gates can be particularly vulnerable to the high accelerations that can occur at these locations, especially if their fundamental frequencies are similar to the frequencies of the ground motions. The structures should be designed to accommodate the upstream/downstream, cross valley and vertical components of the SEE.

The performance criteria for appurtenant structures (safe operation post-SEE) can be more demanding than the performance criteria for dams (retention of reservoir contents without catastrophic release). Structural elements that support gates and valves for safe operation of the reservoir must be designed to ensure the equipment is able to perform its function post-SEE. If the equipment has a lifting function then the support structure must be able to sustain the lifting loads in its post-SEE condition. If access is required to control the reservoir (e.g. manual operation of a dewatering facility) then the extent of acceptable cracking for safe access needs to be assessed.

Other structures that are not critical to the safe retention of the reservoir are usually designed in accordance with the applicable Building Regulation requirements.

6.11.5 Gates and valves that fulfil dam safety functions

Appurtenant structures often incorporate gate and/or valve systems that fulfil dam safety functions during normal and extreme loading conditions, and following extreme loading conditions. The equipment items vary according to the design features adopted for each dam but often include:

- Spillway gates for the retention of the reservoir during normal loading conditions and during and following extreme loading conditions, the controlled release of flood flows during flood events, and the controlled release of dewatering flows in a potential dam safety emergency.
- Spillway gate types include crest mounted radial gates, orifice radial gates, vertical lift wheel gates, flap gates and rubber dams. Table 6.18 has been developed from Chander Sehgal (2000) which outlines selection criteria for spillway gates and their operating equipment. Examples of spillway gate types are shown in Figures 6.12 to 6.16.

Table 6.18: Design Requirements and Suitability of Spillway Gate Types

Design Requirement	Radial Gate (Crest Mounted)	Radial Gate (Orifice)	Vertical Lift Wheel Gate	Flap Gate	Rubber Dam
Flood control	Yes	Yes	Yes	Yes	Yes
Storage above spillway crest	Yes, gate height limited by height of piers	Yes, gate height not critical to storage	Yes, gate height limited by height of piers	Yes, gate height limited to 3 to 4m by high lifting loads	Yes, height limited to 3 to 4m by strength of material
Passage of debris	No, except when gate fully open	No	No, except when gate fully open	Yes	Yes
Sediment sluicing	Yes, but ineffective for high crest heights	Yes	Yes, but not preferred as wheels can be jammed by sediment	No, except when gate fully open	No, except when gate fully open

- Low level sluice gates (orifice radial gates or vertical wheel gates) or valves for the retention of the reservoir during normal loading conditions and during and following extreme loading conditions, and the controlled release of dewatering flows in a potential dam safety emergency. Low level sluice gates can also be used for the sluicing of accumulated sediment and the controlled release of flood flows during flood events.
- Canal inlet gates (radial gates, vertical wheel gates, or slide gates) for the retention of the reservoir during normal loading conditions, and during and following extreme loading conditions. Some canal inlet gates may also be required to assist in the release of flood flows during extreme flood events and the release of dewatering flows in a potential dam safety emergency.
- Penstock intake gates (usually vertical wheel gates) and water intake valves for the isolation of ruptured downstream penstocks and pipelines that could affect dam safety.
- Dewatering pumps and discharge facilities for the control of uplift pressures during normal loading conditions, and during and following extreme loading conditions.
- Power supplies, gate lifting and valve operating equipment, and protection, control and communication systems and the ancillary (backup) features for operation of the above facilities.

Figure 6.12: Crest Mounted Radial Gates – Pukaki Dam (provided by Meridian Energy)

Figure 6.13: Orifice Radial Gate – Clyde Dam (provided by Contact Energy)

Figure 6.14: Vertical Lift Wheel Gate

Figure 6.15: Flap Gate at Paerau Weir (provided by TrustPower

Figure 6.16: Rubber Dam

All gates and valves that fulfil dam safety functions should be designed to criteria which are consistent with the PIC of the dam. As such, in addition to fulfilling their design duties during normal, unusual and extreme loading conditions, they should also be capable of safely withstanding the loading conditions that occur during such events and be operational following any such events. The following recommendations relate to the design of gate and/or valve systems that fulfil dam safety functions. Recommendations relating to the operation, inspection, maintenance and testing of gates and/or valves that fulfil dam safety functions are included in Module 5 (Dam Safety Assurance).

- In addition to normal, unusual and extreme loading conditions, all designs should include the consideration of other loading conditions including equipment malfunction (e.g. hoist rope failure, seized trunnion or roller bearing, jammed gate), gate over-pour, floating debris and sunken log effects, and flow induced vibrations. ICOLD Bulletin 102 includes a detailed discussion on flow induced vibrations and guidelines to limit flow induced vibrations.
- All gates should be designed and detailed to limit deformations. Excessive gate deformation during extreme loading conditions could result in gate jamming and severe loss of sealing. In low level gates excessive leakage could limit access for unjamming operations.
- All gate designs should incorporate material durability in the critical components (e.g. bearings, bushes, pins, etc) and the avoidance of corrosion opportunities overall.
- All structural arrangements should facilitate ready access for the operation, inspection, maintenance, repair or replacement of gates, valves and their components. Due attention should be paid to the necessity for safe access under emergency conditions and during exceptional circumstances (e.g. storm, failure of electricity supply, severe winter conditions, etc).
- Upstream facilities (e.g. bulkheads, guard valves) should be provided to allow the inspection, maintenance and repair of all gates and valves that fulfill dam safety functions. Similar isolation facilities should be provided on the downstream side where access is not readily available due to elevated tailwater conditions. These facilities are not primary flow control devices and will generally only be operable under no-flow conditions. Bulkheads should not be assumed capable of closure against flow unless specifically designed for such an operational scenario. An example of a bulkhead is shown in Figure 6.17.

Figure 6.17: Upstream Bulkhead

- The design should include the completion of a study to assess the potential for failure of gates, valves and their operating and/or control systems, including multiple failures, and the likely effects of such failures during extreme loading conditions. For example, gate unavailability during an extreme flood event could initiate an overtopping failure of an embankment dam or sufficient toe erosion to initiate a sliding failure of a concrete dam.
- Appropriate back-up systems should be included to ensure reliable operation during all loading conditions. Back-up systems could include gate and equipment redundancy (e.g. multiplicity of gates, power supplies, electric motors, pumps, hydraulic pumps with petrol/diesel motor drives), local and remote control, and automatic triggering of safety devices.

- All gates and valves that fulfil dam safety functions and can only be electrically operated should be connected to at least two independent sources of power supply.
- Adequate lighting should be provided for safe access and operation of the facilities at night.
- All control systems and associated equipment (e.g. control cabinets, cabling, batteries) should, where feasible, be located where the rupture of water-carrying conduits cannot threaten their integrity. If this is not feasible, appropriate protection systems should be provided to ensure the operation of the equipment is not adversely affected (i.e. provide fail-safe operation). Any facilities housing control systems and associated equipment must not collapse and prevent equipment operation post-earthquake.
- All associated power supply cables, hydraulic piping, and control and communication cables should be designed and detailed in a manner which ensures their availability following an extreme event (e.g. adequately supported to withstand the SEE, looped connections across vertical contraction joints which may move during a large earthquake).
- Primary and backup power supply cables to gate hoist motors should be routed along separate paths.

The design of all gates and valves that fulfil dam safety functions should be guided by fundamental requirements such as redundancy, diversity, segregation, defence in depth, fault tolerance, and fail to a safe condition. Safe access to the gates, valves and their operating equipment also needs consideration.

Gates and valves that fulfil dam safety functions typically have design lives that are significantly less than the design life of the dam or appurtenant structure. Accordingly, all such gates and valves should be designed and detailed in a manner that enables easy inspection, maintenance, testing and repair, and replacement when they are no longer capable of reliably fulfilling their design functions.

6.11.6 Design details

There are a number of design details for appurtenant structures that can affect dam safety and warrant careful consideration during their detailed design. Design details associated with conduits through and beneath embankment dams, and interfaces between concrete structures and embankment dams are discussed in section 6.5.5. Additional design details associated with conduits, ungated and orifice spillways, and low level outlet facilities are discussed in a number of ICOLD bulletins and are outlined below.

Conduits

- Where conduits are installed through or beneath dams they should be designed for non-pressurised flow conditions. They should also incorporate upstream bulkhead facilities, to isolate the conduit from the upstream reservoir, and be of a sufficient size to enable inspection and the completion of any necessary repairs.
- Where pressurised conduits are installed through or beneath embankment dams, preferably only for Low PIC dams less than 10m in height, they should incorporate suitable facilities for the detection and monitoring of any conduit leakage, and an upstream valve to enable maintenance or replacement of the outlet control valve. They should also be designed to withstand the internal pressures associated with rapid closure of the outlet control valve and be pressure tested to 150% of the maximum operating pressure prior to backfilling.
- Where pressurised conduits are installed through concrete dams they should be steel lined and incorporate an upstream bulkhead facility to isolate the conduit from the upstream reservoir. The steel lining should be designed to withstand the maximum negative and positive internal pressures associated with rapid start up and closure of the downstream control facility (i.e. valve or turbine).

Ungated and Orifice Spillways

Examples of ungated and orifice spillways are shown in Figures 6.18 and 6.19.

Figure 6.18: Ungated Spillway – Upper Mangatawhiri Dam (provided by Watercare Services)

Figure 6.19: Orifice Spillway – Lower Huia Dam (provided by Watercare Services)

- Where local conditions can affect the reliability of gate operation, consideration should be given to the adoption of an ungated spillway. Local conditions that can affect the reliability of gate operation include a remote site, difficult site access, a lack of skills for gate operation and maintenance, debris accumulation, reservoir slope instability and short peaking times for flood events. If an ungated spillway has piers and a bridge, these must be positioned to provide sufficient flow passage and minimize the risk of debris accumulation.
- Wherever it is practicable an auxiliary spillway and discharge channel are recommended to be sited clear of an embankment dam to give extra protection for extreme events and/or failure of the main spillway to take all of its design flow. Where an auxiliary spillway is provided the design discharge for the primary spillway is usually less than the IDF. However, both facilities, in combination, must be capable of safely discharging the IDF.
- Auxiliary spillways with fusing mechanisms to initiate discharge require special care in their design. The sizing and sequencing of the fuse elements require careful consideration. In addition, the incremental consequences of fuse elements breaching and their effects on the downstream area need to be evaluated to determine the height of the fuse elements that would provide an appropriate balance between downstream consequences and flood passage capability. Fusing mechanisms must be reliable and vehicles should not be allowed to travel across fuse plug embankments. Pilot channels or similar features that encourage erosion should be installed in fuse plug embankments to enhance their reliability. An example of an auxiliary spillway with a fusing mechanism is shown in Figure 6.20.

Figure 6.20: Auxiliary Spillway – Opuha Dam (provided by Opuha Water)

- Auxiliary spillways and discharge channels should be located and/or protected to minimise the potential for erosion to threaten the safety of a dam, to result in excessively high downstream discharges, and to result in excessive downstream environmental damage.
- For all spillways the likelihood and consequences of spillway blockage should be carefully evaluated. This is particularly important for orifice spillways with small inlet structures (e.g. tunnel spillways, morning glory spillways) and service spillways for flood detention dams. Usually, where there is a likelihood of spillway blockage, the only option is to provide an auxiliary spillway and discharge channel. An example of a morning glory spillway is shown in Figure 6.19.
- Where flow conditions in approach channels are unsymmetrical, spillway facilities differ from conventional spillway designs, or energy dissipation facilities incorporate flip buckets or nappes discharging into scour holes, hydraulic modeling should be completed to confirm design assumptions and finalise design details (e.g. head/discharge characteristics, chute wall heights, energy dissipation details, flow conditions downstream of energy dissipation facilities). In some cases computational hydraulic modeling will be sufficient (e.g. head/discharge characteristics, chute wall heights); however, physical hydraulic modeling will be necessary for the detailed design of spillways with unsymmetrical inflow conditions, unconventional energy dissipation facilities and flip bucket shapes, and the determination of stable scour hole dimensions.
- Bridges located above spillway gate structures should be suitably restrained to ensure they are operational following the SEE and to ensure they do not impede gate operation following the SEE. Spillway bridge performance is especially important if spillway operating equipment required for post-SEE operation is fixed to the bridge. In addition, any gantry cranes located close to spillway gate structures should be tied down to prevent overturning during the SEE.
- Dividing walls and piers in spillway gate structures should be designed for the cross-valley component of the SEE earthquake loading. Small deformations of piers can exceed spillway gate side tolerances and result in gate jamming. An example of a gate structure with piers is shown in Figure 6.12.
- Ideally, any necessary changes in the directions of spillway chutes should be included where subcritical flow conditions occur. If changes in alignment are necessary where supercritical flow conditions occur, they should be large radius bends and should be designed to ensure the resulting shockwaves are contained within the chute.
- Particular attention should be given to the adverse effects of high velocity flow, turbulence and abrasion. High velocity flow and turbulence effects include cavitation, the initiation of high uplift pressures beneath slabs, and slab vibration. Abrasion effects, which are normally limited to low level orifice spillways, can result in sufficient concrete loss to necessitate the completion of concrete repairs. ICOLD Bulletins 58 and 81 provide guidelines for the effective control of cavitation damage, and the design of chutes/tunnels and energy dissipation facilities.
- Spillway outlet tunnels beneath or adjacent to dams should be designed for non-pressurised flow conditions.

- It is important to consider the effects of high spillway discharges on the safety of a dam. Where spillways are expected to discharge high flows over long periods of time, severe damage can occur and affect the safety of a dam. In such cases it is prudent to adopt conservative design details. Conversely, where spillways are expected to discharge high flows for short durations and will not affect the safety of a dam, design details can be less conservative and any necessary repairs or protective works can be undertaken following flood events.
- Care is required in the design of spillway features to ensure spillway discharges are not adversely affected by physical impediments (e.g. the bottoms of gates in their fully open positions, stoplog storage facilities, bridges, rails, walkways) and high tailwater conditions.
- Tailwater conditions, which affect the design and performance of energy dissipation facilities, need careful evaluation taking into account the potential for long-term changes that could result from modified downstream river conditions.

Low Level Outlet Structures

An example of a low level outlet structure in operation is shown in Figure 6.21.

- For Medium and High PIC dams, the necessity for a low level outlet facility that enables the reservoir to be lowered in a potential dam safety emergency should be considered, particularly where embankment dams are located in the vicinity of active faults. If a low level outlet is not installed for reservoir dewatering, then the ability of other facilities (e.g. deep spillway gates, penstock intake structures and water supply outlets) to provide sufficient dewatering in a potential dam safety emergency should be considered. The risk posed by the remaining pool after reservoir lowering (i.e. the likelihood and consequences of a dam failure following the reservoir lowering) needs to be understood. An understanding of the capability to lower and control the reservoir level under post-SEE conditions is essential for Medium and High PIC dams.
- The design of a low level outlet facility should be such that it does not compromise the safety of a dam and, as such, the recommendations outlined above for conduits and orifice spillways are also applicable to low level outlet structures.

Figure 6.21: Low Level Outlet Structure – Clyde Dam (provided by Contact Energy)

- Low level outlet facilities often incorporate intake/outlet towers which can be free-standing on an enlarged base or foundation mat, partially embedded within embankment dams or structurally tied to the upstream faces of concrete gravity dams. Examples include the shafts of morning glory spillways and water intake towers. The failure of an intake/outlet tower, during or following a large earthquake, could result in the uncontrolled release of a reservoir and, as such, all intake/outlet towers should be designed to accommodate SEE loadings. ICOLD Bulletin 123 provides guidelines for the seismic analysis and design of intake/outlet towers. The partial embedment of intake/outlet towers in embankment dams is not recommended for new dams because of the increased risk of dam failure if slope displacements of the dam were to occur during a large earthquake.

7. Performance monitoring

7.1 Introduction

Dam safety does not only depend on proper design and construction, but also on acceptable long-term performance.

Consistent, reliable visual inspection of dams is considered to be one of the most important tools for monitoring long term performance. However, where particular design assumptions need to be validated, potential failure modes have been identified that require monitoring, or the consequences of failure are high, extensive instrumentation may be necessary for the monitoring of dam performance. The need for instrumentation to check the validity of design assumptions and monitor the performance of a dam or appurtenant structure, and the ability to monitor dam performance (e.g. it can be difficult to monitor seepage at dam toes which are founded on river gravels or inundated by tailwater conditions), should always be considered in the design of a new dam or the rehabilitation of an existing dam. In some cases, where the design assumptions are conservative and the consequences of failure are minor, the expense associated with the installation and ongoing monitoring by instrumentation may be unwarranted.

In addition to the above, instrumentation for existing dams and appurtenant structures is usually less than that for new dams and appurtenant structures because their performance under normal loading conditions, and some unusual loading conditions, has been established and the retrofitting of instrumentation can be expensive.

Where instrumentation is installed it should:

- Not be used as a replacement for regular visual inspections but as an aid to augment the ongoing assessment of dam performance.
- Be appropriate to the dam type and enable the monitoring of identified potential failure modes.
- Be simple, reliable, robust and, where warranted, sensitive with sensors that are easy to install, calibrate, maintain and operate.
- Be installed in a manner which does not adversely affect the integrity of the dam (e.g. the drilling of boreholes and the grouting of piezometers within a dam core can leave potential weaknesses in the core if incorrect techniques are used – refer section 5.2).
- Include sufficient instrumentation for the measurement of parameters critical to dam safety, and incorporate some redundancy to allow for instrument failures and the cross-checking of results.
- Include, where appropriate, an automated monitoring system for the more frequent monitoring of key dam safety parameters such as reservoir water level, piezometric levels, and seepage flows and turbidity levels. ICOLD bulletin 118 includes a discussion on automated monitoring systems and their application to dam safety.
- Where automated monitoring systems are included, manual monitoring backup systems should be available to provide calibration and enable the monitoring of performance in the event of system failure.
- Include the establishment of warning and alarm levels for the items being monitored, beyond which action is taken to review and ensure the continued integrity of the dam.

ICOLD Bulletins 104, 118, 129, 138, 141 and 158 discuss instrumentation objectives and various instrumentation techniques. Instrumentation systems for the monitoring of dam performance are fully detailed in the literature (e.g. FERC (1993), Fell at al (2005)) and technical data sheets produced by instrument manufacturers).

The measurement of reservoir or pond level and, where appropriate, earthquake ground motions is common for embankment dams, concrete dams and tailings dams. The following subsections provide an overview of typical instrumentation systems that can be installed to verify design assumptions and assist in monitoring the long term performance of embankment dams, concrete dams and tailings dams. Guidelines for the monitoring of long term performance and the interpretation and reporting of monitoring results are included in Module 5 (Dam Safety Management).

7.2 Embankment dams

Instrumentation typically installed for monitoring the behaviour of embankment dams includes:

- Observation wells and piezometers for the measurement of groundwater levels in the abutments, and piezometric pressures in the embankment and its foundation.
- Weirs and other measurement facilities for the monitoring of seepage flows.
- Surface monuments for the monitoring of horizontal movements and settlements.

Observation wells and the types of piezometers installed in a dam and its foundation should be appropriate for the ground conditions in which they are installed and for the required characteristics of piezometric response (e.g. time lag). Advantages and limitations of the available types are outlined in Table 7.1.

Table 7.1: Advantages and Limitations of Common Observation Wells and Piezometers

Type	Advantages	Limitations	Can be manually read?	Can be readily rehabilitated?
Observation Well	Simple device, inexpensive, easily automated	Applicable only in uniform materials, not reliable for stratified materials, long time-lag in impervious soils	Yes	Yes
Standpipe Piezometer	Simple device, inexpensive, reliable, easily automated, can be subjected to rising or falling head tests to confirm function	Long lag-time in impervious soils, porous tips can clog due to repeated inflow and outflow, not appropriate for artesian conditions, can be damaged by consolidation of soil around standpipe	Yes	No
Single Tube Piezometer	Same as for open standpipe piezometer	Same as for open standpipe piezometer but appropriate for artesian conditions	Yes	No
Twin-Tube Hydraulic Piezometer	Simple device, moderately expensive, reliable, short time-lag	Cannot be installed in a borehole, generally cannot be retrofitted, moderately complex monitoring and maintenance, periodic de-airing required, moderately complex to automate	Yes	No
Pneumatic Piezometer	Moderately simple transducer, moderately expensive, reliable in the medium term, very short time-lag, elevation of readout independent of tip elevation and piezometric level	Moderately complex monitoring and maintenance, dry air and readout device required, sensitive to barometric pressure, performance can deteriorate after many years, moderately expensive readout, complex to automate and cannot be automated over long distances	No. Requires a readout unit	No
Vibrating Wire Piezometer	Moderately complex transducer, simple to monitor, very short time-lag, elevation of readout independent of tip elevation and piezometric level, output signal can be transmitted over long distances, easily automated	Lightning protection recommended, sensitive to temperature and barometric changes, risk of zero drift but some models available with in situ calibration check	No. Requires a readout unit or datalogger	No

Source: Modified from FERC (1993)

Dual piezometers, or individual piezometer installations, isolated in the core and in the foundation beneath the core (upstream and downstream of any impermeable cutoff) provide information which can be used to establish general seepage behaviour through and beneath a dam. Where these instruments connect directly with a seepage path, recorded piezometric pressures will provide an insight into hydraulic gradients and may indicate the occurrence of internal erosion.

Weirs, parshall flumes and calibrated containers are commonly used for the monitoring of seepage flows. The advantages and limitations of each flow measurement device are as follows:

- Weirs are simple, reliable, inexpensive and require little maintenance. They have the capability to capture sediment being transported by seepage flows and thus allow the identification of developing internal erosion features. However, they require a restriction to the flow channel and a sufficient elevation change to prevent the tailwater from affecting the weir discharge.
- Parshall flumes are simple, reliable and require little maintenance. However, they do not have the capability to capture sediment and they are likely to be more expensive that weirs to install. They should only be used where seepage volume is required and internal erosion is not a concern.
- Calibrated containers are reliable for low flows and they are inexpensive. However, they require a free falling flow, they are inaccurate for large flows and they are labour intensive.

Surface monuments are usually established on the abutments, along the crest and on the downstream slope of an embankment dam for the monitoring of dam deformations. Care needs to be taken to ensure that the monuments are founded on materials that are not susceptible to shrinkage and swelling. A wide variety of survey techniques can be used for the monitoring of dam deformations:

- Alignment surveys are the simplest and most accurate method for the monitoring of horizontal deformations on straight dams.
- Levelling surveys are the simplest and most accurate method for the monitoring of vertical deformations.
- Triangulation and trilateration surveys, using theodolites and electronic distance measuring instruments, are frequently used for the monitoring of horizontal and vertical deformations where measuring points do not lie along a straight line or where lines of sight are obstructed. While such surveys are highly accurate they require an experienced survey team with specialist survey equipment, and involve relatively complex calculations.

In some cases it may be necessary to install additional instrumentation for the monitoring of foundation settlement and embankment consolidation during and following construction (e.g. internal settlement gauges, borehole inclinometers), deformations and joint openings in concrete face slabs and plinths during construction and commissioning (e.g. joint meters), and seepage water characteristics following the identification of increased seepage flows (e.g. seepage turbidity levels, seepage water temperatures).

7.3 Concrete dams

Instrumentation typically installed for monitoring the behaviour of concrete dams includes:

- Observation wells and piezometers for the measurement of groundwater levels in the abutments, uplift pressures at the dam/foundation contact and, if necessary, uplift pressures beneath potential failure surfaces in the foundation and blocks or wedges in the abutments.
- Weirs for the monitoring of seepage flows from internal and foundation drains.
- Survey points for the monitoring of dam deformations.
- Internal deformation instruments to measure tilt, rotation and horizontal deformation.

Piezometers installed from within drainage galleries or from downstream toes of concrete gravity dams enable the confirmation of uplift assumptions adopted during the design of the dam, the provision of uplift pressures for incorporation in stability studies, and the identification of any reductions in the efficiency of drainage systems. In existing concrete gravity dams where piezometers are not installed, uplift pressures can be measured at selected drains. The monitoring of uplift pressures beneath thin arch and buttress dams that are not founded on slabs is not normally necessary as uplift pressures usually have a minimal effect on dam stability.

Weirs and calibrated containers are commonly used for the monitoring of seepage flows, and their advantages and limitations are as outlined in section 6.2. In concrete gravity dams it is good practice to divide the seepage monitoring system into separate catchments to enable the location of any seepage increases or decreases. Reductions in seepage flow may indicate reductions in the efficiency of underdrainage systems.

In concrete gravity dams any loss of structural integrity will usually manifest itself at the vertical contraction joints between adjacent dam blocks. Because of the monolithic behaviour of concrete arch dams, any loss of structural integrity will usually manifest itself as horizontal displacements along the arch. In recognition of the above, deformation systems usually include:

- Survey points along the crests or in the galleries of concrete gravity and buttress dams for the monitoring of upstream/downstream deformations and vertical deformations. Alignment surveys are usually adopted for the monitoring of upstream/downstream deformations, and levelling surveys are usually adopted for the monitoring of vertical deformations.
- Joint meters across vertical contraction joints in concrete gravity dams. Simple scribe marks can be made across all monoliths at the surface or in galleries in concrete gravity or arch dams to detect differential foundation displacements that may develop gradually under static loading or in response to earthquake or high flood loadings.
- Survey points along the crests of concrete arch dams for the monitoring of upstream/downstream deformations and, in some cases, survey points on the downstream faces adjacent to the abutments for the monitoring of chord distances.

As stated above for embankment dams, it may be necessary in some cases to install additional instrumentation for the monitoring of dam performance. Examples include plumblines for the measurement of a dam's response to variations in reservoir level and temperature, inclinometers and extensometers for the measurement of movements within the dam foundation, and instruments for the measurement of concrete and reservoir water temperatures.

7.4 Tailings dams

Instrumentation typically installed for monitoring the behaviour of tailings dams during their construction includes:

- Weirs and other measurement facilities for the monitoring of seepage flows.
- Open standpipe or vibrating wire piezometers for measuring the location of the phreatic surface.
- Open standpipe or vibrating wire piezometers for the monitoring of pore pressures in the tailings, embankment and foundation.
- A survey network for the monitoring of horizontal movements and settlements.

Weirs and calibrated containers are commonly used for the monitoring of seepage flows, and their advantages and limitations are as outlined in section 6.2. Seepage flows are normally manually read but can be automated and continuously monitored in a control room.

Manually read open standpipe or vibrating wire piezometers are usually adopted for monitoring the location of the phreatic surface. Standpipes can be installed on the ground before any tailings are placed and additional pipe added as the tailings rise. Because of the anisotropic permeability associated with the method of deposition, the elevation of the phreatic surface indicated by a standpipe based on the ground is usually lower than the actual surface. More accurate positions of the phreatic surface can be obtained from standpipes installed in the tailings with their intake filters placed a short distance below the position of the phreatic surface indicated by the deeper standpipes.

Pore pressures can be measured by open standpipe piezometers if the pressures are not sufficiently high to result in water level rises to the tops of the standpipes. Where pore pressures are high they are usually monitored from a remote location using vibrating wire piezometers. Vibrating wire piezometers are precise, they can be easily read and automatically recorded, and they are easily installed. In addition, they are not affected by electrical disturbances other than voltage overloading from lightning, against which they should be protected.

Vertical and horizontal deformations of tailings dams constructed by the upstream method are usually monitored along the crest of the starter dam and on the berms of the downstream slope of the tailings dam. Levelling and alignment surveys are usually adopted for the monitoring of deformation; however, more accurate survey methods (i.e. triangulation and trilateration surveys) should always be available to enable the completion of more detailed surveys in a potential dam safety emergency. For tailings dams constructed by the downstream and centreline methods the surfaces of the dam are only provisional before the embankments are raised; however, survey reference points can be placed on the crest of the starter dam and subsequent stages but the monitoring will only be effective for a short time period. More information is included in ICOLD Bulletin 104.

Monitoring of the installed instrumentation during the latter stages of construction of a tailings dam normally continues for closed tailings dams; however, the monitoring frequencies usually become progressively less as the instrumentation demonstrates satisfactory long-term performance of the dam. For tailings dams constructed by the downstream and centreline methods, survey reference points are usually established on the crest and downstream face of the completed dam to enable the monitoring of deformation.

8. Design processes

8.1 Feasibility studies and design of new dams

The dam design process is typically undertaken in a series of stages which include:

- A prefeasibility (or concept) study to identify a preferred dam site for development. The work completed is predominantly office based and utilises existing information that is available in the public domain and from a variety of central and local government agencies (e.g. topographical maps, geological maps, hydrological data).
- A feasibility study to establish the technical and economic feasibility of development at a preferred dam site. The work usually includes field activities (e.g. geological mapping, drilling), laboratory testing of potential construction materials, and office studies to develop a preferred general arrangement for the dam and an estimated cost for its development.
- A preliminary design to address any significant issues identified during the feasibility study, develop preliminary design details for the dam, and refine the estimated cost for its development. The resulting documentation is usually sufficient to support an application for water permits and land use consents.
- A detailed design to resolve all outstanding issues, complete the detailed design for the dam, and prepare all necessary documentation (i.e. drawings, technical specifications, contract documents) for its construction. The resulting documentation should be sufficient to support an application for building consents.

As outlined in section 3, each stage of the design process should be undertaken by personnel with appropriate backgrounds of experience. Significant benefits can result from the early engagement of peer review services for the design of Medium and High PIC dams, and the later engagement of experienced contractors to assist in the identification of construction issues and risks, the assessment of construction methods (e.g. diversion arrangements) and the estimation of construction costs.

The design of a dam usually reflects precedent designs, the results of analytical studies, and the experience and personal preferences of the Designer. While alternative dam designs are often possible for a particular dam site, it is most important that the adopted design reflects the characteristics of the project and the dam site. Project and dam site characteristics that can strongly influence the design include:

- The function of the dam and its proposed operating regime. The reservoir for a hydroelectric scheme usually has a small operating range while the reservoir for a water supply scheme usually has a wide operating range. Impoundment upstream of a flood detention dam only occurs during large flood events.
- A requirement for staged construction to reflect a projected growth in water demand.
- The length of the season available for dam construction. Embankment dams typically have shorter construction seasons than concrete dams.
- The availability and quality of local materials for the construction of a dam. Some sites may have large resources of materials suitable for dam construction, while at other sites the resources may be limited.
- The size and shape of the dam site. Narrow dam sites with steep walls may necessitate special design provisions for an embankment dam or, if other site characteristics are appropriate, the development of a concrete dam.
- The local geology and the quality of the dam foundation. A site with a shallow rock foundation may require little foundation treatment in comparison to that necessary for a site with a deep alluvial foundation.
- The climate and likely weather conditions during the construction of the dam. Fine grained soils require dry weather for construction while coarser grained soils and rockfill can usually be placed during wet weather.
- Diversion requirements during construction. If diversion capacities are exceeded by a flood during construction, embankment dams present a far greater hazard to downstream communities and infrastructure than concrete dams.

8.2 Design of rehabilitation works

The design of rehabilitation works to address identified potential failure modes or dam safety deficiencies would typically be undertaken in a series of stages which include:

- A thorough evaluation of the existing risks and the necessity for the proposed rehabilitation works.
- A preliminary design to identify and consider rehabilitation alternatives, develop preliminary design details for the preferred remediation alternative, and complete an estimated cost for its completion. The resulting documentation should be sufficient to support any necessary applications for variations to existing water permits and land use consents.
- A detailed design to provide the necessary risk reduction, complete the detailed design for the works, and prepare all necessary documentation (i.e. drawings, technical specifications, contract documents) for their construction. The resulting documentation should be sufficient to support an application for building consents.

Personnel requirements for the design of rehabilitation works are similar to those outlined in sections 3 and 8.1.

It is most important that the final rehabilitation works design properly addresses the identified dam safety deficiency, and that the solution is compatible with the characteristics of the existing dam and the dam site. Issues that can strongly influence the design of rehabilitation works for any dam include:

- The effects of the rehabilitation works on existing consents for scheme operation. For example, the completion of the rehabilitation works may necessitate a reduction in the consented reservoir level and variations in the consented discharges to the downstream river.
- The ability of the dam to fulfil its intended function during the completion of the rehabilitation works. For example, the lowering of a reservoir level may have a significant impact on the ability of an Owner to meet bulk water supply targets, or may significantly reduce the head available for electricity generation.
- The risk to the safety of the dam during the completion of the rehabilitation works. For example, the rehabilitation of toe drainage facilities in an embankment dam could affect the stability of the downstream shoulder, and the rehabilitation of a spillway facility could markedly reduce the ability of the dam to safely manage flood events during the construction period.
- The time and cost required for completion of the rehabilitation works. To minimise the effects of rehabilitation works on normal business operations, a dam Owner may consider a rehabilitation option that results in partial reduction of the risk rather than an option that results in full mitigation of the risk.
- The availability and quality of local materials for the construction of the rehabilitation works. Material shortages at some dam sites could significantly influence the scope and characteristics of the rehabilitation works.

8.3 Design oversight and amendments during construction and commissioning

Design details should be complete and constructible, areas of uncertainty should be identified and contingent details in place before construction commences. Dam design is never complete until the dam or dam rehabilitation has been constructed and all facilities have been commissioned.

The Designer must remain alert throughout construction for any changes in conditions or properties from those assumed in the design. For example, foundation excavation may expose important foundation features that were not identified during the site investigation, the quantities and qualities of the borrow materials may be more variable than anticipated in the design, groundwater inflows during construction may necessitate modifications to the designed seepage control measures, and design changes may be necessary to suit a Contractor's preferred construction method. A dam design or rehabilitation must be continuously reviewed and re-engineered during construction to ensure the final design is compatible with the conditions encountered during construction. This is especially true for dam rehabilitation projects where the actual as built conditions found during construction may be different than those presented on available drawings for the original construction.

Any changes to the design necessary to address observed site conditions or Contractor preferences must be completed to the same standards as the original design but, most importantly, must be addressed in a thorough manner to ensure that any changes do not inadvertently create a risk elsewhere. Even small design changes must not be considered in isolation as significant reductions in dam safety can result from a sequence of relatively minor seemingly unrelated modifications. Design changes that materially alter a building consent issued for the construction of a dam or rehabilitation works will require the approval of the Regulator responsible for administering the building consent process.

In the case of tailings dams, construction is normally undertaken in stages with the dam in operation. Detailed design is also undertaken in stages and should take into account the experience obtained during operation, and changes in tailings production and characteristics as well as changes in operating procedures and water management.

Design support is also essential during the commissioning of a dam and its associated hydraulic structures, and the commissioning of any rehabilitation works. The Designer should be responsible for planning the commissioning sequence, preparing all necessary commissioning documentation, ensuring all commissioning personnel are aware of their roles and responsibilities during the commissioning process, monitoring the commissioning process, and reviewing the performance of the dam and its associated hydraulic structures, or the completed rehabilitation works, during and following commissioning. The responsibility for dam safety should remain with the Designer until he/she is satisfied that all structures are safe and performing as intended.

It is essential that the Owner understands the likelihood of design changes during construction and the need for design support during commissioning, with their associated costs, and has appropriate funding in place to support both activities.

8.4 Design documentation

From a dam safety perspective it is most important that a design is translated into clearly understood construction drawings and specifications, and that an appropriate design report is completed which records all design data, philosophies and assumptions, and defines areas requiring re-evaluation or confirmation during construction. Such documentation is required to accompany a building consent application for a dam (refer Module 1).

Construction drawings and specifications must clearly describe any particular requirements to be achieved in areas critical to dam safety. For example, for an embankment dam specific fill materials and compaction requirements may be required adjacent to conduits and concrete structures to minimise the potential for erosion along concrete/embankment interfaces. Typical earthworks specifications for the construction of subdivisions and road embankments are inadequate for the construction of embankment dams. The same applies to concrete dams. For example, specific foundation treatment may be necessary to minimise the potential for erosion along a shattered zone that trends across a rock foundation. While it is not customary practice, consideration should also be given to including a commentary in the construction documents that highlights areas critical to dam safety, the reasons for their specified treatments, and the possible consequences of failing to meet the specified requirements.

Design reports are typically completed at the end of each stage of the design process, whether they are for the design for a new dam or the design of a rehabilitation project. Those completed at the end of the preliminary design should incorporate sufficient detail to support an application for water permits and land use consents, or any variations to existing water permits and land use consents. Those completed at the end of the detailed design should be sufficient to support an application for building consents. The final design report, which should be completed towards the end of construction, should be appropriate to the PIC of the dam and should clearly document all assumptions, criteria and methods adopted for the design of the dam and its associated hydraulic structures or, as appropriate, the design of the rehabilitation works. In many cases it may be sufficient to amend the design report completed at the end of the detailed design and include an appendix that documents any design changes adopted during construction.

The final design report for the design of a new straightforward Low PIC dam designed by precedent will normally be relatively short in comparison to those completed for Low PIC dams designed by empirical methods and those completed for Medium and High PIC dams. However, all final design reports should include:

- A description of the background to the project, the purpose of the dam, and the characteristics of the dam site.
- An assessment of the PIC for the dam and its associated appurtenant structures.
- An assessment of the hazards that can affect the safety of the dam (e.g. floods, earthquake ground motions, reservoir landslides).
- The characteristics of the site geology, the dam foundation, and the materials utilised for dam construction.
- The philosophy adopted for the design of the dam and its associated hydraulic structures, and the criteria and methods adopted for their design.
- The expected performance of the dam and its associated hydraulic structures during normal, unusual and extreme loading conditions.
- The rationale for and a description of any instrumentation installed for the monitoring of dam performance.
- Surveillance and monitoring proposals for ongoing dam safety assurance.
- Relevant appendices (e.g. hydrological data, geological maps, seismic hazard studies, field investigation records, laboratory investigation results).

Similarly, the final design report for the rehabilitation of a straightforward Low PIC dam designed by precedent will normally be relatively short in comparison to those completed for Low PIC dams designed by empirical methods and those completed for Medium and High PIC dams. However, all final design reports should include:

- A description of the purpose and characteristics of the existing dam, the identified dam safety deficiencies, the risks associated with the identified dam safety deficiencies, and the objectives of the rehabilitation works.
- A description of any site specific considerations (e.g. site geology, available materials) or constraints (e.g. timing, flood management during construction, Owner requirements) that influenced the selection and design of the rehabilitation works.
- The philosophy adopted for the design of the rehabilitation works, and the criteria and methods adopted for their design.
- A description of the conditions encountered during the construction of the rehabilitation works.
- The expected performance of the rehabilitated dam during normal, unusual and extreme loading conditions.
- The rationale for and a description of any instrumentation installed for monitoring the performance of the rehabilitated dam.
- Surveillance and monitoring proposals for ongoing dam safety assurance.
- Relevant appendices (e.g. hydrological data, geological maps, seismic hazard studies, field investigation records, laboratory investigation results).

Copies of all key design records, drawings and documentation should be provided to the dam owner at the end of the project.

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MODULE 4
CONSTRUCTION AND COMMISSIONING

Abstract

Dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, operation, assessment and rehabilitation of dams in New Zealand are included in the Parent Document. The Parent Document also includes a glossary of terms used in these Guidelines.

This module provides guidelines for the construction and commissioning of new dams and the rehabilitation of existing dams. While the construction and commissioning of dams involves a wide range of issues and activities, the focus of this module is on those issues and activities that can affect dam safety. The module includes:

- An outline of dam safety risks that should receive close attention during construction and commissioning.
- An outline of the roles and responsibilities of various personnel involved in construction and commissioning.
- A discussion on typical forms of construction contract and the effects that they can have on dam safety.
- A discussion on important issues that should be addressed in planning for construction and commissioning.
- Recommended quality assurance procedures that should be adopted during construction and commissioning.
- Recommendations relating to construction and commissioning documentation and records.

This module includes limited discussion on the role of Regulators in dam safety and reference should be made to Module 1 (Legal Requirements) for a more complete description of their role and responsibilities.

Notice to reader

While this module has been configured to be, as much as practicable, self-contained from a technical perspective, the reader should be conversant with the principles, objectives and limitations expressed in the Parent Document prior to considering the information provided in this or any other individual module.

Document history

Release	Date	Released with
Original	May 2015	Parent and all modules
2023	December 2023	Updates to Parent and Modules 1, 2 and 5

Contents

1. Introduction

1.1 Principles and objectives

The quality of construction and appropriate management of commissioning are important to dam safety. Principle 3 in the Parent Document states that:

Dams and appurtenant structures should be designed, constructed, commissioned, operated and rehabilitated in a manner which ensures they meet appropriate performance criteria.

The objectives of this module are to provide Owners, Designers and Contractors with guidelines for the construction and commissioning of new dams and the rehabilitation of existing dams.

The dam and its associated appurtenant structures will not achieve the level of safety targeted by the Designer if construction materials or the quality of construction do not meet the Designer's requirements. Similarly, the safety of the dam during commissioning will be at risk without appropriate management and Designer involvement throughout the commissioning process.

All of the recommendations included in this module may not be relevant to a particular situation (e.g. increasing the height of a spillway wall). In such cases, the Designer should establish what recommendations included in the module are relevant to his/her project and whether additional safeguards should be implemented during construction and commissioning to ensure the completed project is consistent with the design intent.

1.2 Scope of module

The focus of the module is on those issues and activities that can affect dam safety and, as such, the material presented in the module does not cover all issues and activities associated with construction and commissioning. The module addresses:

- The roles and responsibilities of personnel during construction.
- Dam safety risks associated with alternative types of construction contracts.
- Planning and programming of construction works which can affect dam safety.
- Quality control procedures to ensure dams are constructed in accordance with the design requirements.
- Management and authorisation of design changes that occur during construction.
- The importance of good construction records.
- The roles and responsibilities of personnel during commissioning.
- Procedures and practices for the commissioning of dams.
- The management of commissioning activities.
- The importance of good commissioning records.

A list of reference documents is included at the end of the module to assist the Owner, Designer and Contractor in addressing dam safety risks during construction and commissioning.

2. Construction

2.1 Dam safety risks

Dam safety risks that may occur during construction, or are spawned during construction and may arise at a later date, may be due to such causes as inappropriate management of catchment inflows, a lesser standard of construction than specified, unauthorised changes to the design during construction, and the introduction of specific construction defects. The management of catchment inflows during construction is addressed in Module 3. The remaining dam safety risks during construction can be largely managed by:

- Engaging a Contractor who has a background of experience appropriate to the PIC and complexity of the dam, and is committed to achieving the standards of workmanship specified in the contract documents.
- Ensuring that on-site construction supervision resources, quality assurance procedures, Designer representation on-site, technical design support, and peer review services are appropriate to the PIC and complexity of the dam.
- Ensuring that an appropriate form of contract is adopted for the completion of the project.
- Identifying all aspects of construction that are important for dam safety prior to commencement of the project, and ensuring that these aspects are appropriately supervised and inspected by the Designer during construction before they are covered or enclosed by later construction. The identification of all aspects important for dam safety can be accomplished by a pre-construction meeting attended by the Owner, Designer and Contractor dedicated to this purpose, or by completing an assessment of construction related potential failure modes or a risk assessment with representatives of the Owner, Designer and Contractor.
- Recognising that construction will often reveal site characteristics that were not anticipated during the design and having sufficient funds and procedures in place to properly address any necessary additional work or changes that may affect the design.

2.2 Personnel – roles, responsibilities and experience

Depending on the size, type and PIC of the dam, the following key personnel are involved in construction:

- The Owner.
- The Designer supported by Technical Specialists and Peer Reviewers.
- The Project Manager or Engineer to the Contract, and supporting personnel.
- The Contractor, supported by construction and supervision personnel.
- The Regulator.

This section discusses the roles, responsibilities and experience of the personnel involved in construction.

2.2.1 The Owner

Generally the Owner will delegate construction administration to a Project Manager, the Engineer to the Contract or the Engineers Representative. The most important Owner responsibilities related to dam safety are:

- Accepting industry advice as necessary, to ensure that all parties engaged to investigate, design, construct, commission and operate the dam are suitably qualified and have their roles and authorities properly defined.
- Complying with all regulatory requirements, including any requirements specified in conditions attached to consents issued by Regulators.
- Providing the necessary funding to achieve the required quantity and quality of inputs in a timely manner.

2.2.2 The Designer and Technical Specialists (including Peer Review)

The roles of the Designer, with the assistance of Technical Specialists and, if warranted, Peer Reviewers, are to assure that the dam is built in accordance with the approved design and specifications and that any changes implemented during construction do not affect the safety of the dam. The Designer, his/her on-site representative, or Technical Specialists should review all Contractor submittals (refer section 2.2.4) relating to the design to ensure that the proposed materials and methodologies are consistent with the design intent.

The continuity of Designer, Technical Specialist and Peer Reviewer inputs from the design process through construction is essential for Medium and High PIC dams. This continuity is important as it enables actual site conditions to be evaluated against design assumptions, and the determination of whether any design changes are necessary for the actual site conditions. Guidelines for on-site Designer involvement during the construction of new dams are listed in Table 2.1.

Table 2.1: Guidelines for On-Site Designer Involvement during Construction of New Dams

PIC of Dam	Recomended On-Site Designer Involvement
Low	On-site inspections should be completed by an experienced dam engineer at the commencement of construction, at critical times during construction and whenever observed conditions are different from those assumed in the design. The inspections should be sufficient to ensure: Proper foundation preparation prior to commencing dam construction. Embankment materials to be used are consistent with the design assumptions. Proper placement of any filter and drainage zones in embankment dams prior to them being covered by dam construction. Embankment or concrete dam construction is consistent with the design assumptions. Proper construction of any conduits that pass through an embankment dam and any interfaces between the embankment dam and concrete structures.
Medium	Full time on-site representation is recommended. The on-site design representative should have experience in the design and construction of Medium or High PIC dams. On-site inspections should be thorough, completed by an experienced dam engineer and not limited to the items listed above for Low PIC dams. The Designer should have adequate authority to order additional work necessary for dam safety.
High	Full time on-site representation is recommended. The on-site design representative should have experience in the design and construction of High PIC dams. On-site inspections should be comprehensive, completed by an experienced dam engineer, and not limited to the items listed above for Low PIC dams. The Designer should have adequate authority to order additional work necessary for dam safety.

The guidelines listed in Table 2.1 are also applicable during the refurbishment of an existing dam when the refurbishment work affects dam safety.

Where dam safety related risks are demonstrably low, full time on-site representation may not be necessary for new; Medium PIC dams, or refurbishment works at Medium or High PIC dams. Similarly, provided dam safety related risks are low, reduced representation may be appropriate during certain stages of a dam's construction, or where dams are constructed progressively over an extended period (e.g. Tailings Dams). Where a lesser level of on-site representation is deemed appropriate, the Designer should prepare a programme of on-site representation requirements, and provide this to the Owner and Contractor, in advance of construction works beginning.

The Project Manager, the Contractor, and the support team (construction supervisors, quality control inspectors and field technicians) must have a good understanding of the critical design issues prior to construction commencing. While the specifications and drawings need to identify the key issues, the Designer should explain the key issues to all site personnel in a contract meeting and provide any necessary personnel training prior to the commencement of construction. The Designer should also attend all subsequent and relevant construction meetings to ensure that changes are not being made without the Designer's knowledge.

The Designer should also provide design criteria for, and approve, all engineering design work completed by the Contractor for the permanent works and temporary works that could affect the quality of the permanent works or are incorporated within the permanent works. The Designer should also approve the decommissioning of any temporary works that could affect the quality of the permanent works.

2.2.3 The Project Manager or Engineer to the Contract (including Support Personnel)

The Project Manager is defined here as the person responsible, on behalf of the Owner, for ensuring that the construction work is carried out in accordance with the contract design and specifications. While the Designer is the Owner's technical representative, the Project Manager is the Owner's administrative representative on the project.

In terms of dam safety, the Project Manager's role will be to provide an effective administrative link between the Owner, Contractor and Designer, provide advice on any changed conditions, manage a change control process, and ensure that the dam is constructed in accordance with the design intent. The Project Manager will normally also be responsible for contract administration and may fill the role of Engineer to the Contract under traditional forms of contract (except for the NEC3 Engineering and Construction Contract, which has no Engineer). However, it is important that any administrative responsibilities do not adversely affect the ability of the Project Manager to fulfil his/her technical responsibilities that relate to the safety of the dam. Depending on the project, the Project Manager may have a support team ranging from contract inspectors, quality control inspectors and field technicians to full-time specialists. These persons may be provided by the Designer.

For Low PIC dams the Designer may also fulfil the role of Project Manager. For Medium and High PIC dams the Project Manager may be an appointee of the Designer's company to provide the highest possible level of continuity and communication, and avoid potential conflicts of view and approach which could result in inappropriate actions being taken in areas of critical importance. In design-build contracts the Project Manager may be an independent employee of the Contractor, with sufficient technical expertise to liaise with the Owner, Designer and the Contractor. If the Owner chooses to appoint an independent Project Manager, then the Designer should be satisfied that the appointed Project Manager will fill the role to the required standards.

The experience of the Project Manager is important. Generally the Project Manager should have experience in the construction of a similar dam or in the types of construction which substantially aggregate to the work involved in the construction of the dam. The experience of the Project Manager's support team is also important. For Medium and High PIC dams the personnel in the support team should have experience in the types of construction work involved in the construction of the dam.

Communication skills and an ability to deal co-operatively with the Contractor are also important. If confrontational situations develop and remain unchecked, the risks of something going wrong will be increased. The ability to understand and follow design specifications is also important, so that any features or changes which may impact on design assumptions or criteria can be recognised and brought to the Designer's attention.

2.2.4 The contractor

The Contractor clearly has a vital role to play in achieving a safe dam. In all cases the Contractor must be suitably qualified in terms of personnel, resources, attitude and relevant experience. It is most important that all parties recognise that dam construction has many quality and durability requirements that are not essential for road or building construction, and that these differences are understood by the construction workforce.

It is preferable that the recommended experience requirements for Contractors listed in Table 2.2 are available. There will be cases however when contractors with the necessary experience in dam construction are not available, are too expensive to engage, or are inexperienced in a specific methodology to be employed during construction. While this situation does not preclude using contractors with lesser experience, the Contractor should be able to demonstrate that his/her proposed personnel have the necessary generic attributes to successfully carry out the works in accordance with the design requirements. This might be achieved by engaging key construction experts from outside the Contractor's organisation to ensure critical activities are correctly performed. The engagement of a Contractor with limited experience in dam construction should be balanced by increased on-site supervision and increased site inspections by an experienced dam engineer.

Table 2.2: Guidelines for Experience Requirements for Contractor

PIC of Dam	Recommended Experience Requirements for Contractors
Low	The Contractor should have experience in the construction and successful commissioning of similar Low PIC dams. On-site construction should be managed by a representative of the Contractor with experience in the construction of similar Low PIC dams.
Medium	The Contractor should have experience in the construction and successful commissioning of similar Low or Medium PIC dams. On-site construction should be managed by a representative of the Contractor with experience in the construction of similar Low or Medium PIC dams.
High	The Contractor should have experience in the construction and successful commissioning of similar Medium or High PIC dams. On-site construction should be managed by a representative of the Contractor with experience in the construction of similar Medium or High PIC dams.

The Contractor should have an understanding of the design and should be sufficiently experienced to detect when variations to specified procedures are necessary or when special attention is required to address a potential dam safety deficiency (e.g. foundation treatment, material selection and placement, filter manufacture and testing, concrete manufacture and testing).

Pre-construction Contractor submittals or method statements provide an important mechanism for the Contractor to demonstrate an understanding of the design. These need to be required in the specifications for all important elements of the project and should be reviewed by the Designer to enable any non-compliant methods, equipment or materials to be corrected prior to work commencing. For dams or rehabilitation works that include specialised design solutions or construction techniques (e.g. slurry walls, flat jacks in concrete dams, jet grouting), pre-qualification of contractors may be necessary to ensure the contractors have the competency to satisfactorily complete the works.

Finally, the Contractor's role is integral with that of the Designer in achieving dam safety. The objectives of the Owner can only be achieved with a Contractor who adopts a professional and responsible approach to the construction and participates as part of the overall project development team. In particular this requires the development and maintenance of an open and active working relationship with the on-site representative of the Designer. To achieve this, a conscious effort may be needed in the early stage of the project to gain an understanding of the important dam safety issues. Such understanding is absolutely critical to the overall success of the project.

2.2.5 The Regulator

Regulators are responsible for administering the requirements of the legislation in relation to dams. To satisfy themselves that dams are being constructed in accordance with the requirements of the legislation and any conditions that accompany consents to construct dams, Regulators are likely to require site access for inspections during construction and/or verification from Owners and Designers that specific construction activities have been completed in accordance with the specified design requirements.

Inspection and reporting requirements during construction are matters for each Regulator and will vary according to the size and significance of the dam and the stage of its construction. Consents issued by Regulators may incorporate specific hold points to enable Regulator representatives and their consultants to inspect and sign-off particular construction activities. The specified hold points would depend on the characteristics of the dam, but would most likely correspond with those of most interest to the Designer (e.g. foundation preparation, initial dam construction, pre-commissioning inspection).

Regulators usually require notification of all proposed design changes that materially alter consents issued for the construction of dams or the completion of any necessary remedial works. Regulators will determine if the proposed design change is minor and can simply be recorded as a minor change, or if it is significant enough to warrant an application for an amendment to the consents issued for the construction of a dam.

Obtaining an approval from the Regulator for a significant design change can be time consuming and should be recognised as a construction risk at the commencement of a project. Contingency plans should be formulated to minimise the effects of any such delays on the construction programme.

2.3 Construction contracts

2.3.1 Introduction

Owners should ensure that the administrative and contractual arrangements for the construction of a dam, particularly a Medium or High PIC dam, do not adversely affect dam safety. Dam projects typically include a number of uncertainties (e.g. flood protection during construction, foundation conditions, suitability of available construction materials and construction methodologies). Contract provisions to cover the uncertainties may range from "full recovery by the Contractor of all additional costs and time to meet changes" to "all construction risks being recognised and met entirely by the Contractor without increase in price or time".

There are obvious challenges in both of the above extreme positions. In the first case, an Owner would be concerned about whether or not the changes were really necessary or were cost effective. In the second case, the concern would be that commercial pressures might govern the response to the conditions found, to the detriment of dam safety. To minimise the potential conflicts between the interests of the parties to a contract and to ensure that those that remain do not adversely affect dam safety, all contracts should incorporate an element of construction risk sharing. A schematic illustration of the main contract types available and where the construction risks associated with uncertainties usually lie is shown in Figure 2.1.

Turn key and lump sum fixed price contracts where all construction risks are usually carried by the Contractor, and cost reimbursement contracts where all construction risks are usually carried by the Owner, are not normally appropriate for the construction or rehabilitation of dams where there can be many uncertainties relating to foundation conditions, diversion requirements and material characteristics. Forcing a Contractor to accept a fixed price may lead to eventual bankruptcy and the Contractor going into liquidation. Experience has shown that supposed safeguards, such as guarantees, can be illusory and the Owner may then face a real and significant additional cost to complete the project. Similarly, a cost reimbursement contract can encourage the adoption of inefficient work practices and result in large cost overruns.

Broadly speaking, the most cost-effective form of contract is likely to be one where risk sharing is based on each party's ability to control the construction risk. The best philosophy for risk sharing is that the Contractor should carry the construction risks over which he has control (e.g. his own resources, plant, equipment, any design for which he is responsible, construction activities) and the Owner should carry the construction risks inherent in the project itself (e.g. the hydrology of the catchment, foundation conditions, foundation treatments, general project design). This philosophy is most readily incorporated within measure and value contracts and target price contracts.

Figure 2.1: Main Contract Types and Construction Risk Sharing (Source: ICOLD Bulletin 110)

The simplest form of risk sharing is for the Owner and Designer to identify the areas of construction risk and uncertainty and set tender baseline conditions for the pricing of tenders. The Contractor can then be paid at the tendered rates up to the baseline conditions and, if conditions deteriorate beyond the baseline, variation claims are justified. This concept can be applied to many conditions (e.g. groundwater conditions, weather conditions, foundation conditions, material characteristics, foreign exchange rates).

It should be noted that while there are many models that can reduce the risk to the Owner, the Owner is always exposed to some construction risk. It is therefore prudent for the Owner to maintain an active monitoring role during the contract to measure progress and identify any issues that could affect the cost-effectiveness of the project.

The following subsections provide brief comment on the dam safety risks usually associated with conventional measure and value contracts, where the Owner engages a Designer to complete the large majority of the design, and design-build contracts where the Contractor engages a Designer to complete the large majority of the design.

2.3.2 Design-bid-build-procurement contracts

Procurement using a conventional design-bid-build approach is the most common contract option and New Zealand and overseas contractors are familiar with the contract format. The Designer is contracted to the Owner to undertake the design and following completion of the design, a Contractor is retained by the Owner to carry out the construction.

The Designer is not a party to the construction contract, which may be lump sum, measure and value or a combination of both. So long as the contract documents are equitable to both parties (the Owner and the Contractor) and minimise potential points of conflict, good working relationships exist between the parties to the contract, close attention to detail and workmanship continues throughout the construction of the project, and the contract is managed in a way that results in quick and fair agreement over additional work, the risks to dam safety should be minimal. However, dam safety can be affected by:

- The appointment of a Contractor with inappropriate experience. If the project is too small it will be difficult to attract appropriately experienced contractors; if the project is too large it will discourage specialist contractors whose skills may be needed for the completion of the project (e.g. foundation treatment works). Owners should nominate specialist contractors in the contract documents where they are required for the completion of particular activities that are critical to the safety of the dam.
- The appointment of a Contractor with an insufficient financial resource to withstand project difficulties. To remain solvent such a Contractor may adopt inappropriate construction practices which could result in the introduction of dam safety deficiencies. If the Contractor becomes bankrupt during the project then the project is significantly delayed and the Owner has little or no recourse to resolve an identified dam safety deficiency.
- The use of inappropriate plant or materials in the construction of the works. Designers should require two key items when specifying embankment dam materials and processes – a detailed method statement from the Contractor describing the methodology, plant and materials to be used; and a trial embankment on site using the actual plant and materials to confirm the design assumptions.
- The appointment of an on-site representative of the Designer with insufficient or inappropriate experience. Insufficient or inappropriate experience can result in an inability to identify changed conditions that could affect dam safety, and an inability to identify appropriate solutions to address changed conditions that could affect dam safety.
- Insufficient or inadequate inspections by the Designer to confirm that the design intent is being achieved during construction. It is most important that all hold points requiring Designer inspection and signoff are identified before construction commences, and that all such works are not covered by further construction until appropriate signoffs by the Designer have been completed.
- The Designer having no direct authority to order construction changes to address identified on-site deficiencies. The Designer only has authority through the Project Manager or Owner, which requires the establishment of a close working relationship and strong communication links between the parties. Delays in obtaining approvals for such changes can adversely affect construction progress and dam safety.
- Inadequate consideration of construction risks resulting in damage to the works. For example, unforeseen foundation conditions could result in inadequate foundation clean-up and inadequate stream diversion capacity could result in damage to the dam and delays in project completion.

- Commercial pressures, when construction progress and/or additional costs are deemed more important than dam safety. For example, unforeseen foundation conditions can affect foundation preparation and delay the commencement of embankment construction.
- Quantity variations that grossly exceed those listed in the bill of quantities. If the contracted unit rates reflect a particular work methodology and quantity variations necessitate the adoption of an alternative more expensive work methodology, large quantity variations could adversely affect the profitability of the contract and the Contractor's attitude to the remainder of the works.

2.3.3 Design-build contracts

Design-build contracts may be appropriate where intimate cooperation between the Contractor and Designer will benefit the project in time, cost or quality. They are usually well suited to projects where the end product can be accurately defined and its achievement is within the Contractor's control. However, they can also be used for the construction of less well-defined works if provision is made for the uncertainties that typically accompany the construction of dams. In this form of contract the Designer is retained by the Contractor rather than by the Owner.

Many of the above points that can affect dam safety in conventional measure and value contracts are also relevant to design-build contracts. However, there are a number of additional points that warrant careful attention during design-build contracts. They include:

- The importance of the design element. The design element is of paramount importance for dam safety and if Owner requirements are not sufficiently detailed in tender documents, design-build tenders can become competitions in under-design, with considerations of dam safety being sacrificed in favour of achieving an attractive price or accelerating the design process to commence construction. Minimum requirements for the Designer should be specified in the tender documents, and a significant weighting for the capability and experience of the Designer should be incorporated in the tender evaluation process.
- The Designer is not a party to the construction contract and hence has no contractual status or authority. The role of the Project Manager is therefore crucial in ensuring that the Designer is appropriately involved and consulted throughout construction, and design related decisions are always made in consultation with the Designer.
- The Owner tends to lose control of the design and any design changes will usually come at an additional cost. To ensure that all dam safety issues are appropriately addressed in the design, the contract documents should include provisions for the Owner to remain informed during the design process. As a quality control measure it may be warranted to identify critical dam safety milestones during the design and construction process where signoff is required from the Owner, Designer and Contractor before continuation of the project.
- Conflicts between commercial and dam safety interests. Designers employed by Contractors are invariably placed under pressure to reduce construction costs which can result in dams lacking resilient features, having limited service lives or, at worst, incorporating dam safety deficiencies. In design-build contracts the Owner should administer and supervise the Contractor's design and construction, and take particular care to ensure that commercial interests do not adversely affect dam safety.
- The continuity of design during construction. As previously outlined, dam design does not end with the provision of drawings and specifications, but continues through construction and commissioning. The Designer must be fully involved in the construction phase of the work and provided with access and facilities for inspection, testing and verification. In this respect 'Designer' means the engineer or engineers principally involved in the design and not others of the same organisation who have not been involved in the design.
- The quality of the completed project. In a design-build contract the Designer should give written confirmation that the design meets current accepted practice and that the dam has been constructed in accordance with the design intentions. In addition, the Owner's Engineer should have a sufficient background in dam engineering to fulfill an independent quality verification role and identify any dam safety deficiencies.

2.3.4 Alliance contracts

Alliance contracts are contracts where the Owner, Designer and Contractor form a project team in which the construction risks are equally shared. The team develops the design and estimates the delivery cost against which the eventual outturn cost will be compared. Cost savings and cost overruns are shared between the parties in a pre-arranged way.

This is a particularly powerful form of contract as it requires all parties to work together in good faith, act with integrity and make best-for-project decisions. Projects suitable for alliance contracting are usually characterised by one or more of the following:

- The project has construction risks that cannot be adequately defined or measured prior to tendering.
- The cost of transferring the construction risks to the Contractor is prohibitive.
- The project needs to be started before the construction risks can be identified or the project scope can be finalised.
- The Owner has appropriate in-house skills and capacity to participate in the development and delivery of the project, or the Owner retains a Technical Advisor with broad capabilities in dam design and construction to serve the Owner's interests and provide discernment on all aspects of the project (design, construction and administration).
- Where a collective approach to the assessment and management of construction risks will likely provide a better project outcome than a contracted allocation of the construction risks.

Many of the points outlined above that can affect dam safety in conventional measure and value contracts and design-build contracts are also appropriate to alliance contracts. However, an additional point that warrants close attention during an alliance contract is the 'everybody, somebody, nobody' syndrome. The cooperation/trust/sharing is or is intended to be so good that there may be a tendency to expect that someone else is taking care of a particular issue. The potential for such misunderstandings or oversights to occur requires careful management to ensure dam safety deficiencies are not introduced during the development of a project.

A negative aspect of an alliance contract is the considerable up front cost to the Owner of retaining the constructor's team through the design period. This tends to make alliancing unattractive for small to medium size projects.

2.3.5 Early Contractor involvement (ECI) contracts

ECI contracts are a relatively recent innovation on design-bid-build-procurement contracts. The objective is to provide Contractor input into the latter stages of a detailed design, at relatively low cost, to explore options and to ensure the final design is constructible. The added benefit, particularly in dam construction, is that the Contractor has the opportunity during the design process to gain a strong understanding of the critical dam design issues.

A form of ECI has also been used on design-build contracts but this has similar cost implications to an alliance.

2.3.6 Contract organisation and administration

Dam construction, particularly on larger more complex dams, can involve multi-disciplinary activities, all of which are important if not critical to achieving the Designer's intent. Therefore it is essential that personnel with the skills to match the range and complexity of the necessary activities are included in the Contractor's project team. In selecting staff, the Contractor must ensure that the team is well structured and includes an appropriate balance between field staff and engineering/planning/technical management staff. It is false economy to skimp on staff numbers or quality and, from a dam safety perspective, it is important that:

- The Contractor's project engineer has sufficient knowledge and experience to be able to handle the technical aspects of the construction and has adequate authority within the Contractor's organisation to be able to control the work to the extent necessary to ensure that the specified quality standards are achieved. On larger projects, where the Contractors' project engineer is not the contract manager, it is important that the contract manager gives full support on technical matters and matters of quality to ensure that standards of workmanship and specification compliance are not compromised for reasons of production expediency.

- All of the Contractor's senior site managers are fully familiar with the contract, the drawings and the specifications. Any apparent anomalies, ambiguities, doubts over the interpretation of requirements, or concerns over the practicality or achievability of the specified requirements should be raised as soon as possible to mitigate any adverse effects that could arise. The senior site managers should also be competent to liaise and work with representatives of the Designer and the relevant Regulator.
- Experienced field supervision personnel are appointed to control the work. The field supervision personnel should be aware of the technical requirements for the work and the importance of particular construction activities that affect dam safety.
- The Contractor provides support to the project team throughout the contract but particularly during the early establishment and start-up phase. This can best be achieved by supplementing the project team with some experienced personnel to assist with key early tasks such as training, planning, programming, temporary works design and site infrastructure establishment. Early effort in getting the job up and going and on a sound footing will help significantly in achieving a successful result.
- The project team is continuously monitored by the Owner's Engineer throughout the contract to ensure that performance is meeting expectations. Working and living conditions are often harsh and the early identification of problems is essential if poor quality performance or time delays are to be avoided.

In some cases it may be difficult to appoint senior and supervision personnel who have good records of experience in dam construction. Where the experience of such personnel is limited, training should be provided to ensure they are aware of the key design features of the project and construction activities that can affect dam safety. A representative of the Designer should be utilised in the training programme.

Sound contract administration is also an important aspect of a successful project and must not be underestimated. Dam safety and the technical management of the project can be affected if proper procedures and suitably qualified staff are not in place to handle design changes, contract variations, measurement of the work, financial management (progress claims, variation orders, etc) and financial reporting of the project. For example, inappropriate management of variations (e.g. unforeseen ground conditions) by the Project Manager can adversely affect the profitability of a contract and the Contractor's attitude to the remainder of the works.

Formal procedures, which are understood and adhered to by all site staff, should be established for:

- The control of documents including drawings, site instructions, meeting minutes, contract correspondence, variation orders and the like. It is important to maintain drawing registers and to ensure that obsolete or superseded drawings are removed from use. Accurate and comprehensive records are important for the analysis of contract claims and for future reference during the dams' lifecycle. Systems should be in place for ensuring that all information required by those performing the work, including subcontractors and suppliers, is transmitted and stored promptly and in a controlled manner.
- The procurement of materials. Materials and components incorporated in the works must comply with the specifications and drawings.
- The demonstration of compliance with the specifications and drawings, including verification and signoff by the design support personnel. A Quality Management Plan, Inspection Test Plans and test data should be produced to demonstrate compliance.
- The selection and management of subcontractors. Subcontractors are often major contributors to a dam project and proper selection and management procedures must be adopted if their contribution is to be successful. The head Contractor must actively manage and control the activities of subcontractors and must ensure that they fully understand and fulfil their responsibilities, particularly in relation to quality assurance procedures.
- Regular liaison between the Contractor's project engineer, the Contractor's senior site managers, the Designer and the Project Manager. Regular meetings of senior site personnel provide a forum for clarification and the development of a spirit of cooperation.

2.4 Construction planning

2.4.1 Introduction

Dam construction usually involves multidisciplinary activities, and thorough planning and programming are essential to achieving a safe dam. Construction tasks which affect dam safety and require special consideration during construction planning include:

- River diversion and cofferdam design and construction.
- Foundation preparation and treatment.
- Embankment materials selection, processing, placement and testing.
- Concrete mix design, production, placement and testing.
- The scheduling and sequencing of construction activities.
- Quality control testing.
- Reporting and documentation.

In many cases there will be limited information available to scope the above tasks and their likely effects on the overall programme, and it will be necessary to complete additional work activities to provide a more reliable information base for construction planning. For example, dam construction often necessitates the completion of additional investigation and laboratory testing to select and fully characterise foundation conditions and construction materials.

2.4.2 Temporary works

It is normal practice for the Contractor to design all temporary works necessary for the construction of the project. This usually includes all formwork and falsework, dewatering facilities, and can include cofferdams and diversion works.

Any engineering design work completed by the Contractor for the permanent works and temporary works that could affect the quality of the permanent works or are incorporated within the permanent works (e.g. diversion facilities), must satisfy design criteria provided by the Designer and be approved by the Designer. Furthermore, the decommissioning of any temporary works that could affect the quality of the permanent works must be approved by the Designer. The design of diversion works and temporary works that could affect the permanent works is discussed in Module 3. Contractors often engage specialist design consultants to supplement their in-house skills and complete such design tasks.

Dewatering is often necessary during construction to enable the placement of embankment fill and concrete adjacent to the foundation and abutment areas. Inappropriate dewatering facilities or inappropriate treatment of dewatering facilities when they are no longer required can have significant effects on dam safety, particularly in embankment dams. As such, all proposed dewatering facilities and their final treatments must be approved by the Designer.

2.4.3 Construction programming

Construction programming is vital to the success of a project and must be used as a management tool to assist in achieving a quality product. The programming must take account of the climatic conditions and its impact on weather sensitive activities (e.g. earthworks, concrete placement). The provision of sufficient material stockpiles will prevent shortfalls and minimise the potential for associated construction delays and specification non-conformances. If a meaningful programme is not developed and adhered to, then programme accelerations in the latter stages of a contract can often only be achieved by sacrificing quality and standards. Programme delays often adversely affect the Contractor's costs and cash flow, which can also compromise quality.

Regular short-term programmes should be produced for sections of the work, in conjunction with field staff, for their use in managing their work activities. These should be subjected to regular reviews by the Contractor and Project Manager to identify issues and implement remedial actions before they become irreversible. Regular updates to the project's master programme are also essential and must highlight all critical activities which impact on work quality including the receipt of important design information, materials, equipment and the like. Sufficient lead times must be allowed for appropriate planning and preparation by the Contractor to ensure the orderly and controlled progression of the work.

2.4.4 Emergency action planning

Large flood events represent the most significant hazards during the construction of a dam as they can result in overtopping and failure of cofferdams and embankment dams under construction, damage to downstream infrastructure and the environment, and possible loss of life. While the overtopping and failure of a cofferdam during the construction of a concrete dam can have similar consequences to those outlined above for an embankment dam, limited overtopping of concrete dams under construction does not usually result in dam failure and any damage is largely limited to the dam itself or to the Contractor's plant and temporary works.

Emergency Action Plans should be prepared for the construction of all Medium and High PIC dams, particularly if they are embankment dams. Guidelines for the development of Emergency Action Plans are included in Module 6.

2.5 Quality control

2.5.1 Objective

The objective of quality control is to ensure that all construction is completed in accordance with specified design requirements. Without an appropriate level of quality control, through a quality management system or plan, there is the potential for design requirements and/or standards not being met which will adversely affect dam safety.

2.5.2 Quality planning

Key Requirements

The scope of a quality control system during construction will vary with the PIC of the dam and the degree of protection built into the design. While a quality control system for a Low PIC dam need not be as detailed as those for Medium and High PIC dams, all quality control systems during construction should include:

- Continued application of the requirements of AS/NZS ISO 9001 (Quality Management Systems – Requirements) by the Designer.
- The establishment of a system complying with the intent of AS/NZS ISO 9000.2 (Quality Management and Quality Assurance Standards – Generic Guidelines for the Application of ISO 9001, 9002 and 9003), and AS/NZS 3905.4 (Quality System Guidelines – Guide to Quality System Standards AS/NZS ISO 9001) by the Contractor.

Additional key requirements that should be incorporated within quality control systems for the construction of Medium and High PIC dams include:

- Designer and independent peer review continuity throughout construction.
- An appropriate Contractor selection process. The selection process should deliberately focus on the Contractor's track record and the availability of key personnel. This may be by a formal prequalification process involving specific questions and a formalised evaluation system, or by the direct selection of potential bidders.
- Thorough team briefings. It is vital that the members of the Contractor and Designer site teams are thoroughly briefed on their duties and responsibilities and that the teams are selected in full recognition of the individual characteristics of the project. This may mean, for example, placing specialists full time in supervision teams at certain stages of the project or providing a larger supervision team because of particular issues that are critical to dam safety.
- On-site inspection and testing procedures, throughout construction, to verify that all construction is in accordance with the design.
- Appropriate design change procedures. Any change, however minor, departing in any way from the approved initial design must be developed, checked and approved by the Designer before its construction. In addition, any design change which materially affects the consent issued for the construction of a dam will likely require approval by the Regulator before its construction. Site staff may propose changes to the approved design or specification to suit circumstances, but only the Designer and Regulator can authorise the changes. Small changes in detail constitute design changes and what may appear to unqualified persons as very small changes may have an effect which only the Designer can fully appreciate.

- Appropriate authority for the Designer to make changes through the Project Manager or the Engineer to the Contract. Contracts between the Owner and the Designer, and between the Owner and Contractor, must give the Designer authority to make such design changes as are necessary during construction to achieve the required level of dam safety and performance. Situations can arise, particularly during foundation work, where changes to the design are necessary to ensure the design intent and dam safety requirements are met.
- Appropriate off-site manufacture procedures. The quality control system must include appropriate procedures for confirming the quality of off-site manufacture, including the effects of transportation. Even standard supply items need thorough consideration when imperfections or failure could adversely affect dam safety. Appropriate quality control records should be provided by the supplier and verified by the Designer.
- Good record keeping. Comprehensive record keeping is essential for future diagnosis and to enable any necessary certification to meet legislative requirements. Section 2.6 addresses construction records in more detail.

Construction/Design Interface
Close coordination between design and construction personnel, both on-site and off-site, is an essential component of any quality control system. Close coordination ensures that construction personnel are aware of the design intent, that new field information acquired during construction is assimilated into the design, that the design assumptions are confirmed, and that the dam is constructed according to the design intent.

Quality Plan
All construction work should be completed in accordance with a Quality Plan which sets out the scope of the quality control system and the quality control procedures that will be implemented to demonstrate compliance with the specified requirements. The Quality Plan, which should be a specified requirement for the Contractor to develop, should document:

- The overall scope of the quality control system for the project.
- Quality control personnel, including their roles and responsibilities.
- Visual inspection procedures and records.
- Field and laboratory testing procedures and records.
- Independent testing authorities and their testing and reporting responsibilities.
- Verification, signoff and recording procedures for each element of the works.
- Compliance and non-compliance criteria, and procedures for logging and dealing with non-compliances.
- Hold points for inspection and signoff by the Contractor and Designer.
- Schedules, forms and checksheets for the inspection, testing and reporting of all quality control activities.

The Designer should approve the Quality Plan and monitor its effectiveness throughout construction. Test records should be reviewed by the Designer's site personnel for compliance with the specifications and the design assumptions.

2.5.3 Quality Control

On-Site Organisation and Responsibilities

The size and composition of the on-site quality control team should be sufficient for the inspection of construction activities, the completion of all necessary field and laboratory tests, the review of all inspection and test results, the identification of all non-compliances, the documentation of all inspection and test records, and the completion of quality control reports. On large projects the scope of the work may necessitate the appointment of a Quality Control Manager and a team of support staff for the completion of inspection and testing activities. On smaller projects it may be appropriate for the quality control function to be managed by a senior member of the on-site team, with an independent testing authority engaged for the completion and reporting of all field and laboratory tests.

The Contractor is usually responsible for quality control during construction. It is important that the Contractor fully understands the scope and importance of the quality control function and adequately allows for the work involved. Inspection and testing of the work to verify its compliance with the contract requirements is essential for the completion of a safe dam.

The Designer is normally responsible for quality assurance and, as such, reviews and approves the Contractor's Quality Plan. The Designer should have the ability, through the Project Manager or the Engineer to the Contract, to undertake additional independent inspections and tests considered necessary to confirm that the construction is completed in accordance with the design intent. Guidelines for on-site Designer involvement during construction are listed in Table 2.1.

Visual Observations

The extent and frequency of visual observations will vary depending on local conditions, the importance of the work being inspected, and the skill of the inspector. More frequent inspections are usually necessary during the initial stages of construction when foundation conditions are exposed, foundation treatments are completed, material trials are completed and initial dam construction gets underway. In addition and in comparison to inspection requirements for Low PIC dams, more frequent inspections are usually necessary during the construction of Medium PIC dams and full time supervision of construction should be mandatory for High PIC dams.

Visual inspections and signoffs determine whether the requirements of the drawings and technical specifications are being met and, in some cases, whether completed work can be covered by subsequent construction. Experienced inspectors with the ability to identify acceptable and unacceptable construction work are essential for effective quality control.

The Contractor's quality control procedures should include inspection sheets for individual elements of the work. These sheets should identify the particular element of the project, the date, the type of work, the tests carried out and verification by the Contractor's supervisor that the work has been completed and checked. Finally, the Owner's representative should sign the inspection sheet to authorise the next stage of construction to proceed.

Field and Laboratory Testing

The extent and frequency of testing depends on the amount of material to be placed and the importance of the material to dam safety. Examples of important field and laboratory tests for dams are listed in Table 2.3.

Table 2.3: Important Field and Laboratory Tests for Embankment and Concrete Dams

Dam Type	Field and Laboratory Tests
Embankment Dams	• Material properties (Atterberg limits, gradations, permeabilities, water content, shear strengths) • Material compatibility (core, filter, drainage, shoulder and foundation material interfaces) • Durability of filter and drainage materials • Density (Proctor compaction, relative density) • Grout curtains (lugeon) • Grout quality (viscosity, density, strength)
Membrane-faced Embankment Dams	• Material properties (Atterberg limits, gradations, permeabilities, water content, shear strengths) • Density (Proctor compaction, relative density) • Membrane acceptance tests • Membrane joint leakage tests • Grout curtains (lugeon) • Grout quality (viscosity, density, strength)
Concrete-faced Rockfill Dams	• Material properties (gradations, permeabilities, shear strengths, rock quality) • Density (relative density) • Concrete (aggregate gradation and moisture content, cement properties, slump, compressive strength) • Grout curtains (lugeon) • Grout quality (viscosity, density, strength)
Concrete Dams	• Concrete (aggregate gradation and moisture content, cement properties, slump, compressive strength, aggregate quality) • Reinforcing steel properties • Pozzolan and flyash acceptance tests • Grout curtains (lugeon) • Grout quality (viscosity, density, strength)
Roller Compacted Concrete Dams	Concrete (aggregate gradation and moisture content, cement properties, vebe, compressive strength, aggregate quality) Pozzolan and flyash acceptance tests Lift joint tensile strength Grout curtains (lugeon) Grout quality (viscosity, density, strength)

The numbers of field and laboratory tests should be statistically significant and spread throughout the dam component being tested, and testing should continue until the completion of construction. As stated above for visual inspections, more frequent testing is usually necessary during the initial stages of dam construction to verify that the physical characteristics of the materials meet design requirements and that the adopted construction methods are appropriate, and to enhance the ability of inspectors to identify acceptable and unacceptable construction. In addition and in comparison to testing requirements for Low PIC dams, more frequent testing is usually necessary for Medium PIC dams and full time control testing should be mandatory for High PIC dams.

All field and laboratory testing should be completed in accordance with relevant procedures included in New Zealand standards or standards published by internationally recognised organisations with comprehensive backgrounds in dam engineering (e.g. USBR, USACE). Nuclear density meters and other field testing equipment utilised during construction should be calibrated at frequencies recommended by manufacturers to ensure they provide consistently reliable results. All laboratory testing facilities, whether they are Contractor-owned or independent testing facilities, should be IANZ (International Accreditation New Zealand) registered.

Critical Areas and Construction Signoffs
All areas that are critical to meeting the design intent and achieving dam safety should be identified before construction and highlighted in the Quality Plan as hold points for inspection and signoff by the Contractor and Designer. Areas and items which most commonly fall into this category are:

- Foundation preparation including such items as shaping, strength, surface texture, foundation defects and dewatering.
- The preparation of pre-work such as formwork, reinforcing steel, embedded items and pour cleanout for concrete pours.
- The quality and consistency of key materials whether they be concrete, earthfill, filter or drainage materials.
- The bedding, jointing, backfilling and protection of any penetrations through embankment dams.
- The installation, protection and reading of any instrumentation for the monitoring of dam performance.
- The installation of embedded items for equipment critical to dam safety, the fabrication/procurement and installation of gates and valves critical to dam safety, the installation of stressed anchors and the like, and the installation and testing of gate or valve control and backup systems that are critical to dam safety.

Producer Statements
Refer section 3.5 in Module 1 (Legal Requirements).

2.6 Construction records

Accurate and comprehensive construction records are extremely important and provide a background for future dam safety evaluations, and the design and construction of any necessary rehabilitation works. They can also reduce the likelihood of unnecessary expenditure to investigate construction uncertainties during the dam's lifetime. The level of detail will of course vary with the size, complexity, function and the PIC of the dam.

The safekeeping of records is of vital importance and the following construction records should be stored in an appropriate records system and backed up to a separate location:

Investigation Records
Records of all investigation activities completed during construction including drillhole logs, backhoe and dozer trench logs, shaft logs, investigation photographs, field and laboratory test results, and investigation reports.

Foundation Records
All excavations forming part of the permanent works and all foundation areas for Medium and High PIC dams, and Low PIC dams where the geology is not straightforward, should be logged, photographed, mapped and interpreted in a foundation report. The excavated foundation profile should also be recorded.

Day-to-day Construction Records
If a quality management system is employed during construction (as should be the case for all dams), there will be a comprehensive paper trail of day-to-day activities that include correspondence, progress reports, minutes of meetings, design changes, site instructions, grouting records, activity reports, test results and the like.

Quality Control Records
All visual inspection and testing records (e.g. inspection check sheets, field and laboratory test results, test reports, quality control reports).

Monitoring Records
Any monitoring records gathered during construction which could have a present or future impact on dam performance and dam safety (e.g. rainfall, river flows, seepage flows, construction pore pressures, settlements, concrete temperatures).

Construction Photographs
A systematic record of construction activities, suitably annotated with dates, locations and descriptions. Particular attention should be given to foundation conditions and treatments, material preparation and placement, filter and drainage systems, construction and contraction joints, and embedded items associated with facilities that are essential for dam safety (e.g. gate guides, gate supports).

As-Built Drawings
As-built drawings are essential to provide a clear depiction of what was actually constructed. The preparation of as-built drawings requires the recording of as-built data as construction proceeds.

For all dams a construction report should be completed following the completion of construction. The construction report for an uncomplicated Low PIC dam will normally be brief in comparison to those completed for Medium and High PIC dams. However, all construction reports should provide an accurate summary of the construction process with a focus on:

- Construction methods and equipment.
- Any observed differences between assumed and actual site conditions.
- Any necessary changes during construction to address actual site conditions.
- Any problems that arose and how they were dealt with during construction.
- As-built records.
- A summary of all field and laboratory test results.
- A selection of supporting photographs.

Copies of all key construction records, drawings and documentation should be provided to the dam Owner at the end of the project.

2.7 Insurance during construction

There is a wide range of insurance policies that can be adopted for the management of risks during dam construction. Most construction projects include Contractor's all risks polices, which protect the insured against accidental loss or damage to the works that results from construction activities, and civil liability policies which protect the insured against liabilities to third parties that may result from construction accidents. Other insurances can include Contractor's plant and machinery policies, which protect the insured against damage to plant and machinery items utilised during construction, and all risks erection policies which protect the insured against losses arising from the erection, installation, testing and commissioning of machinery and plant.

A discussion on the relative merits of alternative insurance solutions is beyond the scope of these Guidelines and Owners and Contractors should discuss their specific project insurance requirements with appropriate insurance agencies. However, many construction risks can be minimised through active on-site management which should not be discounted in preference to a comprehensive insurance policy. Examples include:

- The identification and treatment of unsuitable foundation conditions.
- The management of flood events during construction.
- The identification and resolution of potential dam safety deficiencies during construction.

3. Commissioning

3.1 Dam safety risks

Initial impoundment or commissioning provides the first test of the design and construction of a dam. For example, many historical dam failures initiated by internal erosion or piping have occurred on first filling or in the first five years of operation. It is therefore most important that commissioning procedures are appropriate to the dam and enable the Designer, and later the Owner, to regularly monitor its performance during and following reservoir filling. It is also most important that Designer involvement is maintained throughout the commissioning process to ensure that the performance of the dam and its appurtenant structures are consistent with the design philosophy and intent.

3.2 Personnel – roles and responsibilities

Personnel involved in the commissioning process and their usual roles and responsibilities are summarised as follows:

- The Owner and Project Manager (if a Project Manager is appointed by the Owner), who are customarily reliant on the Designer for advice on commissioning and must give freedom to the Designer to act appropriately if dam safety is in question during commissioning.
- The Designer, who normally advises on and monitors commissioning, and is given authority by the Owner to manage the process and initiate any necessary actions to preserve dam safety. In certain situations, the Owner may appoint a separate Project Manager to oversee all activities but all decisions by the Project Manager should fully recognise advice from the Designer.
- The Contractor, who implements commissioning under instructions and must be equipped and prepared to act appropriately and rapidly in the event of unsatisfactory performance of the dam or its associated appurtenant structures during commissioning.
- Technical Specialists and Peer Reviewers, who provide specialist inputs as required in support of the Designer or, in the case of Peer Reviewers, in support of the Owner (or Project Manager).
- Regulators, who ensure, usually by delegation to an independent consultant and by conditions included in consents, that the dam is commissioned in accordance with appropriate commissioning procedures.
- Operating Personnel, who, in the case of large and operationally complex dams, participate in commissioning to learn about the dam and its safe and effective operation during the commissioning process.

The personnel and numbers involved in the commissioning of a dam will vary depending on the characteristics of the dam and its appurtenant structures. In the case of a straightforward Low PIC dam commissioning may only directly involve the Owner, Contractor and Designer; however, for Medium and High PIC dams that incorporate appurtenant structures with gate/valve outlet facilities, commissioning will necessarily include the Owner or Project Manager, Designer, Contractor, operating personnel, and technical specialists for monitoring the performance of the dam and gate/valve operation. It is essentially a matter for the Designer to determine the necessary scope of the commissioning team.

3.3 Planning for commissioning

3.3.1 Introduction

In many cases facilities are available to control the rate of commissioning (e.g. a low level outlet in a water storage dam), in other cases no facilities are available to control the rate of commissioning (e.g. a water storage dam without a low level outlet facility), and in some cases a formal commissioning process is impossible (e.g. a flood detention dam where the outlet facility is uncontrolled).

The following subsections outline recommended procedures and practices for the formal commissioning of dams. In the special case of flood detention dams, where formal commissioning is often impossible, appropriate procedures should be prepared to enable the monitoring of dam performance during initial impoundment by a flood event.

3.3.2 Commissioning procedures

The Designer should prepare appropriate procedures for the commissioning of any dam. The procedures should reflect the PIC of the dam, its complexity, and any conditions included in consent documents that relate to commissioning. Recommended minimum commissioning procedures for Low, Medium and High PIC dams are listed in Table 3.1.

Table 3.1: Recommended Minimum Commissioning Procedures for Dams

PIC of Dam	Minimum Commissioning Procedures for Dams
Low	The procedures need not be comprehensive and a list of items that should be inspected or monitored during and following commissioning should be sufficient. The commissioning should be attended by the Owner, Contractor and Designer. The Designer should complete a letter report on the results of the commissioning which highlights any unexpected results and comments on any necessary actions that were taken to address the unexpected results.
Medium	The procedures should outline responsibilities, pre-commissioning requirements, commissioning procedures and performance evaluation procedures. An Emergency Action Plan should be included. The commissioning should be attended by the Owner (or the Owner's Project Manager), Contractor and Designer. The Designer should complete a brief report on the results of the commissioning which summarises the commissioning process, highlights any unexpected results and comments on any necessary actions that were taken to address unexpected results.
High	The procedures should be comprehensive and reviewed by the Peer Reviewer. An Emergency Action Plan should be included. The commissioning should be attended by the Owner (or the Owner's Project Manager), Contractor and Designer. The Designer should complete a comprehensive commissioning report.

Commissioning should not proceed until all necessary planning has been completed, and procedures have been established and communicated to the personnel responsible for commissioning. From a dam safety perspective, the commissioning procedures for Medium and High PIC dams would normally address the following:

- The definition of all parties involved and their responsibilities, the names of key personnel including backup personnel, and all personnel contact details.
- The physical works that must be completed before commissioning can commence.
- The rate of reservoir filling, reservoir level hold points and their duration, and criteria for the continuation of reservoir filling.
- A set of initial (baseline) measurements for all instrumentation and survey marks immediately prior to commissioning.
- The establishment of expected performance ranges for instrumentation by the Designer, to provide a guide for evaluating actual dam performance during and following commissioning.

- The commissioning procedure including, where appropriate:
  - walkover inspections to check for any indications of unexpected behavior
  - identification and measurement of seepage flows or changes in seepage behavior
  - measurement of piezometric pressures and groundwater levels (at prescribed frequencies or reservoir elevations)
  - measurement of settlements and deformations (at prescribed frequencies or reservoir elevations)
  - measurement of concrete stresses and temperatures (at prescribed frequencies or reservoir elevations)
  - testing of installed plant and equipment critical to dam safety (e.g. spillway gates)
  - testing of spillway performance
  - inspections and/or monitoring of the dam and/or reservoir shoreline at specified hold points.
- The recording and communication of monitored data, interpreting the monitored data, and evaluating the performance of the dam against acceptable performance criteria.
- Actions to be taken in the event of a developing dam safety emergency.

Typical contents of a commissioning procedures document prepared for a Medium or High PIC dam are listed in Figure 3.1.

Readiness is a critical aspect of planning and commissioning should not proceed until the Designer or the Owner's Project Manager has carried out appropriate readiness checks and is satisfied that commissioning may proceed. Prerequisites for commencing reservoir filling may, depending on the scale and complexity of the project, include the:

- Completion of minimum works on the dam, structures and reservoir area.
- Installation and dry testing of equipment, controls, telemetry and alarms.
- Installation of all instrumentation and the establishment of monitoring systems, including the establishment of expected performance ranges for all installed instrumentation.
- Provision of on-site materials and equipment for possible emergency use (e.g. filter materials, rockfill stockpiles, excavators, bulldozers).
- Preparation of commissioning procedures, which include any necessary limitations on the rate of rise in the reservoir level, and communication of them to relevant commissioning personnel.
- Confirmation that all statutory requirements have been and will be met during commissioning.
- Completion of other activities not directly related to dam safety.

As part of a formal quality control system, detailed readiness checklists should be prepared and utilised for various components and activities.

COMMISSIONING PROCEDURES

CONTENTS **Page No.**

Figure 3.1: Typical Contents of a Commissioning Procedures Document (Medium or High PIC Dam)

3.4 Management of commissioning

3.4.1 Control

The need for effective control by the Designer has been stated. This aspect cannot be over emphasised and control must be exercised in a thorough manner. Control starts with proper planning but must incorporate the ongoing evaluation of all data gathered and feedback to those implementing the commissioning. In addition, the control must provide for rapid and effective responses to situations which warrant or demand action to preserve dam safety. This may put pressure on the Designer and Owner to take actions which are adverse to the Owner's commercial objectives; however, the parties must be prepared to implement all actions necessary for dam safety.

It is vital that there are clear and workable arrangements for the rapid evaluation of data, decision making and the initiation of actions to preserve dam safety.

3.4.2 Typical commissioning issues

A number of issues can arise during the commissioning process which require consideration by the Designer. They often include:

- A desire by the Owner to commence operation as soon as possible. This is not surprising, particularly for commercial projects (e.g. irrigation or hydroelectricity) where income streams will assist in the reduction of loans secured for financing the projects. It is most important that dam safety interests are given priority over commercial interests, and that commissioning is completed at a pace that is judged appropriate by the Designer.
- Inspection and monitoring frequencies during commissioning. Inspection and monitoring frequencies should be specified by the Designer in the commissioning procedures and they will vary depending on the characteristics of the dam, the parameter being monitored (e.g. seepage, piezometric pressure), and the stage of the commissioning process. Daily and even round-the-clock observations are usually necessary above certain reservoir levels during the initial commissioning period and, as more stable conditions develop, observations usually become less frequent (e.g. weekly). Once the dam is deemed operational and the Designer has confirmed that the dam is performing as expected, observation frequencies usually reduce to weekly or monthly.
- The commissioning of spillway facilities. Where practical, commissioning should include the completion of spillway tests; however, in many cases, the performance of spillways cannot be tested until the occurrence of large flood events. In such cases appropriate commissioning procedures (e.g. inspections, monitoring of installed instrumentation) should be prepared for use during a future large flood event and, wherever practical, the Designer should witness the performance of the spillway during the large flood event.
- The duration of commissioning. Commissioning should continue until the Designer is satisfied that the dam is performing in accordance with design expectations. Sometimes it will be necessary for the Designer to commission a dam before stable conditions are reached. For example, piezometric pressures and seepages in a zoned embankment dam often do not stabilise for many months or years following reservoir filling, and it will be necessary for the Designer to commission the dam when observations indicate acceptable behaviour.

3.4.3 Confirmation of satisfactory performance and handover

Handover marks the point where the Designer is satisfied with the performance of the dam and its associated hydraulic structures, and the Owner is assigned full responsibility for operating the dam. As outlined in section 3.4.2, handover will sometimes occur before all seepage and piezometric measurements have stabilised and spillway facilities have been tested.

The Designer must, on the basis of the performance of the dam during commissioning, determine the handover point and any associated conditions, and convey them clearly to the Owner. The Designer must ensure that the Owner is fully conversant with all operating, maintenance and surveillance requirements and, for Medium and High PIC dams, the Emergency Action Plan. The Designer must also ensure that the Owner and any operating personnel have been fully trained, are capable of operating and maintaining all facilities in accordance with the specified procedures, are capable of completing all routine surveillance and monitoring, and have a clear understanding of their roles and responsibilities in a dam safety emergency.

3.5 Commissioning records

The commissioning process must be recorded in an appropriate commissioning report completed as soon as is practicable following handover. This report provides an important permanent record of initial performance compared with design expectations, and any actions undertaken during commissioning to address unexpected performance. The report will constitute a benchmark for ongoing surveillance and safety evaluations, and may fill a vitally important role in any subsequent examination of a developing dam safety deficiency.

As outlined in section 3.3.2, a letter report which comments on the commissioning results, highlights any unexpected results, and comments on any necessary actions that were taken to address the unexpected results is normally sufficient for a Low PIC dam. Typical contents of a commissioning report prepared for a Medium or High PIC dam are listed in Figure 3.2.

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2.0 COMMISSIONING

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2.2 Timeline

2.3 Results and Consequent Actions

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2.3.2 Seepage Records

2.3.3 Piezometric Records

2.3.4 Deformation Records

2.3.5 Spillway Performance

2.3.6 Intakes and Controls

2.4 Conclusions and Recommendations

TABLES Seepage Records

Piezometric Records

Deformation Records

DRAWINGS

APPENDICES

Figure 3.2: Typical Contents of a Commissioning Report (Medium or High PIC Dam)

References

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MODULE 5
DAM SAFETY MANAGEMENT

Abstract

Dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, operation, assessment and rehabilitation of dams in New Zealand are included in the Parent Document. The Parent Document also includes a glossary of terms used in these Guidelines. Dam safety is assured through the implementation of sound dam safety management practices, including the resolution of any dam safety issues that may arise during the lifetime of a dam.

Dam Safety Management Systems detail procedures and activities for the management of dam safety, and importantly, provide an auditable record of dam performance and Owner commitment to dam safety. This module provides a framework for the development and implementation of a Dam Safety Management System (DSMS). It outlines the objectives of dam safety management and includes:

- A framework for the management of dam safety management activities, decision making and supporting processes.
- Recommended competencies and training for personnel with responsibilities for dam safety management.
- Recommended practices for the development and implementation of an appropriate DSMS.
- Recommended practices for the ongoing review of a DSMS.

These Guidelines recommend all dams have a Dam Safety Management System commensurate to the consequences of failure to support asset longevity, business risk management, license to operate, insurance and lending. The DSMS should contain the elements listed in Table 1 below. Note that seven of the DSMS elements align with the regulatory minimum Dam Safety Assurance Programme (DSAP) elements required by the Building (Dam Safety) Regulations (2022) (Regulations (2022)) for a Medium or High PIC dam (refer Module 1: Legal Requirements for more information on these requirements).

This module also includes a limited discussion on the role of Regulators and Recognised Engineers in dam safety and reference should be made to Module 1: Legal Requirements for a more complete description of their role and responsibilities.

Notice to reader

While this module has been configured to be, as much as practicable, self-contained from a technical perspective, the reader should be conversant with the principles, objectives and limitations expressed in the Parent Document and Module 1: Legal Requirements prior to considering the information provided in this or any other individual module.

Table 1: Elements of a Dam Safety Management System

Element	Reference section	Type of element	
		Recommended practice	Regulatory minimum DSAP (Note 1)
Governance	2.1	√	
People	2.2	√	
Dam and reservoir operation and management	4.1	√	√
Surveillance	4.2	√	√
Appurtenant structures and gate and valve systems	4.3	√	√
Intermediate dam safety reviews	4.4	√	√
Comprehensive dam safety reviews	4.5	√	√
Special inspections and dam safety reviews	4.6	√	
Emergency preparedness (refer Module 6)	4.7	√	√
Identifying and managing dam safety issues (refer Module 7)	4.8	√	√
Information management	4.9	√	
Audits and reviews	4.10	√	
Notes 1. Elements of a DSAP required by the Regulations (2022) (refer Module 1).			

Document history

Release	Date	Released with
Original	May 2015	Parent and all modules
2023	December 2023	Updates to Parent and Modules 1, 2 and 5

1. Introduction

1.1 Principles and Objectives

The Fundamental Dam Safety Objective as discussed in the Parent Document is to protect people, property and the environment, present and future, from the harmful effects of a dam failure or an uncontrolled release of the reservoir contents. The Parent Document outlines principles that underpin and support the achievement of that objective; Principles 4, 5 and 6 relate to this module. Principle 4 in the Parent Document states that:

The responsibility for the safety of the dam rests with the Owner.

The dam Owner is directly responsible for the safe management of a dam. This is both a moral and legal obligation. The responsibility should include:

- Verifying that dams and appurtenant structures are designed, constructed, commissioned and operated in a manner which ensures they meet appropriate performance criteria.
- Ensuring the safe containment of the reservoir and control of outflows.
- Establishing appropriate procedures and arrangements for dam safety to be maintained under all conditions.
- Establishing and maintaining personnel with appropriate experience and qualifications for ongoing dam safety management.
- Monitoring the performance of the dam and appurtenant structures.
- Maintaining and repairing or rehabilitating the dam and appurtenant structures as necessary to ensure ongoing safe performance.

Principle 5 in the Parent Document states that:

A Dam Safety Management System, commensurate with the consequences of dam failure and incorporating policies, procedures and responsibilities, should be in place for all dams.

Effective dam safety management is primarily achieved through the development and implementation of procedures, commensurate with the consequences of dam failure, which are incorporated within an overall DSMS. The DSMS should reflect the Owner's dam safety policy and provide a structured framework for the completion of dam safety activities, reaching appropriate dam safety decisions, and addressing identified dam safety issues. A DSMS should incorporate:

- A dam safety policy, dam safety statement or dam safety standard.
- A description of the DSMS and its elements including dam safety management activities and resources for completing these activities.
- Responsibilities and procedures for implementing the DSMS.
- Procedures for checking and reviewing the performance of the dam and the DSMS.
- Procedures for identifying and addressing any dam safety issues, including deficiencies in the performance of the dam and the DSMS.
- Procedures for regular reporting on the performance of the dam and the adequacy of the DSMS to the Owner and, where appropriate, Regulators.
- Appropriate supporting systems for management, staff training, communications and information management.

This module is applicable to the safe management of dams, ranging from small Low PIC dams through to a portfolio of Medium or High PIC dams on a river system. The DSMS should include procedures for the operation, maintenance and testing of mechanical and electrical equipment and systems that fulfil dam or reservoir safety functions (e.g. spillway gates, low level outlets, valves, power supplies, control and protection systems, communication systems). The procedures should cover normal, abnormal and emergency operating conditions and include any procedures to lower the reservoir level in response to a dam safety emergency. In some cases it may be appropriate to prepare a separate operations and maintenance (O&M) manual; however, it is important that the linkage to dam safety is not diluted.

These Guidelines recommend that where the consequences of dam failure would adversely affect people, property and the environment, Owners should consider developing and implementing a DSMS irrespective of the PIC of the dam. Recognising and acting on a potential dam safety related condition as early as possible is likely to result in the best chance of an economical resolution.

Principle 6 in the Parent Document states that:

All reasonable efforts should be made to prevent and mitigate accidental releases, dam safety incidents, and dam failures.

Dam safety incidents and dam failures do not necessarily correlate with complexity or improbable loadings. Technical issues or errors under normal operating conditions have been the cause of many dam incidents and dam failures, including combinations of small factors which together have resulted in dam safety incidents and dam failures.

To assure dam safety, appropriate measures should be taken to prevent:

- The occurrence of abnormal conditions or incidents that could lead to an uncontrolled release of part, or the entire reservoir.
- The escalation of any such abnormal conditions or incidents to dam safety emergencies.

The primary means of preventing abnormal conditions or dam incidents is effective dam safety management (e.g. diligent visual inspection and monitoring, good communication practices, proper training, and regular maintenance and testing). The primary means of mitigating the consequences of incidents, should they arise, is resilience. This is achieved through an appropriate combination of effective management, operational processes and robust engineering features that provide safety margins, diversity and redundancy.

Resilient engineering maximises the ability of a structure or system to safely manage an abnormal, unexpected or unpredictable condition (refer Module 3: Investigation, Design and Analysis). Natural hazards are examples of loading conditions which can vary considerably from the idealised product of a hazard identification process. Resilient dam safety practices can mean both smart engineering and redundancy and, when properly implemented, should ensure that no single technical, human or organisational malfunction leads to a dam safety incident. Resilient dam safety practices should also ensure that the combined malfunctions necessary to result in a dam safety incident have an acceptably low probability of occurrence.

The objective of this module is to provide Owners with a framework for the development and implementation of a DSMS.

1.2 Dam Safety Management System

An overall DSMS provides the dam Owner with a framework for dam safety management activities, decision making and supporting processes. These Guidelines recommend that the Owner appoint an Accountable Executive (a named individual) who would report directly to the Owner to be accountable for and to drive the organisation's commitment to meeting its dam safety objectives.

The DSMS should incorporate arrangements for governance including oversight, enabling, delegated authorities and resourcing. An example DSMS is presented in Figure 1.1. Guidelines for establishing a DSMS are presented in Sections 3 and 4. ICOLD Bulletin 154: Dam Safety Management – Operational Phase of Dam Lifecycle (ICOLD, 2010) and McGrath & Stewart (2013) provide further discussion on DSMSs and effective dam safety risk management.

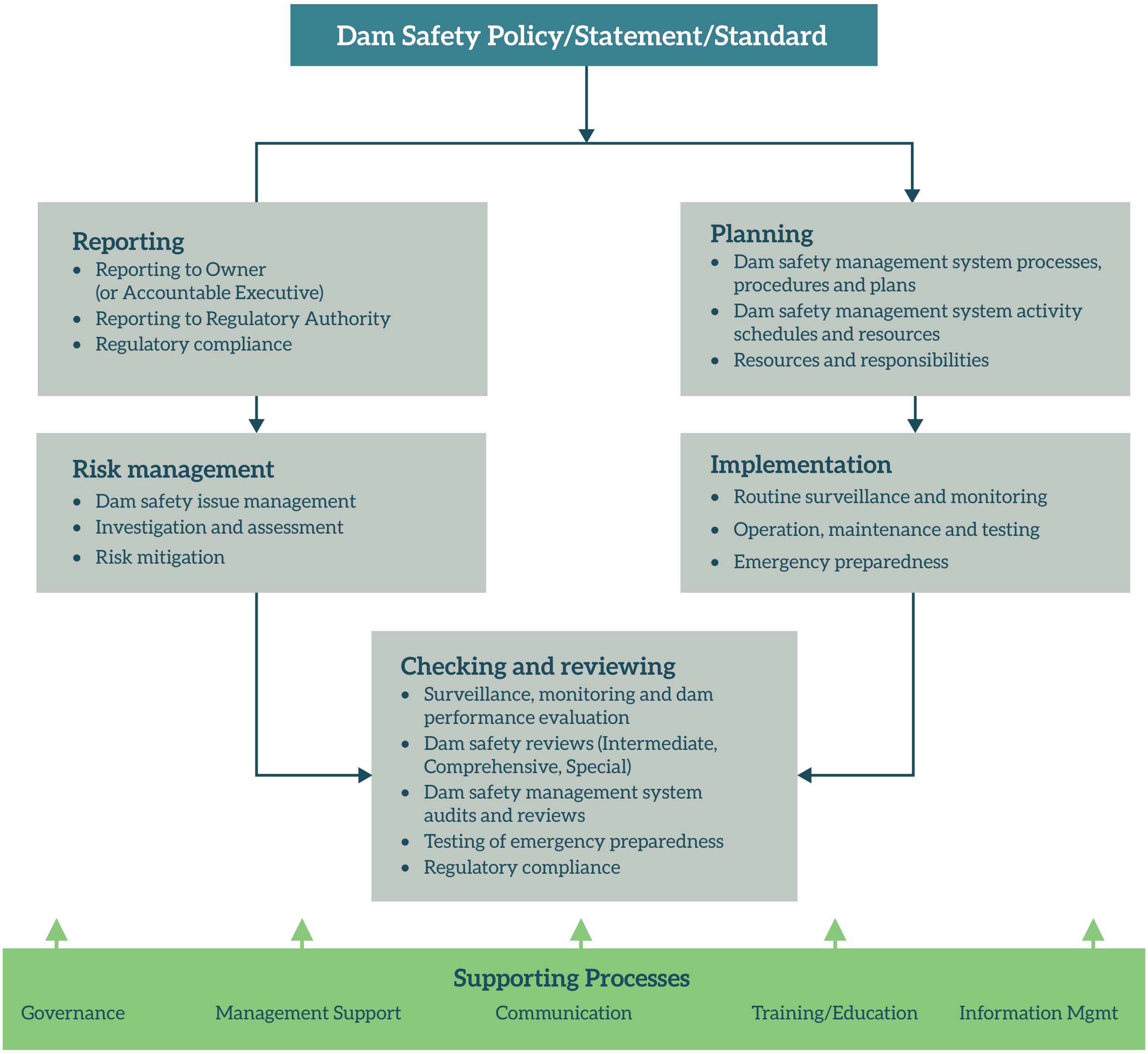

Figure 1.1: A Dam Safety Management System

A DSMS, such as that shown above, can be applied equally effectively to a small single dam, where one person fulfils the dam safety roles and responsibilities, to a portfolio of dams where roles and responsibilities are distributed across a team of people internal to and external to an organisation. The key responsibility is with the dam Owner to ensure that an appropriate DSMS is in place to safeguard the public, property and environment from a potential dam failure.

1.3 Scope of module

This module provides a framework for the development and implementation of a DSMS. It includes:

- An outline of the importance of governance and people to an effective DSMS.
- An account of what should be considered in developing a DSMS.
- A description of the various elements that should be included in a DSMS.
- Recommendations relating to change management and continuous improvement.

This scope of this module is DSMSs (DSMS) for all dams. The regulatory minimum Dam Safety Assurance Programme (DSAP) requirements of the Regulations (2022) for a Medium or High PIC dam are outlined in Module 1: Legal Requirements. The required DSAP elements align with seven of the DSMS elements recommended in this module. A list of reference documents is included at the end of the module to assist Owners in the development and implementation of DSMSs.

2. Governance and people

There are numerous elements that should be considered in the development and implementation of a DSMS. Governance and people are two elements that apply across all other elements of a DSMS.

2.1 Governance

2.1.1 Dam Safety Policy/Statement/Standard

Dam safety should be a primary consideration for any dam Owner, whether an individual, public authority or private company. The overall responsibility for an effective DSMS remains with the Owner and its Accountable Executive, and these Guidelines recommend that any Owner of a Medium or High PIC dam should have a dam safety policy, statement or standard.

A dam safety policy, statement or standard articulates an Owner's commitment to dam safety management including the linkage of its dam safety objectives to:

- Applicable regulations.
- Industry practice.
- Public safety.
- The protection of third party property, public infrastructure and the environment.
- The Owner's organisational goals and values.

Furthermore, a dam safety policy, statement or standard provides the organisation's directive to its personnel accountable and responsible for implementation of the DSMS.

2.1.2 Owner actions and priorities

An Owner's actions and priorities should promote the recognition of, and commitment to, the safe operation of its dams and reservoirs. Effective dam safety management requires responsibilities to be fulfilled at all levels in the Owner's organisation, from the Accountable Executive to field personnel. The Accountable Executive should take all steps to remain aware of the key activities and decisions relating to the safe management of their dams. Post-disaster enquiries following catastrophic dam failures and industrial accidents often identify failings in this area as a contributory factor towards a disaster.

These Guidelines recommend that the implementation of a DSMS, including the resolution of dam safety issues that may arise during the lifetime of a dam, should be considered and prioritised appropriately in conjunction with wider business and organisation objectives.

However, dam safety risks do not often align with normal business risk management models because of the sometimes very low probability of the consequences, which may be extreme compared to normal business risks and, in the case of potential loss of life, it is considered morally unacceptable to assign a monetary value to the loss of a life. Furthermore, the loss of a life could have criminal consequences for the Owner that cannot be captured in a business risk model. While these differences need to be recognised by Owners, a risk-informed dam safety framework (refer Module 7: Lifecycle Management) will allow Owners to understand the nature and significance of the risks, prioritise the risks, target resources effectively, and demonstrate a prudent approach to reducing risks associated with their dams. Risk-informed decision making is an additional tool that can be utilised by Owners for the assessment of dam safety issues.

2.1.3 Delegated authority and enabling

A clear line of authority and accountability for dam safety in an Owner's organisation should be established and unambiguously stated. This should include the Accountable Executive (a named individual) with accountability for dam safety and reporting to the Owner.

Those persons responsible for implementation of a DSMS should have the appropriate resources (financial and personnel) and delegated authority to effectively fulfil their responsibilities. Levels of resourcing should allow for the timely completion of all dam safety management activities in accordance with organisational and regulatory requirements, including the investigation and resolution of any dam safety issues that may arise during the lifetime of the dam.

2.1.4 Communication

Owners should have effective communication processes in place that ensure important dam safety issues are promptly reported to the appropriate accountable and responsible personnel, and escalated appropriately to key decision makers and, where necessary, to external authorities. The organisational culture should promote upwards communication of dam safety information.

An Owner's dam safety policy, statement or standard and its dam safety achievements should be communicated throughout the Owner's organisation.

Effective communication and coordination will be achieved through integrating dam safety activities within the wider business.

Owners may be required to provide background data and information on a potential dam safety issue to external parties such as Regulators, emergency agencies and other stakeholders (e.g. affected property owners and recreational users). Legal requirements associated with demonstrating dam safety compliance are discussed in Module 1: Legal Requirements.

Finally, Owners may wish, for the benefit of their relationships with, and education of, other parties, to communicate information concerning their dam safety practices to stakeholder communities and interest groups.

2.1.5 Review

Internal and external reviews of the effectiveness and appropriateness of an Owner's DSMS is an important part of governance. Such reviews ensure that the stated dam safety objectives are appropriate and are being met, and that a pathway towards continuous improvement is being maintained.
This is discussed further in sections 4.10 and 5.3 of this module.

2.1.6 Additional governance for tailings dams

Owners of tailings dams should consider the additional governance recommendations provided by the Global Industry Standard on Tailings Management (GISTM, 2020) and ICOLD Bulletin 194 Tailings Dam Safety (ICOLD, 2023). They include appointment of an Accountable Executive (owner team), Responsible Tailings Facility Engineer (Owner team) and Engineer of Record (EOR), and for Very High or Extreme consequence dams an Independent Tailings Review Board (ITRB).

2.2 People

2.2.1 Competence

The effective management of dam safety generally involves a wide range of skills. As this range of skills typically does not reside in a single person, an effective DSMS will usually involve a number of people from the Owner's organisation that includes managers, technical personnel and operational personnel. The Owner is responsible for ensuring that appropriately competent personnel are engaged to oversee or implement all elements of the Dam Safety Management System, and that all involved parties understand and are competent to fulfil their roles and responsibilities. In some cases Owners may not be fully conversant with the technical requirements for dam safety management and they will therefore be reliant on advice received from the Designer, in the case of a new dam, or Technical Adviser in the case of an existing dam.

It is important for the Owner to ensure that the technical advice is provided by competent and qualified personnel with appropriate backgrounds of experience in dam engineering and dam safety. Designers and Technical Advisers play key roles in ensuring dam safety and it is vitally important that Owners and their Designers and/or Technical Advisers understand the extents of their roles and the boundaries of their responsibilities.

On-the-ground routine surveillance and monitoring is commonly completed by the Owner's permanent staff or, in the case of a smaller dam, by the Owner personally. On-the-ground routine surveillance and monitoring is recognised as the first line of defence in dam safety and is one of the most important aspects of a DSMS. Evaluation of the surveillance and monitoring results, the assessment and reporting on dam performance, and the completion of intermediate dam safety reviews should be undertaken by people competent in the evaluation of surveillance and monitoring results. This is usually undertaken by the Owner's senior dam safety staff and Technical Advisers. All people with dam safety responsibilities should understand the conditions and hazards that can affect dam safety, the potential failure modes for the dam, the early signs for the development of each of the potential failure modes, and the surveillance and monitoring procedures relevant to each of the potential failure modes.

Typical competencies required for personnel involved in ongoing dam safety management are listed in Table 2.1.

Table 2.1: Competencies for People involved in Dam Safety Management

Role	Principal areas of competence
Dam Owner/Manager/ Accountable Executive	• Legal, regulatory and duty of care responsibilities relating to dam safety • Understanding of dams and reservoirs as systems, how they are designed to function, how they should operate, and how they may fail to function (potential failure modes) • Understanding of dam safety hazards and risks • Understanding of Dam Safety Management Systems, principles and practices, and emergency planning and response procedures • Understanding of quality assurance principles • Understanding of public safety around dams and reservoirs
Technical Adviser	• Understanding of dams and reservoirs as systems, how they are designed to function, how they should operate, and how they may fail to function (potential failure modes) • Understanding of dam safety hazards and risks • Structural, geotechnical, seismic, hydrologic and hydraulic design • Dam construction techniques • Understanding of Dam Safety Management Systems, principles and practices • Operation, maintenance and testing procedures • Surveillance and performance assessment • Response to dam safety issues • Emergency planning • Emergency response • Managing dam safety issues • Gates and valves including associated power supplies, control and protection systems, and communication systems
Operation and Maintenance Personnel[1]	• Safe operation of dams and reservoirs including recognition of departures from intended operation • Safe operation of gates and valves • Maintenance and testing practices • Dam safety and surveillance principles and practices • Emergency response procedures including escalation process for alerting others • Emergency response
Dam Safety Field Personnel (e.g. Surveillance Inspectors)[1]	• Dam safety and surveillance principles including visual recognition of departures from intended operation and the onset of potential failure modes and dam safety deficiencies • Potential failure modes • Understanding of dam safety hazards and risks • Emergency response procedures including escalation process for alerting others • Safe operation of gates and valves (if appropriate)
Key Emergency Personnel[2]/ Civil Defence	• Understanding of the potential effects of a dam system failure and uncontrolled releases • Emergency planning • Emergency response
Recognised Engineer (PIC, DSAP – for regulatory certification, audit and annual compliance)[3]	• Chartered Professional Engineer (CPEng) and Recognised Engineer qualification and competency requirements (refer Module 1: Legal Requirements)
Regulators	• Understanding of the implications of legislation relating to dam safety

Continued over page >

Role	Principal areas of competence
Public at Risk	• Understanding of safety around dams and reservoirs • Emergency awareness and response
Notes: 1. Depending on the dam, Potential Impact Classification (PIC) and the Owner, these roles may be performed by the Owner in some cases and, in other cases, by a single person or team of people. 2. Depending on the dam, Potential Impact Classification (PIC) and the Owner, the Technical Adviser can be an external contractor or consultant, or the Owner's personnel. 3. Refer Module 1: Legal Requirements regarding who can fulfil the Recognised Engineer role and how to manage conflict of interest).	

2.2.2 Training and Education

A long term perspective is required in the training of people for dam safety. Experienced technical expertise is scarce and training is necessary to up-skill new entrants in the industry. Succession planning is vital to maintaining consistent dam safety expertise.

Training and education programmes for all personnel with responsibilities for dam safety should be geared towards developing and maintaining appropriate awareness and competencies, and should take into account:

- The organisational structure and governance arrangements.
- The characteristics of the dam, reservoir and appurtenant structures and surveillance procedures.
- The potential failure modes for the dam and appurtenant structures.
- The gate and valve systems that fulfil dam and reservoir safety functions.
- Site-specific issues including any potential or confirmed dam safety deficiencies.
- Changes in the facilities or operating procedures.

In some cases it may be appropriate to prepare and issue a concise statement (e.g. 1-2 pages laminated) that outlines a dam's potential failure modes, things to watch out for, and response actions if unexpected changes are observed.

Training will depend on the nature and the PIC of the dam, and may range from the Designer or Technical Adviser training the Owner/Operator of a small Low PIC dam to Operators of High PIC dams completing structured training courses, seminars, audits and refresher courses. Training may include:

- Attendance at relevant courses and seminars (e.g. dam safety management courses, conferences and workshops).
- Attendance at technical workshops, seminars, symposia and conferences.
- In-house courses on the implementation of operational procedures.
- Interaction with other dam Owners to share and learn from their experiences.
- Keeping up to date with dam safety practice, through the acquisition and review of dam safety guidelines, technical papers, training materials, special interest journals, and participation in technical interest groups.
- Involvement in dam safety management activities and processes.
- Review of and familiarisation with potential failure modes, intermediate dam safety reviews and comprehensive dam safety reviews.
- Participation in dam safety reviews.
- Attendance at emergency management courses (e.g. Coordinated Incident Management System) and participation in emergency management exercises/ simulations.

The personnel involved must understand what is required to fulfil their respective roles and be suitably trained in their areas of accountability and responsibility. This is particularly the case for managers, caretakers and operational staff who may be recruited into their positions without prior dam safety experience.

Training records should be maintained for all personnel with dam safety accountabilities and responsibilities.

3. Establishing a Dam Safety Management System

3.1 Form and Content

As noted in section 1.1, these Guidelines recommend that where the consequences of dam failure would adversely affect people, property and the environment, Owners should consider developing and implementing a DSMS irrespective of the PIC of the dam.

The form and content of a DSMS will vary to some extent depending on the Owner and the characteristics of the dam (or dams). However, a DSMS should:

- Be consistent with the dam safety principles given in the Parent Document of these Guidelines.
- Be appropriate to the type, size and PIC of the dam and its appurtenant structures.
- Contain dam and reservoir operation and maintenance procedures or, if appropriate, a reference to separate operation and maintenance procedures.
- Detail requirements and frequencies for routine surveillance and monitoring, data evaluation, and reporting to the dam Owner.
- Detail requirements and frequencies for the routine inspection and maintenance of appurtenant structures and inspections, maintenance and testing of gate and valve systems that fulfil dam and reservoir safety functions.
- Assign competencies for the routine operation, surveillance, monitoring, inspection, testing, data evaluation and reporting tasks to ensure they are carried out by appropriately qualified and experienced people.
- Contain requirements for intermediate dam safety reviews.
- Contain requirements for comprehensive dam safety reviews.
- Contain an emergency action plan or, if appropriate, a reference to a separate emergency action plan.
- Contain procedures for the identification, evaluation, and resolution of dam safety issues.
- Include appropriate governance, management, communication, training and information management systems.
- Contain continuity and contingency planning to be prepared for disruptions and prolonged events (e.g. pandemics, widespread natural events)

Regulatory requirements for dam safety assurance are discussed in Module 1: Legal Requirements.

3.2 Dams systems

3.2.1 Defining and understanding the dam system

As stated in the Parent Document of these Guidelines, dam safety requires consideration of the total system surrounding the dam and should not be limited to the dam structure. It is important to consider the interaction between parts of the dam system – not only the technical and physical components (such as reservoir, dam, foundations, abutments, appurtenant structures), but also the non-physical components. Non-physical components include human and organisational processes, procedures and factors that the dam system depends on for safe function (such as inspections, monitoring, maintenance, operations, testing, emergency response, supervision, management, information flow, control decisions, and documentation). Effective information flow and communication is critical to the safe operation of dam systems, particularly at interfaces and boundaries, both internal and external to the system.

To support safe dam and reservoir operation and management it is important for the dam Owner, Manager and Technical Advisor roles (refer Table 2.1) to have sound appreciation and documentation of:

- how the dam system is defined, including its reservoir and the boundaries where the total system is impacted by, and impacts on, the external domain
- how the dam system is designed to function and how it should operate (operational states), including human and organisational factors
- how the dam system was constructed and how it is functioning and operating (compared with how it was designed to function and operate)
- how the dam system's components are designed to function, including controls and interdependencies between components and human and organisational factors
- how the components were constructed and how they are functioning (compared with how they were designed to function)
- external and internal hazards that threaten the dam system and its components, including human and organisational factors
- how the dam system and its components may fail to function, i.e. potential failure modes including reservoir safety and operational failure modes
- the consequences of dam system failure to function and component failure to function
- monitoring and change control process for changes to the dam system (e.g. physical, non-physical, hazards and threats)

Detailed discussion of dams as systems can be found in Operational Safety of Dams and Reservoirs (Hartford, Baecher, Zielinski, Patev, Ascila and Rytters, 2016) and Canadian Dam Association (CDA) Technical Bulletin Failure Modes Analysis (Part 1: Identification of Failure Modes and Mechanisms) (CDA, 2023). The Oroville Dam Spillway Incident Independent Forensic Team Report, Appendix J, provides a useful Human Factors Framework and Methodology.

3.2.2 Reservoir considerations

The reservoir, or stored contents, is the fundamental hazard to people, property and the environment created by the presence of a dam. It is therefore important to consider a dam's operation and safety in the wider context of the reservoir that it impounds, and thus the zone of awareness in the DSMS should address the total dam and reservoir system, including, and in some cases extending beyond, the impounded reservoir. The DSMS should consider other structures that retain the same reservoir (e.g. subsidiary dams, appurtenant structures, gates and valves), and the effects of upstream hazards that could affect the safety of the dam (e.g. erosion and sediment, upstream landslides). All issues and effects that could affect safe containment, conveyance and control of the reservoir must be thoroughly considered.

When a dam is in a 'cascade' environment (refer Module 2: Consequence Assessment and Dam Classification), the outflow from a failure of an upstream dam can affect the safety of some or all of the downstream dams. In certain cases an Owner may have little control over the potential adverse physical effects resulting from an upstream dam failure but, with an understanding of the characteristics of the upstream dam, an Owner of a downstream dam should be able to respond appropriately at their dam and provide any necessary warnings to the downstream population and affected agencies. A similar situation occurs where a natural dam forms upstream of an Owner's dam, as a result of a landslide or other accumulation of debris, and impounds inflows forming a new reservoir whose failure may affect the safety of the Owner's dam and any downstream dams.

A dam Owner and/or Operator should have a wide appreciation of the dam system and public safety implications of inflows to, and outflows from, the dam's reservoir under all conditions.

Other issues which can affect reservoir safety and should be considered in the development and implementation of a DSMS include:

- Off-river storage dams, where the reservoir inflows and operation are predominantly controlled.
- Water transfers between catchments which can alter natural inflow regimes.
- Changes of land use around a reservoir which can affect inflow rates and may introduce debris and water quality issues that could affect dam safety.

3.3 Dam system considerations for developing a Dam Safety Management System

A dam system is unique with respect to its configuration, geologic setting, design, construction, hazards, threats, operational context, human and organisational factors, inherent condition and historical performance. Therefore each dam system has its own features, capabilities, operation, characteristic behaviours and potential failure modes.

Accordingly, the following questions should be considered in developing a DSMS to ensure that the content and activities are appropriate to the dam system:

- Are the dam system and its components well defined and documented, including functions, operation, controls and interdependencies?
- What resilient features are built into the dam system that give it capacity to withstand changing conditions caused by sudden shocks, gradual stresses and cumulative change (e.g. defensive design, fail to safe, redundancy, segregation, diversity, backup, access, training)?
- What are the dam type and features?
- What are the foundation type and features?
- What are the appurtenant structures, gate and valve systems, and their operational requirements?
- What are the reservoir and catchment features?
- What are the human and organisational factors required for the dam system to function and operate?
- How does the public interact with the dam system (e.g. public safety and security)?
- What physical security and cyber security aspects may threaten dam and reservoir safety?
- Are the external and internal hazards that threaten the dam system monitored and reviewed for change?
- What are the consequences of functional failure to third parties, their property and infrastructure, and the environment?
- What are the consequences of functional failure to the Owner and Owner's business?
- What are the primary and other purposes and functions of the dam and reservoir?
- What are the dam and reservoir's operational parameters (e.g. inflows, outflows, daily/seasonal/flood reservoir range)?
- What is the dam's design, construction and performance history?
- What are the specific loading conditions for the dam?
- What are the performance expectations for the dam under all loading conditions?
- Is the characteristic behaviour well understood for all loading conditions?
- What is the dam's inherent condition?
- Is the instrumentation appropriate and does it work?
- What are the dam system's credible potential failure modes, what initiating condition is required, and what would be the early indicators of the onset of the potential failure modes?
- How quickly could the potential failure modes develop?
- What timeframes are available to intervene should a potential failure mode develop?
- Is intervention possible if a potential failure mode is developing?

The DSMS should be fit for purpose and commensurate with the consequences of dam system failure (including component functional failures) and the required dam system performance under all loading conditions. The minimum legal requirements for dam safety assurance must be met (refer Module 1: Legal Requirements); however, these Guidelines recommend that additional elements and measures should be considered and incorporated into a DSMS appropriate to the particular dam system and its complexities. An effective DSMS supports asset longevity, business risk management, license to operate, insurance and lending.

An effective DSMS should adapt dynamically to change and seek to continuously improve. Change management and improvement are discussed in section 5 of this module.

Knowledge management is a critical aspect of a DSMS that embodies a range of activities to support deep understanding of dam systems and their safe operation. Knowledge management activities include training, capability management (refer section 2.2 People), information management and information security (refer section 4.9 Information Management).

For new dams the DSMS should reflect the results of the completed investigation, design, construction and commissioning processes.

For existing dams it may be necessary to compile data on the dam from a variety of sources, including existing documents and verbal reports from personnel involved in the dam's design, construction and/or operation, and develop a DSMS from the resulting information. Verbal reports from designers and constructors often provide valuable insights into matters not normally archived, so they should be transcribed into written reports.

3.4 Failure Modes And Effects Analysis (FMEA)

3.4.1 Uses and benefits

Failure Modes and Effects Analysis (FMEA) provides enhanced understanding of the key vulnerabilities of the dam system and enables surveillance, operation, maintenance and emergency preparedness requirements in the DSMS to be targeted for the identified potential failure modes. The FMEA should identify surveillance requirements to provide early warnings of the development of the potential failure modes. FMEA provide valuable information for the safety evaluation of existing dams and minimise the potential for overlooking important issues relevant to the safe performance of dam systems. FMEA also assists in the prioritization of future investigation and design activities and dam safety enhancement projects.

FMEA is most appropriate for Medium and High PIC dams, with the level of detail appropriate to the dam and its complexities. However, FMEA may also be applied to Low PIC dams where the operational value of a dam, or the business consequence of a dam failure, is significant.

Where an FMEA has not been completed for a Medium or High PIC dam it should be carried out prior to or during the completion of a Comprehensive Dam Safety Review (CDSR). After the completion of an initial FMEA for an existing dam, subsequent CDSRs should review the results of the FMEA and highlight any identified shortcomings in the FMEA report as well as any changes to the dam system that should be reflected in an FMEA update (refer Section 4.5).

Refer to Module 3: Investigation, Design and Analysis and Module 6: Emergency Preparedness for related detail on the development and use of potential failure modes.

3.4.2 Identification and assessment of potential failure modes

The identification and assessment of potential failure modes for a dam system (new or existing) can be achieved through the completion of an FMEA. In these Guidelines FMEA is defined as a systematic method for identifying and assessing dam system and component potential failure modes and effects based on a sound appreciation of:

- dam system and component functions, operation, interdependencies, and controls
- hazards and threats
- human and organisational factors
- dam system and component failures to function

A potential failure mode is a mechanism or set of circumstances that could result in the uncontrolled release of all or part of the contents of a reservoir. These guidelines recommend that potential failure modes include component level failures to function and their effects on the safe performance of the overall dam system.

An FMEA is best completed through considered preparation and review of relevant material, site visit (as needed), facilitated workshop and reporting. Preparation and review of relevant material ahead of the workshop should include appropriate analyses to support effective identification and assessment of potential failure modes. The facilitated workshop should be attended by representatives of the dam Owner, Technical Advisers and others (such as designers, contractors, operators, maintainers and surveillance staff) with relevant knowledge of the dam system's design functions, construction, hazards, threats, operation and its historical performance. FMEA results inherently reflect the capability and knowledge of the people performing the FMEA based on the information available at the time. The facilitator has the important role of systematically asking structured, open questions that allow full and thorough consideration of the hazards and threats to the dam system and component functions. Experiences such as the Oroville Dam spillway failures have shown that reliance on free thought and an unstructured approach can be unsuccessful in identifying and understanding key dam system vulnerabilities. The Hazards and Failure Modes Matrix (HFMM) developed by BC Hydro, and adopted by Canadian Dam Association, is an example of a systematic and structured approach to screening and identifying dam system hazards and potential failure modes. Canadian Dam Association (CDA) Technical Bulletin Failure Modes Analysis (Part 1: Identification of Failure Modes and Mechanisms) (CDA, 2023) provides detailed guidance on such a systematic approach to identifying potential failure modes, including use of the HFMM and a supporting table of questions to ask contributing participants. The Oroville Dam Spillway Incident Independent Forensic Team Report, Appendix F3, provides a useful commentary on Failure Modes Analysis. Failure Modes and Effects Criticality Analysis (FMECA), event tree analysis and fault tree analysis are further methods that can be used to analyse potential failure modes and identify system vulnerabilities. FMECA adds a step to FMEA to address the criticality of each failure mode; failure modes are assessed for probability and consequence, and ranked according to risk.

The FMEA should:

- Review the available design, construction and dam safety study documents, and operational and surveillance records for the dam.
- Review the dam system functional descriptions and diagrams to appreciate the dam system and component functions and operation, as well as controls and interdependencies, including human and organisational factors. Each dam system component's dam safety or reservoir safety function should be stated (e.g. containment, conveyance, control). Where dam system functional descriptions and diagrams don't yet exist, they may be developed ahead of, or as part of, the FMEA.
- Seek inputs from individuals and specialists with specific knowledge on the hazards and threats (both originating external to the dam system and internal to the dam system) and the performance of the dam system.
- Identify all potential failure modes related to the safe performance of the dam system's containment, conveyance and control functions. Potential failure modes relating to reservoir safety (not dam safety) and operational events (load conditions smaller and more likely than unusual and extreme), may also be identified for public safety and business risk management reasons. Industry operational events and incidents continue to demonstrate that component-level functional failures can have significant to high consequences (e.g. unusual combinations of probable events).
- Categorise the potential failure modes as credible, not credible, or as having insufficient information (to categorise). Highlight those of greater significance. Credible means the potential failure mode is physically possible and not so remote a possibility as to be not reasonable to postulate. Several dam potential failure mode categorisation systems are available. For example the US Federal Energy Regulatory Commission Part 12D Refresher Training Potential Failure Modes Analysis (FERC, 2020) provides a four-category system that can be used to categorise and highlight potential failure modes based on physical possibility, significance, potential for occurrence, magnitude of consequence and likelihood of adverse response, and whether sufficient information is available.

- Assess (qualitatively or quantitatively) the likelihoods of the development of the credible potential failure modes.
- Identify the loading conditions, visual and instrumented performance indicators, and surveillance and emergency preparedness requirements for the potential failure modes. Where practicable, identify the rate that each potential failure mode could develop and what timeframes may be available to intervene should the potential failure mode develop.

The FMEA may also:

- Identify any potential or confirmed dam safety deficiencies relating to the potential failure modes.
- Identify knowledge gaps that require further investigation to obtain an improved understanding of the dam's potential failure modes.
- Assess the nature of the breach or uncontrolled release and the downstream consequences for selected credible potential failure modes (refer Module 2: Consequence Assessment and Dam Classification).

The process and outcomes of the FMEA should be fully documented, including: 1) a summary of other failure modes that were identified but considered not credible (with reasons for their rejection as credible failure modes); and 2) other failure modes where there was insufficient information to classify as credible or not credible.

3.5 Documentation

A DSMS, including all relevant operation, surveillance, maintenance, testing and emergency procedures, should be well documented and available at all times for those responsible for its implementation and review. The DSMS may be prepared as a stand-alone document, or as a 'core' explanatory document that is supported by other documents that detail specific elements of the DSMS. Nevertheless the DSMS should be clear, user friendly and easy to implement.

All documentation relating to a DSMS should be controlled using appropriate document management processes. The documents should be stored securely, appropriately backed up and able to be accessed in normal and emergency conditions. While electronic formats provide significant technological and access advantages, hard copies may also be required for conditions where electronic access may become compromised.

4. Elements of a Dam Safety Management System

A DSMS includes elements that are minimum regulatory requirements (e.g. surveillance and dam safety reviews for Medium and High PIC dams) and recommended practice (e.g. governance and information management for all dams). Owners should include all elements in their DSMSs to ensure effective and appropriate dam safety management. The 12 elements that should be included in a DSMS are listed in Table 4.1. Seven of the elements are required by the Regulations (2022) to be included in a Dam Safety Assurance Programme (DSAP) for a Medium or High PIC dam (refer Module 1: Legal Requirements).

An effective DSMS will not only provide a framework for an Owner to assure safe dam and reservoir operation, for any dam irrespective of its PIC, but it will also support asset management practices and allow an Owner to maximise the value of their asset.

Two of the elements are addressed in sections 2.1 and 2.2, and the remaining 10 elements are addressed in sections 4.1 to 4.10 of this module.

Table 4.1: Elements of a Dam Safety Management System

Element	Reference section	Type of element	
		Recommended practice	Regulatory minimum DSAP (Note 1)
Governance	2.1	√	
People	2.2	√	
Dam and Reservoir Operation and Maintenance	4.1	√	√
Surveillance	4.2	√	√
Appurtenant Structures and Gate and Valve Systems	4.3	√	√
Intermediate Dam Safety Reviews	4.4	√	√
Comprehensive Dam Safety Reviews	4.5	√	√
Special Inspections and Dam Safety Reviews	4.6	√	
Emergency Preparedness (refer Module 6)	4.7	√	√
Identifying and Managing Dam Safety Issues (refer Module 7)	4.8	√	√
Information Management	4.9	√	
Audits and Reviews	4.10	√	
Notes: 1. Elements of a DSAP required by the Regulations (2022) (refer Module 1).			

4.1 Dam and reservoir operation and maintenance

4.1.1 Procedures and protocols

4.1.1.1 Dam and reservoir operation

The Owner should understand the dam system's design functions and operation, including the parameters within which their reservoir is to be operated for normal, unusual and extreme loading and operating conditions. These parameters usually include measurable inflows, outflows, and reservoir level thresholds, and are typically embodied in protocols in consent conditions for a dam, reservoir or scheme.

From a dam safety perspective the operation of a reservoir and wider dam system should not present undue risk to people and property, the environment upstream and downstream of the dam, and downstream dams that form part of a cascade development on a river system. The Owner should also understand any operational conflicts that may exist in their dam system between dam safety, consent compliance and public safety drivers.

Some dams may have a limited ability, or no ability, to operationally control inflows or outflows and therefore reservoir level. Moreover, the available storage in a reservoir will often not be sufficient to attenuate maximum outflows during large or extreme inflows. Procedures for the operation of reservoirs in a cascade development should be developed considering the safety of the whole cascade system.

Owners should ensure that their dam and reservoir operational plans and protocols are appropriate and provide sufficient margin to ensure the safety of the dam under all loading conditions and foreseeable operational scenarios. Sufficient freeboard should be available between the full supply level and the dam crest (refer Module 3), and neighbouring property and infrastructure, to prevent overtopping or flooding during unusual and extreme inflow scenarios. There may also be a need to limit the rate at which a reservoir level is lowered, via outflows, to ensure that the stability of the dam and reservoir shoreline is not adversely affected.

Dam and reservoir operation and maintenance procedures may be documented in an operation and maintenance manual or similar documented system. Where the operation and maintenance procedures are straightforward and simple, it may be appropriate to include them directly in the DSMS document.

If the operation and maintenance procedures and requirements are more complex, then a summary of the procedures along with a reference to where the details can be found should be included in the DSMS document.

4.1.1.2 Dam and reservoir safety

A DSMS for High and Medium PIC dams should include the following operation and maintenance procedures:

- Reservoir operation procedures during normal, unusual, extreme and emergency conditions (i.e. conditions that could result in dam failure if appropriate actions are not initiated).
- Operating procedures for gate and valve systems that fulfil dam and reservoir safety functions (e.g. reservoir level thresholds, gate/valve openings and discharge ramping rates).
- Maintenance procedures for gate and valve systems that fulfil dam and reservoir safety functions (e.g. visual inspections, battery/fuel checks, changes in lubricating fluids, major overhauls). Refer to section 4.3.4.
- Testing procedures for gate and valve systems that fulfil dam and reservoir safety functions, including power supplies, operating systems, and control and protection systems, to ensure ongoing functionality and reliability. Refer to section 4.3.4.
- Civil works maintenance procedures (e.g. internal drainage system cleaning, instrument repair, vegetation and debris clearing, upstream erosion protection reinforcement).
- Any procedures for the monitoring of upstream reservoir slopes and downstream banks (e.g. the stability of upstream landslides during high reservoir levels or rapid reservoir drawdown, and the stability of downstream river banks during high discharges).

Generally, the level of detail in operation and maintenance procedures related to dam safety should reflect the complexity of the dam system and its consequences of failure.

4.1.1.3 Review and test

The Owner, with support from appropriate technical and operations and maintenance personnel, should periodically review and test the dam's operation and maintenance procedures and protocols, particularly those where dam and reservoir safety is dependent on the correct operation of gates and valves.

4.1.2 Operator experience and training

Operating personnel should be competent, appropriately qualified and trained to fulfil the requirements of the dam and reservoir operation and maintenance procedures. As well as fulfilling the functional requirements of the relevant procedures, operating personnel should be able to recognise significant threats to the safe performance of the dam and indicators for the development of its potential failure modes, and understand how to initiate appropriate response actions and when to seek specialist technical advice.

The level of experience, qualifications and training of the operating personnel should be commensurate with the complexity of the dam and appurtenant structures. The nature of the dam's potential failure modes (especially those related to inappropriate operation or accidental mis-operation) and the consequences of dam failure (including unintentional flow releases) should be clearly understood by the operating personnel. The training process and operator competence certification should be documented in the Owner's quality assurance records.

4.1.3 Reservoir operation records

It is important that parameters associated with a reservoir's operation are consistently and accurately recorded and stored securely in a way that allows their consideration during routine dam safety monitoring, and annual and comprehensive dam safety reviews. Parameters that are important for the evaluation of dam safety include rainfall, reservoir inflows, reservoir lake levels, reservoir outflows, and all operations (including inspections, maintenance and testing) of gates and valves.

Incidents such as unusual loading conditions, operations, and occurrences, together with any evaluations and lessons learned, should also be recorded.

4.1.4 Dam and reservoir maintenance

There is a range of regular maintenance activities that contribute to the ongoing safety of dams and their reservoirs. Such activities will also maintain, or enhance the value or life of the asset and may minimise more extensive maintenance requirements and associated costs, or prevent the need for costly repairs or remedial works that could otherwise arise.

The following are common examples of maintenance activities, many of which will be required in some form for any dam. However, each dam and its setting is unique and will therefore have its own set of maintenance requirements. In recognition of this, maintenance requirements should be determined in consultation with appropriate Technical Advisers.

4.1.4.1 Reservoir shoreline and erosion

The reservoir shoreline can be susceptible to the effects of a dam's operation and the following maintenance activities, where necessary, should be completed:

- Repair rip-rap damage or surface erosion on the dam face.
- Repair excessive beaching or erosion of the reservoir shoreline.
- Maintain any facilities provided for the management of shoreline stability.

4.1.4.2 Concrete and embankment dams

Maintenance activities will be somewhat dependent on the dam type and its characteristics, and the actual loading and operating conditions. Any damage should be photographed and recorded. The following maintenance activities, where necessary, should be completed:

- Maintain and repair surface and joint sealing systems (including waterstops).
- Repair cracks and defects.
- Maintain or restore freeboard provisions.
- Repair wave-induced surface erosion.
- Repair concrete damage, and reinforcement or steelwork corrosion.
- Repair seepage-induced erosion and/or slumping.

4.1.4.3 Appurtenant structures and debris management

Spillway and intake facilities that fulfil dam safety functions should remain unobstructed to provide their full flow capacity on demand. In addition, appurtenant structures such as spillways, conduits and open channels (canals, flumes) may require periodic maintenance to ensure they remain capable of safely discharging their design flows.

The following maintenance activities, where necessary, should be completed:

- Repair damage such as scour, erosion, cracking or waterstop failure in spillway chutes, stilling basins and outlet conduits.
- Maintain the functionality of drainage channels below spillways and of venting/air supply features included in discharge facilities to prevent cavitation.
- Maintain booms to prevent debris entry to spillway outlets and water intake facilities.
- Remove dead or unstable timber from the reservoir shoreline and the dam face.
- Manage and/or remove aquatic weed growth in the reservoir.
- Clean screens on intakes and outlet facilities.

4.1.4.4 Drainage systems

Dams, their abutments, appurtenant structures and reservoir landslides (where they exist) often rely on effective drainage of surface and sub-surface water for their ongoing stability and safe performance. Usually, effective drainage will also improve the ability to effectively monitor dam performance indicators such as seepage, leakage and uplift.

To maintain the effectiveness of surface and sub-surface drainage systems the following maintenance activities, where necessary, should be completed:

- Maintain adequate surface drainage at dams, abutments and reservoir landslides, such that they are not unnecessarily saturated or eroded, and effective inspection and measurement of seepage/ leakage is possible.
- Maintain adequate sub-surface (internal) drainage systems at dams, foundations, abutments, reservoir landslides (where they exist) and structures such as spillway chutes, stilling basins and retaining walls to relieve piezometric pressures and/or foundation uplift, and allow effective inspection and measurement of uplift and seepage conditions.
- Periodically drain dam and abutment seepage areas and dam toes inundated by tailwater levels, where possible, to allow effective visual inspection and monitoring of seepage flows.

Dam and foundation internal drainage systems should be monitored for condition and performance with respect to their design assumptions and cleaned, if necessary and appropriate, to maintain their effectiveness. When choosing and implementing cleaning methods, extreme care should be taken to ensure the dam and foundation are not pressurised or eroded by the cleaning operation, and the drains are not damaged. Monitoring and recording of uplift pressures and drainage flows should be completed prior to and following cleaning (after conditions have stabilised) to verify the effect of the drain cleaning and the sensitivity of the drains to plugging, and to allow an appropriate drain cleaning frequency to be established.

4.1.4.5 Vegetation control

Vegetation on and adjacent to a dam and its abutments should be kept to a minimum and, in particular, trees and large vegetation should not be allowed to establish on the dam or in the vicinity of its abutments and toe. Grass cover on embankment dams should be kept short.

The objectives of vegetation control are to:

- Prevent root penetration, which could affect the safety of a dam.
- Allow unimpeded observation of dam performance indicators such as seepage, leakage, slumps, instability and deterioration of materials.

Where vegetation has been allowed to establish on dam or abutment faces, the removal of the vegetation should be planned and executed with inputs from a Technical Adviser.

Dam and abutment slopes should also be kept clear of animal burrows, and activities that can result in rutting/tracking on dam faces (e.g. grazing and vehicle activities) should be minimised. Where it does occur, rutting and tracking should be repaired.

4.1.4.6 Infrastructure and services on dams

It is common for infrastructure and services (i.e. roads, power cables, communication cables, and water and gas pipelines), owned and operated by third parties, to be routed across dams and appurtenant structures. Dam Owners must ensure that they are informed and consulted about installation, operation and maintenance activities for the infrastructure and services, and that the safety of the dam and appurtenant structures is not compromised by the presence or maintenance of these items.

4.2 Surveillance

4.2.1 Philosophy

A robust and continuously improving surveillance process is the Owner's 'front line of defence' for the safe operation of their dams and reservoirs. Surveillance provides the cornerstone for effective management of dam safety and operational risks and includes routine visual inspections, instrument monitoring, data review and evaluation, and reporting on the safety of the dam.

Dam systems are inherently dynamic and therefore surveillance processes may need periodic review and be adaptive in order to capture changing conditions and circumstances.

The United States Federal Guidelines for Dam Safety (FEMA 2004) includes the following statement:

> **Monitoring existing dams and reacting quickly to inadequate performance or to danger signals is a continuing critical aspect for dam safety. Careful monitoring and quick response can prevent failures, including those caused by poor construction.**

It is useful to define varying levels of surveillance for implementation as they are needed:

- **Routine surveillance** is undertaken during normal 'everyday' operating conditions.
- **Enhanced surveillance** is undertaken during, and/or for a period following, unusual or unprecedented loading conditions (e.g. floods and earthquakes), or when a potential dam safety deficiency exists. Additional and/or more frequent surveillance and monitoring is carried out to provide more detailed characterisation of the dam and/or foundation's behaviour and to assist with future actions should they be required.
- **Intensive surveillance** is required when there is a confirmed dam safety deficiency (when relevant load condition is occurring) or there is a developing dam safety threat. Intensive surveillance and monitoring can be round the clock, with experienced personnel and an enhanced means for reporting changes or anomalies to the Owner and their technical personnel or Technical Adviser. It targets specific aspects of dam and/or foundation performance but should include broader observation of the dam system in the event there is an unusual response elsewhere. Emergency and regulatory authorities may be notified of the condition and put on alert.

4.2.2 Objectives

The level of surveillance should be appropriate to the individual dam considering its type, foundation, design, construction, operational context, consequences of failure, inherent condition, historical performance, characteristic behaviour and potential failure modes. The objectives of surveillance are primarily to:

- Monitor dam and foundation performance, compare the performance with expected behaviours, and ensure that the characteristic behaviours are well understood for a range of loading conditions.
- Provide a baseline of performance information against which future changes in performance can be assessed.
- Be targeted to ensure that any changes in condition are noted to determine if they are possible early indications of the onset of a potential failure mode for the dam system. Such awareness may make it possible for intervention to occur (i.e. to prevent a potential failure mode from developing or to minimise the consequences of the occurrence of a potential failure mode).
- Identify and initiate the evaluation of dam safety issues arising from visual or measured/instrumented surveillance.
- Be dynamic and adaptive, such that the level of surveillance can be varied in a pre-determined manner in response to changing conditions and circumstances (e.g. loading, seasonal, operational, time or event based changes).
- Provide accurate and consistent data throughout the life of a dam.
- Be robust and auditable.

4.2.3 Process and procedure

An Owner's surveillance process and procedures should be well defined and functional. They should be established and documented in a way that clearly describes:

- What is to be done.
- Who is responsible for doing it.
- When and how often it is to be done (timing and frequency).
- How it is to be done.
- How it will be evaluated, documented and quality assured.
- How any anomalies will be addressed.
- How issues will be escalated for consideration by Technical Advisers or other dam safety specialists.
- Events that could trigger the need for enhanced and intensive surveillance.
- Provisions for enhanced and intensive surveillance.

The documentation should be controlled and readily available to, and understood by, those responsible for the implementation of surveillance activities. It should also be regularly reviewed and updated to reflect changes in processes or requirements, and allow improvements in the effectiveness of surveillance activities.

4.2.4 Quality

A high level of quality is required in the data and information that is gathered, stored and interpreted for the monitoring and evaluation of the safety of a dam during its lifetime. The surveillance process can be thought of as a 'quality chain' – a multi-linked chain where each step in the process forms a critical link. Without rigorous attention to assuring the quality at each step, links in the chain can become tenuous or broken, compromising the integrity of the whole chain, and hence the safety of the dam. The quality chain starts with the personnel undertaking surveillance activities in the field, continues with regular review of the information by appropriate technical specialists, and is completed with feedback to the field personnel (relative to the nature of continued surveillance) and reporting to the Owner on the safety of the dam and the need for specific responses or required actions.

4.2.5 Visual inspections

4.2.5.1 Philosophy

Visual inspection by competent and trained personnel is the most effective means of dam surveillance. There is no substitute for the observations and preliminary judgements of individuals who:

- Are familiar with the dam's layout and features.
- Are familiar with the objectives of instrument monitoring and measurement, and instrument monitoring and measurement procedures.
- Are aware of the characteristic behaviour of the dam and installed instruments.
- Can detect, record and report any change in condition.
- Understand the dam's potential failure modes and vulnerabilities.
- Are able to recognise indicators of adverse dam performance and the initiation of potential failure modes.

Visual inspections should follow a repeatable checklist of items that is appropriate to the dam (and foundation) type, characteristic behaviour and potential failure modes. Inspection checklists should be developed and reviewed in conjunction with a Technical Adviser. An example checklist for an embankment dam is provided in Figure 4.1. Note that this example is provided to illustrate the nature of the checklist, and as such, items E1 to E10 are not all inclusive. The checklist developed for each dam should be geared to the specific nature, features, characteristics, identified credible potential failure modes and performance history of the dam.

An open ended question at the end of each section of the checklist should be included, such as, 'Are there any other conditions or observations of interest?'. It is very important that the checklist should not be so prescriptive that the inspector is not encouraged to look at other areas and features that may have a bearing on dam safety and this principle should be emphasised in the inspector's training.

Photographs of general and specific features, from repeatable locations provide an effective long term record of inspection observations. Video recording of features or unusual events can also be particularly valuable. Unmanned Aerial Vehicles (UAVs, also referred to as drones) and underwater Remotely Operated Vehicles (ROV) fitted with video cameras or Light Detection and Ranging (LiDAR) are particularly useful for inspecting areas that are unsafe, difficult, or otherwise not possible to access, including during gate testing and emergency conditions. A competent and trained inspector should be part of the UAV/ROV inspection to witness the video footage, reference observations and support best understanding of key areas of interest at the time of inspection.

Figure 4.1: Example Routine Visual Inspection Checklist for an Embankment Dam

Routine Inspection List for Blue Dam		
Inspected by: **Date and time:** **Weather:**		
Potential Failure Modes and what to look for: • PFM1: Embankment seepage and internal erosion leading to piping failure (e.g. unusual seepage, depressions) • PFM2: Foundation seepage and internal erosion leading to piping failure (e.g. unusual seepage, depressions) • PFM3: Flood-induced overtopping of embankment and erosion leading to failure (e.g. loss of freeboard, erosion) • PFM4: Earthquake induced embankment cracking leading to seepage, internal erosion and piping failure (e.g. cracking, unusual seepage, depressions) • PFM5: Earthquake induced embankment deformation leading to loss of freeboard and overtopping failure (e.g. loss of freeboard, deformation) • PFM6: Operational flow imbalance induced overtopping of embankment and erosion leading to failure (e.g. loss of freeboard, erosion)		
Item no.	**Description**	**Observation/Comment**
E1	Record reservoir level (e.g. metres above mean sea level)	
E2	Is there reservoir shoreline instability or erosion?	
E3	Is the upstream face showing any erosion, instability, depression or cracking?	
E4	Is the dam crest showing any deformation, misalignment, depressions or cracking?	
E5	Is the left abutment showing any instability or seepage, including where the dam embankment contacts with the abutment?	
E6	Is the right abutment showing any instability or seepage, including where the dam embankment contacts with the abutment?	
E7	Is the downstream face showing any instability, deformation, depression, cracking or seepage?	
E8	Is the dam toe showing any erosion or seepage?	
E9	Measure the total dam seepage (e.g. time to fill 1 litre container, or mm head over a 90 degree v-notch weir)	
E10	Is the spillway entrance obstructed? Is the spillway chute or plunge pool damaged or eroded?	
Other Comments/Observations (e.g. unusual events since last inspection, vegetation issues, operating issues):		

4.2.5.2 Frequency

The frequency of routine visual inspections and the evaluation of collected data should be appropriate to the PIC of the dam, and the particular importance or vulnerability of the dam. Recommended frequencies for High, Medium and Low PIC dams, other than flood detention dams, are listed in Table 4.2. Flood detention dam should be inspected on an annual basis, and during and immediately following flood events.

Table 4.2: Suggested routine visual inspection frequencies (assuming no dam safety deficiencies)[1]

Type of Inspection	Potential Impact Classification (PIC)		
	Low	Medium	High
Routine	Monthly[2] to Quarterly	Monthly[2]	Weekly[3] to Monthly[2]

Notes

1. In some cases alternative inspection frequencies may be appropriate or required (for the reasons outlined in the paragraph below). If a potential or confirmed dam safety deficiency exists, the inspection frequency should be reviewed and if necessary amended.
2. Monthly inspections should include a minimum of 11 inspections each year with no more than 6 weeks between inspections.
3. Weekly inspections should include a minimum of 50 inspections each year with no more than 10 days between inspections.

In some cases the dam Owner and Technical Advisor may select an alternative inspection frequency appropriate for the dam under consideration. The following characteristics should be evaluated when considering alternative inspection frequencies:

- The time required to detect and intervene if a potential failure mode is initiated.
- Potential or confirmed dam safety deficiencies or inherent vulnerabilities.
- The availability of 'other' observations of key dam/foundation features that would provide early indication of the initiation of potential failure modes (e.g. proximate Owner personnel or public, telemetered instrumentation).
- Unusual events (natural or operational) that result in a change to the dam's loading condition (e.g. rapid drawdown/filling, historic low/high reservoir level), or that require additional surveillance (e.g. construction, rehabilitation or investigation activities).
- Practical considerations such as the dam's location and the ability to access and inspect the dam (e.g. remote locations, adverse weather conditions).

4.2.6 Performance Monitoring Instrumentation

4.2.6.1 Philosophy

There are many available options for the instrumented measurement of dams, reservoirs and their features to monitor their performance. Where possible, when determining what instruments are required to monitor dam system performance throughout its operational lifetime, Owners and Technical Advisers should adopt a 'simple and targeted' instrumentation philosophy.

All instrumentation should have a clear purpose that is linked to one or all of the following objectives:

- Improving the understanding of a reservoir, dam or foundation's characteristic behaviour during normal operation, and during unusual and extreme events.
- Providing close monitoring of the reservoir and early indication of departure from normal operation.
- Providing early indication of the onset of potential failure modes for a dam.

Note that, in some cases, instrumentation may assist with the identification of features, trends or conditions that are indicative of a potential failure mode that was not identified during earlier studies. The information available during the completion of the earlier studies may not have allowed a particular potential failure mode to be identified, or may have indicated that a particular potential failure mode was not credible.

Performance monitoring instruments should be robust, durable, require little maintenance and able to be read easily and consistently, often by non-specialist personnel. Most importantly, the instrument should be "the right tool for the job". That is, it should measure as directly as possible a parameter, condition or quantity that supports the aforementioned performance monitoring objectives. The operational lifetime of a dam system is typically tens of decades, and the surveillance instrumentation should be selected so that either it has a similar life span, or that components with a shorter life can be safely maintained and/or replaced.

The overall instrument array should be resilient and include redundancy where appropriate. Redundancy is specifically important for dams where piezometric (or uplift) information is measured using vibrating wire instruments, or where it is gathered and reported using telemetry or other means of electronic transmittal that can be affected by lightning strikes or power loss. In such cases backup manual measurements of embankment piezometers or uplift pressures in concrete dams at key locations should be provided.

Survey monuments installed to allow measurement of a dam's deformation or settlement (or the displacement of an appurtenant structures) are not typically considered to be 'instrumentation'; however, they do provide the same function in that they can yield important information relative to some potential failure modes and allow the behaviour of the dam to be monitored.

Dam performance monitoring instruments predominantly measure geotechnical, hydrologic or structural parameters and, in their selection and maintenance, should not be confused with the types of instrument used to measure and monitor mechanical and electrical systems.

The need for and value of performance monitoring instrumentation will depend on the requirements for the particular dam system. Most instrumentation is selected during dam design and installed during construction, and may have a primary purpose related to the monitoring of commissioning parameters rather than those parameters required for the long- term management of dam safety. Hence, it may be appropriate to consider additional instruments to ensure performance monitoring needs are met or, where instruments are found to be redundant, it may be appropriate to decommission instruments. Additional or different instrumentation may also be installed when a potential dam safety deficiency is being investigated and assessed.

Technological advances in instrumentation types and systems will occur over the life of any dam. It is therefore likely that the original instrumentation will be augmented or replaced by new systems over time. Where possible, a period of monitoring overlap should occur to ensure that historical data can be correlated to information obtained from new systems.

Module 3 (Investigation, Design and Analysis) provides further detail on instrumentation for embankment dams, concrete dams and tailings dams. In addition, a number of ICOLD bulletins that address dam instrumentation are referenced at the end of this module.

4.2.6.2 Key Dam Performance Parameters and Instrument Types

Universal to all dams, the most important parameters to measure quantitatively and evaluate, where possible and appropriate, are:

- Reservoir level.
- Dam and foundation seepage and/or leakage rates.
- Dam/abutment internal water pressures and phreatic surfaces.
- Foundation uplift pressures.
- Dam deformation and displacement.

The above key parameters for embankment and concrete dams are shown diagrammatically in Figures 4.2 and 4.3 and are discussed in the sections that follow.

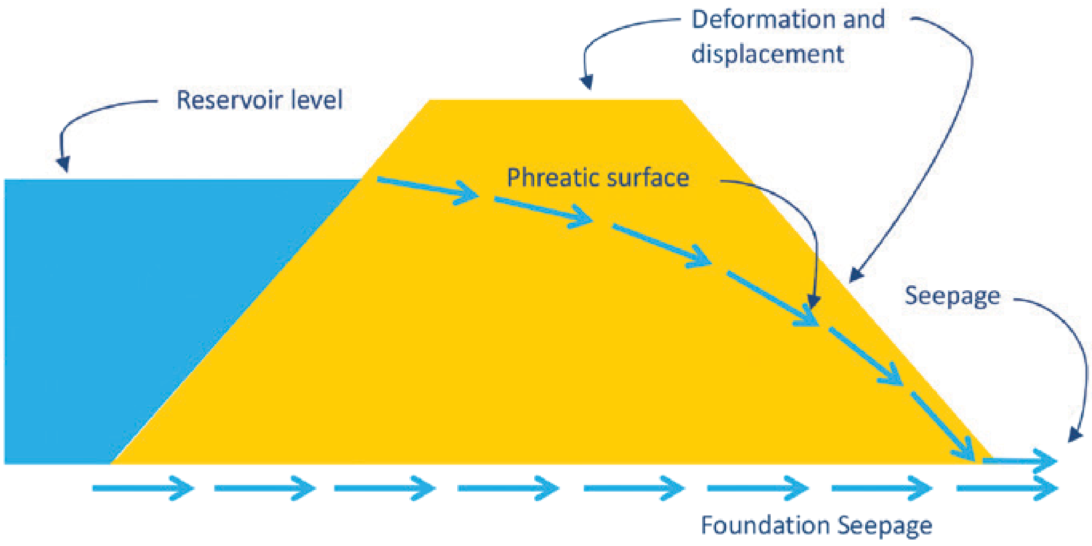

Figure 4.2: Embankment Dam Performance Parameters

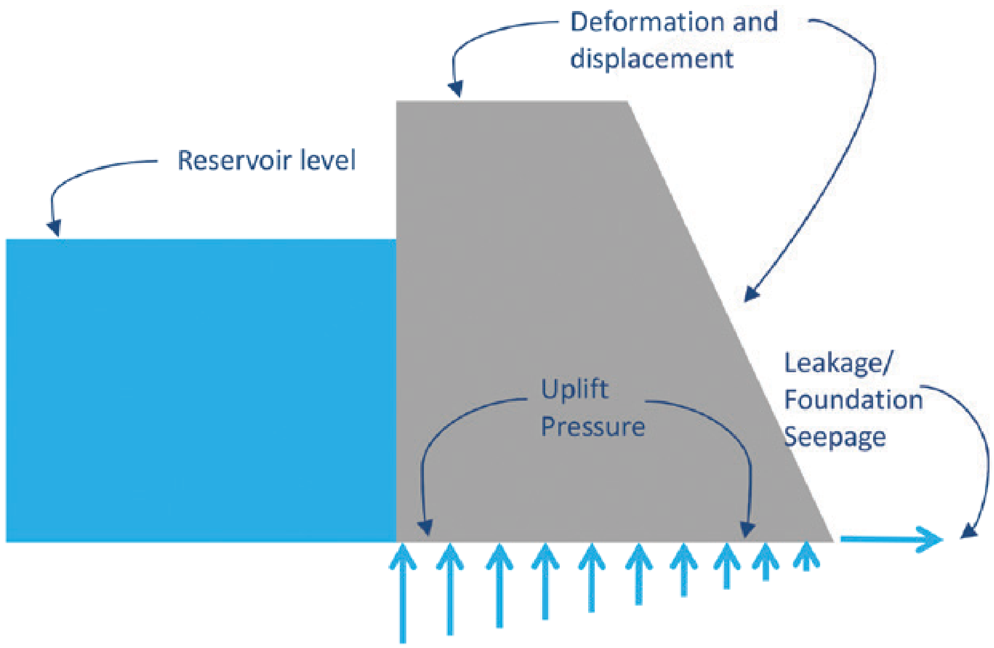

Figure 4.3: Concrete Dam Performance Parameters

4.2.6.3 Reservoir level, inflows, outflows and rainfall

Reservoir level is a fundamentally important measure of the loading condition, and therefore the driving head that the dam and its foundation are subject to, and the freeboard available to avoid overtopping. As a minimum, reservoir level should be recorded when visual inspections and instrumented measurements are completed so that meaningful correlations of the effects of different loading conditions can be made. Catchment rainfall, reservoir inflows and outflows, and reservoir level should also be monitored for operational purposes with scope, reliability and frequency commensurate to the dam safety, reservoir safety and public safety consequences.

While water level sensor instruments are commonly employed (allowing automated and frequent monitoring), a water level staff gauge that can be read manually should be installed in all reservoirs. Water level staff gauges are simple, effective and reliable (they do not need a power source or have electronic components) and where water level sensors are installed they provide an important calibration check. Water level staff gauges should be dimensioned to allow measurement of the full operational (including flood and dewatering) range of reservoir levels and positioned so that they can easily be read in all loading and weather conditions. They should also be sited to allow reading without placing personnel at risk.

Reservoir level should optimally be measured in metres above mean sea level for ease of correlation with dam features and other measured performance parameters such as piezometric levels and foundation uplift.

4.2.6.4 Seepage and/or leakage rate

Seepage and/or leakage rate is an indicator of the performance of impermeable (or low permeability) elements installed in the dam and foundation, and the performance of the abutments and foundation where no impermeable elements are installed. The objective of measuring seepage flows is generally more about the identification of seepage trends and understanding the overall performance of the dam, rather than the recording of absolute values. Decreasing seepage flows may need to be scrutinised just as much as increasing seepage flows as they may indicate a change relevant to dam performance.

The ability to measure rate of seepage and leakage through the dam, foundation or abutment usually relies on directing the seepage or leakage, through appropriate collection and drainage facilities, to a measurement point close to the dam's toe or at the location where the seep or leak emerges from the dam, foundation or abutment.

Seepage and leakage flow is best measured volumetrically, either by measuring the time to fill a container of known volume, or by installing a weir or flume with a theoretical (or calibrated) rating that allows the measured head to be converted to flow rate. For the purpose of ongoing monitoring and evaluation of a dam's performance the most important aspect of seepage and leakage rate measurement is repeatability, rather than absolute precision. Weirs should be sized for the anticipated flows and weir boxes should be large enough to provide calm water surfaces behind the weir plates. In some cases baffles may be needed to achieve this. V-notch weirs provide precision for the measurement of seepage flows; however, for large flows, broad crested weirs or flumes will be necessary. The observation of seepage and leakage flows via the use of weir boxes also allows the detection of any materials being transported by the seepage flows. The detection of turbid seepage or soil particles in seepage flows is important as they may be an indicator that internal erosion (backward erosion piping or seepage erosion) is taking place within the dam, in its abutments or in the foundation. In order to detect whether or not soil particles in a weir box are the results of internal erosion, the weir box may have to be covered to protect it from windborne material and periodically cleaned to enable the captured material to be examined and weighed.

For dams built on permeable foundations (e.g. river gravels), or dams that have toes inundated by tailwater conditions, the collection and measurement of seepage or leakage can be difficult to achieve. In such cases the dam design may reflect the inability to monitor seepage or leakage at the dam toe. However, if seepage monitoring is required at a dam toe that is founded on permeable materials or inundated by tailwater, temperature sensing methods are available for the targeted detection of seepage within a dam or through its abutments or foundation. Also, as noted above, the toe may be able to be periodically dewatered (outflow shut off or diverted and standing water pumped out) to allow the measurement and observation of seepage outflows.

4.2.6.5 Internal water pressure and foundation uplift pressure

Internal water pressure and foundation uplift pressure are measured to allow the stability of the dam to be evaluated against performance expectations and design assumptions. The absolute measured values are therefore of prime importance; however, changes recorded over time also need to be examined and understood.

Water pressure is usually measured using a piezometer. Internal piezometric pressures are most relevant to embankment dams or tailings dams, and the foundations and abutments of all dams. The measurement of internal water pressure at a number of points in the body of the dam, or in its abutments or foundation, allows the phreatic surface (below which the materials are saturated) to be understood. Saturation of the downstream shoulder of an embankment dam is undesirable for dam stability.

Uplift pressures are most relevant to concrete dams and their foundations, and allow their stability to be evaluated. Uplift pressures at or near the toe of embankment dams may also be relevant if a blowout condition or potential piping condition exists.

There are a number of piezometer types including open standpipes (observation wells), ported/slotted standpipes, and hydraulic, pneumatic, vibrating wire and fibre optic piezometers. Piezometers are typically installed during the construction of a dam, and built into the dam body or foundation. This makes the replacement of certain types of piezometers a difficult and potentially risky process. Therefore the maintenance of installed piezometers, to preserve their accuracy and maximise their service lives, is very important and usually requires the input of an appropriately skilled and competent Technical Adviser (specifically a geotechnical Instrumentation specialist). Where piezometers are unable to be replaced if they malfunction, backup piezometers that are long lasting and can be replaced should be considered.

Where retrofit or replacement of piezometers is considered necessary (e.g. for replacing failed instruments, characterisation of a special feature or the monitoring of a potential failure mode), extreme care should be taken in planning and installing the instruments to avoid damage to the dam and its foundation. An appropriately experienced Technical Adviser or Technical Specialist should be consulted in such cases. In some cases the dam safety risks associated with installing a new piezometer may outweigh the benefits of the instrument.

Foundation drains in concrete dams can be used as piezometers, either by measuring the depth to the water level (if the water level is below the top of the drain) or by installing a pressure gauge (if water is flowing from the drain). However, this approach may have limitations that include a slow response time and a general measurement of pressure as drains are usually not slotted or isolated to a particular zone. Furthermore, if an overflowing drain is capped with a gauge, or has an upstand pipe installed to elevate the water level, the resulting increase in foundation uplift may encourage the development of an adverse condition.

An appropriately experienced Technical Adviser or Technical Specialist should be consulted in such cases. For correct evaluations of dam performance it is important that the locations of piezometers in the body of a dam or foundation are accurately known (position and level), that the instruments are correctly identified, that their precision and accuracy are regularly assessed, and that they are appropriately maintained.

4.2.6.6 Deformation and displacement

Deformation and displacement can be effective performance indicators for instability, settlement, and a number of other potential failure modes. They are also useful to characterise the behaviour of dam and foundation components. They are most commonly observed by visual observation during routine surveillance, and measured by traditional survey methods such as precise levelling and Electronic Distance Measurement (EDM) of targets installed at key locations on the dam and its foundation.

Visual observations can generally identify anomalous deformations, such as cracks, joint openings, depressions, bulges, tilting or out-of-line movements in a structure or abutment. Instrumented measurement and surveying are the most effective methods for measuring and monitoring changes at specific locations and features, and establishing movement trends or verifying visual inferences of movement. A Technical Adviser with experience in the particular dam type should be consulted when designing a dam deformation survey layout to ensure that the dam's performance monitoring objectives are met.

As well as traditional survey methods, there are a number of alternative methods and technologies available for the measurement of deformations and displacements. Examples include pendulums, inclinometers, tilt meters, joint meters, Global Navigation Satellite Systems (GNSS), continuous survey monitoring (CSM), robotic total station and laser scanning (ground mounted or airborne). Fundamentally, the method and/or technology adopted should be selected such that it meets the dam performance monitoring objectives related to precision and accuracy, and can be readily calibrated.

For High and Medium PIC dams, deformation surveys should be conducted by specialist surveyors with equipment and methodologies that achieve the required precision and accuracy (within 1 to 2 mm vertically and 3 to 4 mm horizontally). For Low PIC dams, if deformation survey is necessary, the Designer or Technical Adviser may set the precision or accuracy required. However, it should be recognised that lower precision or accuracy will significantly reduce the value of the deformation monitoring. A survey control network on stable ground remote from the dam structure should be utilised to minimise survey errors and a specialist surveyor should be consulted in designing the control network. Generally, the size of the structure and its survey control network will influence the achievable precision and accuracy of the deformation survey. To be reproducible and detect changes, periodic surveys should generally be taken at the same time of year and where possible with similar reservoir level (especially important for concrete dams). To understand variation of deformation due to reservoir and temperature, surveys may be timed alternately to coincide with greatest upstream and downstream movements. Embankment dam moisture content, particularly where swelling clays exist, can also influence deformations. Also, when surveying methods or survey personnel change, a close examination of the results should be completed to establish the validity of the results and their correlation with past surveys. Vegetation management plays a significant part in the effectiveness of deformation monitoring. For visual observation, clear dam and abutment faces allow the identification of surface anomalies. For instrumented surveys, vegetation and man-made additions (e.g. handrails or fences) may block lines of sight between survey pillars and monitoring points.

4.2.6.7 Other available performance monitoring instruments and systems

There is a vast range of other instruments and systems available that can be used for repeated measurements/surveys for the monitoring of dam system performance and the monitoring of hazards. Some common examples include, but are not limited to:

- The use of simple scribe marks across monoliths of concrete dams, on the crest or within galleries, to indicate relative movements of blocks. Two or three dimensional crack monitoring devices can also be attached to the concrete for greater accuracy.
- Chemical analysis tests for determining seepage and leakage origins.
- Turbidity meters (indicators of internal erosion).
- Video cameras for real-time visual observations, including the internal inspection of conduits (drains and outlet tunnels).
- Trip wire systems (e.g. displacement/rupture of an active fault, or a dam itself).
- Post-tensioned cable anchor load testing (to confirm anchor tensions).
- Temperature sensing systems for the identification of seepage in dams or foundations (e.g. distributed temperature sensing and resistance temperature devices). Temperature sensors can provide valuable data on the flow time and flow source of seepage water, particularly when complemented by other measured parameters such as piezometric pressure, seepage flow rate, and the temperature of the reservoir and other potential sources (such as ambient groundwater or tailwater).
- Early warning upstream rainfall collection and catchment modelling systems for predicting the size of incoming floods or extreme weather conditions (an important aspect for surveillance and emergency preparedness).
- Rainfall measurement to assist with the interpretation of seepage observations, and the evaluation or correlation of landslide and abutment slope movements.
- A seismic monitoring network for detecting and notifying the location and strength of earthquakes (an important aspect for emergency response). The NZ Geonet system is publically available.

- Strong motion seismic sensors for the measurement of ground motions. These may be helpful where the NZ Geonet network coverage is limited and/or where measurement of ground motions at the dam site is required. The locations for installation of strong motion recorders should reflect the site conditions and preferred locations, in order of usefulness, are:
  - the base of the dam to record the peak ground acceleration
  - the abutments to record topographic amplification of the peak ground acceleration
  - the dam crest to record the amplification of the peak ground acceleration.
- Remote sensing deformation monitoring systems, such as: Global Navigation Satellite Systems (GNSS), Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LiDAR), and photogrammetry.

Instruments and systems such as these may be built into or near a dam at the time of its construction, added during the life of a dam to supplement or enhance existing instrumented monitoring, used to address a specific potential failure mode, used to investigate a potential or confirmed dam safety deficiency, or used for periodic monitoring.

4.2.6.8 Instrument installation, calibration and maintenance

All instruments must be correctly installed (location, method), and calibrated and maintained at appropriate intervals to ensure the ongoing provision of reliable data. They must also be carefully installed to ensure their installation does not result in damage to the dam or its foundation. Documentation and drawings of instrument location, purpose, calibration and maintenance should be accurate, regularly reviewed, safely stored and available to operational staff, Technical Advisers and reviewers. If instruments do not have complete as-built information and calibration details, considerable time and effort may be spent attempting to interpret their data (for the lifetime of the dam). In some situations a meaningful or correct interpretation may not be possible.

4.2.6.9 Instrument monitoring frequency

The frequency of instrumentation monitoring should be initially set and periodically reviewed by the Designer or Technical Adviser and should be appropriate to the particular dam, the consequences of its failure, and the dam performance monitoring objectives (monitoring for understanding of characteristic behaviour and indication of a potential failure mode; refer section 4.2.6). The monitoring frequency should also appropriately reflect:

- The time required to detect and intervene if a potential failure mode is initiated.
- Potential or confirmed dam safety deficiencies or inherent vulnerabilities.
- The availability of 'other' observations of key dam/foundation features that would provide early indication of the initiation of potential failure modes (e.g. proximate Owner personnel or public, telemetered instrumentation).
- Unusual events (natural or operational) that result in a change to the dam's loading condition (e.g. rapid drawdown/filling, historic low/high reservoir level), or that require additional surveillance (e.g. construction, remediation or investigation activities).
- Practical considerations such as the dam's location and the ability to access and read the instrumentation (e.g. remote locations, adverse weather conditions).

The frequency should be dynamic and adaptive in response to changing observations and needs. As a general guide, Table 4.3 provides suggested routine monitoring frequencies for different instrumentation types.

Table 4.3: Suggested routine monitoring frequencies

Type of instrument	Potential Impact Classification (PIC)		
	Low	**Medium**	**High**
Reservoir level	At Routine Inspection	Continuously monitored (refer Note 1)	Continuously monitored (refer Note 1)
Seepage and/or leakage	At Routine Inspection (refer Note 2)	Refer Note 1 (minimum at Routine Inspection)	Refer Note 1 (minimum at Routine Inspection)
Phreatic surface and/or uplift pressure			
Deformation monitoring	Refer Note 1 (min. 10-yearly)	Refer Note 1 (minimum 5-yearly)	Refer Note 1 (minimum 5-yearly)
Rainfall		Daily (refer Note 3)	Daily to hourly (refer Note 3)
Seismic event notification		Refer Note 4	Refer Note 4
Turbidity (of seepage)		As required	As required
Chemical analysis		As required	As required
Post-tensioned anchor cable loads		10-yearly	5-yearly

Notes

1. Determine frequency in consultation with appropriate experienced Technical Adviser considering reservoir operation regime, dam and foundation type, the specific dam performance monitoring needs (refer section 4.2.6), the consequences of failure, and the instrument monitoring frequency items listed above the table.
2. If instrumentation exists.
3. Rainfall measurement at, or near to, the dam site assists with seepage/leakage evaluation. Rainfall measured in or close to the dam's catchment (where available), assists with flood forecasting.
4. For dams located in close proximity to known active faults it is recommended to access a seismic monitoring network that provides timely notification of the locations and magnitudes of earthquakes relative to the dam site. A public notification service based on a national network of instruments is available (GNS Science's Geonet).

4.2.6.10 Manual reading and recording method

Where instruments are read manually, data should be recorded using systematic checklists that include alert levels. Alert levels should be set by a Technical Adviser familiar with the dam and instrument performance and should optimally provide both a "data entry" check (e.g. whether the reading is within the instrument's range) and a check against performance expectation (refer section 4.2.8). Usually, instruments are read during the routine inspection and therefore alert levels can be included in the routine inspection checklists. This provides an important quality assurance check at the point of reading and provides the inspector with an indication of normal and/or expected instrument behaviour, and an alert in the event of an incorrect reading or change.

Owners may use paper-based or electronic field datalogger-based checklists. Electronic datalogging systems have the advantage of allowing direct transfer/upload to a monitoring system, therefore reducing the possibility of transcription error. Common data management errors include incorrect readings, incorrect data entries (numerical or data entered in wrong field), inconsistent data measurement methods and incorrect data reductions/calculations. Alert levels can be built into electronic devices and may be supported by an on-demand display of previous readings for a given instrument. Whatever method is used to record observations and readings, all records must be carefully stored as part of the dam's long term surveillance record.

For those potential failure modes highlighted in the FMEA as most significant to the safety of the dam, the individual completing the monitoring (e.g. surveillance inspector, operator) should be aware of the relevant alert levels and be able to immediately alert the Owner or the Owner's Technical Adviser who routinely reviews the monitoring results.

4.2.6.11 Automated and remote data acquisition

Automated and remote aquisition of data from the dam site to the Owner's monitoring system can be beneficial in a number of applications. Generally, it is most useful for dams and reservoirs with significant consequences of failure, when there is a need to carry out enhanced or intensive data collection to gain an improved understanding of a dam's characteristic behaviour, to provide early indication of the onset of a particular potential failure mode, or to monitor a potential or developing dam safety threat. Remote aquisition of data provides frequent packets that enable a timely response, whereas data accumulated at the instrument over a number of weeks and intermittently downloaded may provide insufficient time for a rapid reaction to an undesirable trend.

Remote acquisition of data is particularly useful where access is limited or not possible. Examples include remote or hazardous locations (such as confined spaces or heights), or areas where access is blocked or dangerous (such as after an earthquake or during a flood or storm). The design of an acquisition system should consider the conditions that the system will be required to operate in (e.g. inclement or extreme weather) and should incorporate appropriate robustness and reliability.

The most common issues associated with acquisition systems are the provision of reliable power supplies and communication links. Where the consequences of dam failure are significant it is advisable to build redundancy into the system, such as a backup power supply and communication link. Where communication reliability is inadequate relevant to the importance of the measurement site, on-site data logging and storage should be included to allow manual download (transmittal of the information) in the event of communication failure.

4.2.7 Monitoring data management

4.2.7.1 Philosophy

The volume of data that is collected over a dam's lifetime can be very large, but it is essential to have an appropriate system in place for collecting, processing, storing and reviewing the data. For the simplest of dams this may be a paper-based system; however, for most dams, particularly more complex dams which have a greater number of visual and instrumented observation points, it is usual and convenient to use a computer-based system. The monitoring system should include alert thresholds set around performance expectations (refer section 4.2.8).

The monitoring data is part of the asset and its value, and should be transferred with the asset should it change ownership.

A number of ICOLD bulletins that address monitoring systems for dams are referenced at the end of this module.

4.2.7.2 Safe storage

Whether operating a paper-based or computer-based monitoring system, it is important to provide safe storage, including the frequent backup of data to an alternative location and an established plan for the continuity of dam surveillance under adverse conditions such as the loss of the primary dataset. Common data storage errors that may occur include the loss of data through adverse events such as deletion, overwriting or electronic file corruption.

The data should be managed and stored in a system with an appropriate quality management process, in a way that both raw and transformed readings are kept (e.g. measured head at a v-notch weir and the calculated flow), and that accidental or inappropriate deletion or modification is not possible. Comments that relate to observations, interpretations or changes in operating condition/environment should be permanently 'tagged' to the relevant dataset.

The data should also be formatted and stored in such a way that long term records remain accessible and usable when an electronic system is changed or replaced.

Photographs and videos (and other media) used to record conditions of key observations should be appropriately referenced and easily retrieved to help answer current and future questions.

4.2.7.3 Presentation of time and spatially based data

It is essential to store and present surveillance data in a way that allows it is to be effectively evaluated, both in the immediate and full term history. This applies to both visually observed and instrumented data.

A unique identifier should be applied to each observation point (visual or instrumented), to serve as a reference in the paper or computer-based database. Data can then be presented in time-based lists and/or plots for review.

Quantitative data can readily be plotted in time-based charts. Qualitative data such as visual observations an also be plotted in this way by using a numerical recording system such as '0' for 'acceptable/normal', and '1' for 'not acceptable or abnormal' (i.e. something has changed), with relevant explanatory comments tagged to the data point ('1' should trigger an alert for follow-up). As another example, the visual assessment of a seep can be rated as '0 = dry', '1 = drip', '2 = trickle', '3 = flow', and '4 = alarming flow' ('4' should trigger alert for follow-up).

Over time it is likely that sets or groups of instruments will respond in a correlated way to events such as lake level or rainfall changes. It is beneficial if the monitoring system adopted allows multiple instruments to be grouped and presented together. This can highlight when anomalous responses are occurring or if a particular instrument has stopped working.

A monitoring system should also have the ability to present spatially-variable data. For example, this may include surveyed deformations that vary with distance along a dam's length, or piezometric pressures (or phreatic surface) that vary through a dam's cross- section.

4.2.7.4 Quality assurance

A monitoring system should be designed and implemented with appropriate review, audit, escalation and sign-off processes to assure:

- The quality of the data collected.
- The correct data transformations are used.
- The data is evaluated and reviewed by competent Technical Advisers.
- Issues and anomalies are identified, resolved or escalated as appropriate, and signed off by a competent Technical Adviser.

4.2.8 Dam performance evaluation

4.2.8.1 Philosophy

Competent Technical Advisers should be employed to establish performance expectations and evaluate dam performance appropriate to the consequences of failure and the complexity of the dam being evaluated. In some situations Technical Specialists may be required (e.g. complex foundation and/or dam behaviour, complex structural or geotechnical analysis, high or extreme consequences of failure, or the management of a dam safety deficiency).

The evaluation of visual observations and instrumented data with respect to a dam's safe performance is an essential part of a dam surveillance programme.

Performance evaluation should be undertaken following the completion of each routine surveillance inspection in a timeframe that reflects the dam condition and performance. During normal operating conditions the evaluation timeframe should reflect the PIC of the dam (e.g. within one inspection cycle for a High PIC dam, within one month for a Medium PIC dam and within 3 months for a Low PIC dam). Where there are unusual events or potential or confirmed dam safety deficiencies the evaluation timeframe should reflect the rate of event development and the level of risk.

The completion of an effective evaluation requires an understanding of the dam's behaviour, under all loading conditions, and the use of evaluation techniques that reflect the expected behaviour of the dam, the detail of the surveillance records, and the available information for the dam (e.g. design, construction, operation and maintenance records, rehabilitation records, and records of unusual events and incidents). Importantly, the evaluation must consider the dam's 'performance as a whole' in the context of the dam setting, design philosophy, construction features, condition, historical performance and potential failure modes. Judgements should not be made based solely on isolated observations or instrument readings. Instead, the wider dam and foundation context should be considered, with conclusions drawn and supported by bringing together a range of relevant performance parameters and other information relevant to the safety of the dam.

4.2.8.2 Setting expectations

A Technical Adviser should approach an evaluation of a dam's performance with:

- An expectation of behaviour based on:
  - how the dam should behave in general terms based on its operational context, dam and foundation type, and design assumptions/limits
  - an understanding of the dam's characteristic behaviours – how the dam and foundation typically perform, including precedent loading conditions and observations
- An understanding of the dam's potential failure modes and their key performance indicators
- Established alert thresholds (acceptable performance limits) for key performance indicators.

While precedent observations or conditions are an important part of evaluating a dam's performance, it is not satisfactory to evaluate dam performance solely on the basis of deviations from previous performance.

4.2.8.3 Evaluation methods

As noted in section 4.2.7, there are a range of presentation methods that can be used by a Technical Adviser for the interpretation and evaluation of dam performance.

There are also a range of evaluation techniques that are applicable for interpreting complex conditions and observations. This module does not endeavour to present these in detail; however, reference can be made to the relevant ICOLD bulletins referenced at the end of this module.

4.2.8.4 Commentary on the use of Artificial Intelligence

The use of artificial intelligence (AI) to support dam performance evaluation has grown significantly and AI is being utilised for complex analysis on large datasets where the timeframe for analysis by a human may not be manageable. Several AI techniques have been used for the analysis of scientific and engineering data and include, for example, Mathematical Optimisation, Machine Learning, Fuzzy Logic, Artificial Neural Networks, Natural Language Processing, Deep Learning and many more.

There are specific requirements for data to be suitable as learning datasets for AI systems to be trained on, and as with all models the quality and understanding of the output will be governed by the quality of the input and a comprehensive understanding of the system/technique used. The dam owner should take necessary steps to ensure appropriate levels of quality assurance and factual reporting for all aspects of dam performance evaluation. Appropriate care and consideration should be given to data accuracy, size, data fit purpose, consistency, validity, uniqueness, completeness, and timeliness to minimise the potential for AI biases and other unreliable outputs e.g. AI hallucinations.

AI systems/techniques are becoming increasingly accessible and available, and due to developments in computer resources and performance can be readily implemented. However, using and maintaining these systems requires a certain level of expertise and resources which may not suit in-house operations. Where an external provider is engaged the dam owner should take the necessary steps to ensure the level of quality assurance set out in their DSMS is maintained.

There are many unknowns surrounding how effective and reliable output from an AI system is, especially where the input data, technique and accuracy of the trained model may not be fully understood by the end users. If outputs are used to support dam safety decision making they should always be ground-truthed and fact-checked.

If AI systems/techniques are to be incorporated into a long-term strategy for dam performance evaluation and decision-making the dam owner should understand the longevity and dependability of the AI systems/ techniques used and how they would:

- Perform consistently for the life span of the dam system.
- Be dependable and accessible (e.g. for emergency preparedness, changing conditions and circumstances of the dam owner and/or service provider including succession planning).

4.2.9 Follow-up, escalation and reporting

As part of the surveillance process, an Owner should have an established procedure for the follow-up and resolution of untoward observations or situations, whether they are confirmed or unconfirmed. For example, this may include actions to be taken when alert thresholds are exceeded for monitoring data, or when an abnormal or unprecedented loading condition is experienced. The procedure must clearly identify the process for escalation of issues to those appropriately competent to deal with them. For Medium and High PIC dams (as a minimum) there should be an appropriate link that allows the Emergency Action Plan for the dam to be initiated (refer Module 6: Emergency Preparedness).

An important output of the surveillance programme is regular reporting to the Owner and relevant stakeholders on the performance of the dam, including any issues that arise and their resolution. Such reports play an important role in the safety review of individual dams, and more broadly, the audit and review of the DSMS.

4.3 Appurtenant structures and gate and valve systems

4.3.1 Definitions

Appurtenant structures are structures other than the dam itself that are designed and are required for the safe containment and control of the reservoir contents and reservoir discharges under all loading conditions.

They may be at or near the dam or, for a large reservoir, they may be some distance from the dam; the key is that they impound and/or control the same reservoir. Pipelines and penstocks downstream of intake structures should be considered appurtenant structures if there are no gates or valves designed to isolate them from the reservoir contents.

Appurtenant structures frequently incorporate gates and/or valves (refer to Module 3 Section 6.11 for how to identify appurtenant structures). Gates and/or valves that fulfil dam and reservoir safety functions are part of the total dam system and should not be considered in isolation, but rather as an integrated sub-system that includes the gates and/or valves, their lifting/operating systems, and their associated power/energy supplies, and control, protection and communication systems. Such an integrated sub-system is implied when, for simplicity, these Guidelines refer to 'gates and valves' or 'gate and valve systems'. Some owners designate these as 'dam safety critical systems' and 'reservoir safety systems'. Identifying gate and valve systems should be completed in the context of the total dam system, components, design functions, operation, controls and interdependencies (including human and organisational factors), how the dam system and components may fail to function (potential failure modes including reservoir safety and operational failure modes), and the consequences of failure to function. For further detail on dam systems, functions and failure modes refer to Section 3.2 Dams Systems and Section 3.4 Failure Modes and Effects Analysis.

Inspection, maintenance and testing of gate and/or valve systems are carried out for the complete lifecycle, including but not limited to routine inspection and maintenance, functional and performance testing, condition monitoring, testing for faults, testing for commissioning or recommissioning, comprehensive inspection and performance assessment. The recommendations in this module are applicable to all of these aspects.

Because of their importance in fulfilling dam and reservoir safety functions, appurtenant structures and gate and valve systems need to be incorporated in a DSMS. Regulatory requirements for appurtenant structures and gates and valves are discussed in Module 1: Legal Requirements.

4.3.2 Dam and reservoir safety functions

For dam and reservoir systems and their components, Dam safety functions support safe the dam's function to containment of the reservoir (e.g. safe dam performance). Reservoir safety functions support safe reservoir conveyance and control to prevent other uncontrolled reservoir releases (e.g. inappropriate gate operation, gate malfunction, gate failure, penstock or pipeline rupture).

Broadly, appurtenant structures fulfil or contribute to one or more of the following three dam and reservoir safety functions:

- Safe containment of the reservoir under all loading conditions.
- Safe conveyance and control of reservoir inflows and outflows (e.g. normal operation or flood discharges).
- Reservoir drawdown in response to a dam safety incident or emergency (conveyance and control).

Appurtenant structures that fulfil the above functions typically include or incorporate:

- Debris booms.
- Spillway control structures, chutes and stilling basins.
- Low level outlet structures.
- Penstock intake and canal inlet structures.
- Pipelines, penstocks, conduits and surge tanks with no means to immediately isolate them from the reservoir, and/or they are designed or intended for reservoir lowering.
- Gates and valves and their lifting/operating systems, including ancillary systems such as power supplies, and control, protection and communication systems.
- Pumps for the transfer of water into pumped storage reservoirs.

It should be noted that dams will often contain, or be adjacent to, a range of structures that may not have been designed or intended to have any role in dam or reservoir safety. While such structures are not appurtenant structures, changing circumstances over time (such as an increase in PIC) may require such structures to fulfil a dam or reservoir safety role.

If this occurs they may require upgrading to address deficiencies that would otherwise prevent them from performing their dam or reservoir safety roles and would need to be incorporated in the DSMS.

An uncontrolled release of the reservoir is an event during which there is no control over the quantity of the stored contents released or the rate of discharge from the reservoir. Examples of conditions at appurtenant structures that could result in an uncontrolled release of the reservoir include:

- Inappropriate operation, malfunction or failure of gates and valves that fulfil a dam or reservoir safety function.
- Rupture of an appurtenant structure such as pipelines, penstocks, conduits and surge tanks
- Overtopping and subsequent erosion downstream of an appurtenant structure, or erosion of a dam or abutment adjacent to an appurtenant structure.
- Internal erosion in the foundation beneath an appurtenant structure, or in a dam or abutment adjacent to an appurtenant structure.
- Instability of an appurtenant structure.

4.3.3 Inspection, maintenance and testing

4.3.3.1 Civil appurtenant structures

Appurtenant structures are usually constructed from mass, reinforced, pre-stressed or post-tensioned concrete, or from steel (e.g. pipelines, penstocks), or from earth and/or rock materials.

Owners should inspect appurtenant structures, at frequencies appropriate to the structures and their complexities, to ensure that their condition and performance are well understood. The inspection and review of appurtenant structures should be appropriately included in routine dam surveillance, Intermediate Dam Safety Reviews (IDSRs) and Comprehensive Dam Safety Reviews (CDSRs). Special access may be required for the inspection of some areas (e.g. spillway chutes, dewatering tunnels).

The Owner should also maintain a regular programme of maintenance to ensure long term reliable performance of the structures. Examples include the repair of concrete and steel surfaces and joints, and the cleaning of drainage systems in spillway chutes and stilling basins.

Performance monitoring and surveillance of appurtenant structures will usually involve measurements and observations similar to those for dams (e.g. seepage flow, water pressure and displacement).

4.3.3.2 Gate and valve systems

Gate and valve systems installed in appurtenant structures vary in complexity and the number of components, all of which must operate as intended to ensure that the dam or reservoir safety function is fulfilled. Some may be simple (e.g. hand operated valves), whereas others may have multiple modes of operation and power supply and energy sources to provide appropriate levels of redundancy and diversity.

Gate and valve systems largely consist of mechanical and electrical components and equipment and, accordingly, have specific functional performance requirements. They require appropriate inspection, maintenance and testing by competent operation and maintenance personnel (refer also section 2.2 and 4.1.2) to ensure they are in good working order and capable of performing normal and emergency operation under all conditions. Inspection, maintenance and testing competencies should be evaluated for each dam system, especially where personnel cover multiple dam systems and the gates and valves systems vary between dam systems. Moreover, the performance monitoring of gates and valves differs from that required for dams and appurtenant structures; it is dominated more by direct inspection and testing rather than by surveillance and monitoring. An additional difference is that gate and valve equipment and components can fail instantaneously, which is less likely to be the case with civil structures. Therefore, mechanical and electrical components and equipment require a different approach and design to ensure the risk of loss of function is minimised or avoided altogether. Dam system analysis, event tree analysis, fault tree analysis, Failure Modes and Effects Analysis (FMEA), and Failure Modes and Effects Criticality Analysis (FMECA) are examples of processes available to maximise the understanding of reliability and robustness of gate and valve systems. Robustness with respect to power sources, control methods, access, communication and mechanical equipment is typically provided by removing 'single points of failure' providing backup sources or methods, and maintaining a ready supply of critical spare parts (e.g. hydraulic pump, electric motor, winch brake). Regular inspection, maintenance and testing also ensures that operational personnel are familiar with the equipment and its performance, particularly if the equipment is infrequently used or has been recently modified.

Inspection, maintenance and testing programmes, plans and procedures should be developed by the dam Owner in consultation with appropriately skilled and experienced Technical Advisers with consideration to each unique dam system and its gate and valve system. The programme and procedures should reflect a deep understanding of the system and component functions, operation, controls, interdependencies (including human and organisational factors), how the system and components may fail to function and the consequences of failure to function. Such appropriately skilled and experienced Technical Advisers should also be part of gate and valve system performance reviews and assessments. For further detail on dam systems, functions and failure modes refer to Section 3.2 Dams Systems and Section 3.4 Failure Modes and Effects Analysis.

Inspection, maintenance and testing activities for gates and valves typically include but are not limited to:

- Lubricating moving parts and keeping oil levels topped up.
- Ensuring suitable fuel is available.

- Controlling or repairing corrosion.
- Operation of equipment that is infrequently used (e.g. standby generators).
- Ensuring batteries are charged.
- Repairing and replacing worn or damaged equipment.
- Condition monitoring (e.g. oil condition, motor currents, hydraulic pressures, gate speeds, operating temperatures and visual inspections).
- Testing of control, protection and communication systems.
- Functional testing under a range of load conditions and all available control methods and power sources.

The scope, standard and frequency of inspection, maintenance and testing will vary according to the required function of the gate and valve system and the consequences of failure to function. Requirements for gates and valves that support normal facility operation, and fulfil no dam or reservoir safety function, may be determined by the Owner taking into account reliability targets and commercial considerations. Inspection, maintenance and testing requirements for gates and valves that fulfil dam or reservoir safety function, on the other hand, should ensure very high levels of operational reliability under all foreseeable conditions commensurate to the consequences of failure to function.

If a gate and valve system has been repaired, modified, overhauled or replaced then appropriate testing or commissioning should be performed to prove that the system functions correctly when reinstated. For works where plant performance data is collected during testing and commissioning, the commissioning test results can serve as a baseline reference for the long-term condition monitoring of the system.

4.3.3.3 Functional testing of gates and valves

Programmes and plans for the testing and commissioning of gates and valves should include functional testing to confirm that the system (including backup power supplies and controls) fulfils its dam or reservoir safety function reliably. With the exception of commissioning tests, gates and valves that are used regularly (as part of normal operations) can be tested as part of normal operations provided that appropriate test objectives are met, and that the tests are witnessed and documented by appropriate technical personnel or Technical Advisers. Gates and valves that are rarely used (not used in normal operations) should be tested at appropriate frequencies that reflect the importance of their function and the consequences of their failure to function. Again, appropriate test objectives should be met and the tests should be witnessed and documented by appropriate technical personnel or Technical Advisers. Generally, for a given dam system, gates and valves that fulfil a flood management function should be tested more frequently than gates and valves that fulfil a reservoir dewatering function. However, for a dam system where the likelihood of a damaging earthquake or other failure mode that could require reservoir dewatering is comparable to that of a large flood, the testing frequencies should be similar.

Functional testing of gate and valve systems should include opening (e.g. spillway gates) or closing (e.g. penstock intake or canal inlet gates) using both normal and backup power supplies and all possible control modes (automatic, remote and local). For electric motor driven winch gear, mechanical screw drives and electric motor driven hydraulic systems motor currents should be recorded. Gate operating speeds can be a good performance indicator for some gate systems (e.g. fluid coupling). For all hydraulic systems (including diesel-hydraulic backup systems) hydraulic pressures should be recorded. Motor currents and hydraulic pressures are valuable condition monitoring parameters, and should also be compared against settings of motor overload relays and pressure relief valves respectively. The settings of pressure relief valves should also be confirmed. It is also important to record the reservoir level and tailwater level (if applicable) during the gate/valve tests. The repeatability of the above measurements by ensuring the same measurement setup, using calibrated instruments and measurement locations will provide a meaningful condition monitoring of the gate and valve system's performance. Inversely, if the repeatability of the measurements is not ensured, then the long-term monitoring and trending of the data collected can become incomparable. Similarly, significant changes to operating equipment should be documented to assist in interpreting the long-term condition monitoring and evaluating performance of the gate and valve system.

A backup power supply test on any new portable power supply should be performed on the gate and valve that is physically farthest away from the source, for all gate and valve type it services, as it would experience the largest voltage drop.

Owners should allow for adequate allocation of resources for the inspection, maintenance, testing and commissioning of gate and valve systems.

Economic, environmental and public safety considerations can affect the practicability of tests that result in large flows. In such cases Owners may choose to develop alternative test procedures that meet appropriate objectives and may include, for example:

- Performing the tests during scheduled spills or normal operations.
- Performing 'balanced' (no flow) tests in air or water with bulkheads in place. Gate/valve and bulkhead arrangements will vary and the limitations of such alternative testing need to be understood.
- Performing 'unbalanced' tests in water with upstream bulkheads in place (limited flow only). Again, gate/valve and bulkhead arrangements will vary, and the limitations of such alternative testing need to be understood.

In many cases, balanced testing is inadequate to fully verify the performance of a gate or valve system in comparison to unbalanced testing to verify gate lifting and closing margins. However, full range balanced testing is important to verify the gates and valves' total movement range without resulting in a large discharge downstream.

The extent, standard and frequency of the testing programmes, plans and procedures should reflect:

- The PIC of the dam (or the gate/valve's appurtenant structure, if it has a higher PIC than the dam).
- The complexity of the dam system
- The gate and valve system functions, performance requirements and consequences of failure to function.
- The equipment available to perform the dam or reservoir safety function (e.g. numbers of gates, type of lifting equipment, backup power supplies, energy sources and alternative means of operation).
- The age of the equipment.
- The condition of the equipment.
- For commissioning or testing after maintenance, the importance of the equipment or component being replaced, repaired, reprogrammed or checked.
- The degree/extent of maintenance performed.

Testing programmes, plans and procedures should be developed by the Owner in consultation with appropriate Technical Advisers and/or Technical Specialists (e.g. Gates Specialists, Mechanical Engineers, Electrical Engineers, Controls Engineers and Communications Engineers). Dam system analysis, event tree analysis, fault tree analysis, Failure Modes and Effects Analysis (FMEA), Failure Modes and Effects Criticality Analysis (FMECA) and reliability assessments can allow gate and valve system testing to be targeted at vulnerabilities. Test and inspection scopes and frequencies should be commensurate to the consequences of failure to function. Reliability targets may also assist. Generally, in relative terms, for higher system reliability targets testing frequency should be higher, and similarly, if the system's reliability can be improved (e.g. through design improvements) then testing frequency may be lower.

As a general guide, not as a replacement for developing appropriate testing programmes, plans and procedures for each unique dam system, Table 4.4 provides suggested testing frequencies for gate and valve systems installed in High and Medium PIC dams and appurtenant structures. Such approaches may also be appropriate for Low PIC dams and appurtenant structures where failure to function presents business risk, dam safety risk or reservoir safety risk.

Some reservoir dewatering gates may also provide passage of flood function in some circumstances. The Owner, in consultation with appropriate Technical Advisers and/or Technical Specialists, should determine the degree of testing required for those gate or valve systems to achieve the required degree of reliability for all functions. This could be reviewed as part of the Comprehensive Dam Safety Reviews and adjusted where and when appropriate. The objective should be to maintain dam safety, reservoir safety and public safety while considering the risk of operating a gate or valve.

Table 4.4: suggested gate and valve testing frequencies for high and medium PIC dams and appurtenant structures (may also be appropriate for Low PIC dams and appurtenant structures where failure to function presents business risk, dam safety risk or reservoir safety risk). This table does not replace testing programmes, plans and procedures developed by the Owner in consultation with appropriate Technical Advisors and/or Technical Specialists for each unique dam system.

Gate/valve dam or reservoir safety function	Backup power/energy source test	Unbalanced head (flow) test	Balanced head (no flow) test
Passage of floods (refer Note 1)	**Monthly** Minimum opening (refer Note 2). Initiated by backup power source (i.e. battery and motor startup checks).	**Annual** 15% opening (refer Note 3). Initiated by normal and backup power supplies and all control modes.	**5-yearly** Full range. Initiated by normal and backup power supplies and all control modes (refer Note 7).
Reservoir dewatering (refer Notes 1 and 4)	**Six-monthly** Minimum opening (refer Notes 2 and 5). Initiated by backup power source (i.e. battery and motor startup checks).	**5-yearly** 15% opening (refer Notes 3 and 5). Initiated by normal and backup power supplies and all control modes.	**10-yearly** Full range (refer Note 5). Initiated by normal and backup power supplies and all control modes (refer Note 7).
Machine or water supply intake (refer Note 6)	N/A	**5-yearly** Full-flow trip testing.	N/A

Notes

1. The risk of the gate or valve not returning to its pre-test position should be evaluated before the test.
2. The minimum opening to 'crack' the gate open (or open valve to minimum safe position), with sufficient movement to wet the downstream sill and demonstrate operation and loading of the backup power source.
3. The basis for a 15% gate opening, as an example, is based typically on a full rotation of a wheel on a vertical gate to free the bearings should there be any seizing, to lubricate the wheel bearings, and to dislodge any debris that may be caught. These reasons (and other relevant reasons) should be taken into consideration when selecting an appropriate gate opening for all gate and valve types. For large spillway gates or dewatering outlets this may result in very large discharges, in which case an appropriate alternative may be determined in consultation with a Technical Adviser or Technical Specialist.
4. Where the equipment is designed for reservoir dewatering or the Owner intends to use it for reservoir dewatering.
5. Where the likelihood of a damaging earthquake that could require reservoir dewatering is significant (e.g. dams with low seismic robustness in a moderate to high seismicity region, and with high consequences of failure), consider the necessity of a higher testing frequency in consultation with an appropriate Technical Adviser or Technical Specialist, taking into consideration the performance requirements of the gate/valve and the consequences if the gate/valve fails to operate.
6. Where intakes have automatic 'trip' closing, trip circuit testing (without gate closure) at a minimum annual frequency should be considered.
7. Due to the infrequent use of backup supplies and backup drives, the owner should consider testing all backup supplies and backup drive systems through the full gate range.

4.3.3.4 Witnessing and record keeping

Record keeping is an important part of an inspection, maintenance and testing programme. Owners should ensure that all activities are carried out under the supervision of suitably competent personnel and are properly planned and documented. The documentation should include the preparation of test plans, test procedures and checklists (including specific inspection requirements, data to be obtained and the normal or 'expected' values for critical data), and the recording of inspection observations and all test results. Any observed test failures or deficiencies should be documented, investigated, corrected and communicated/reported to appropriate responsible personnel.

For events, failures to function and potential or confirmed dam safety deficiencies observed between Dam Safety Reviews, e.g. through operational use and DSMS- implementation, the Owner should record the issue and as appropriate follow the recommended process for managing dam safety issues (refer Module 7, Section 4 Identifying and Managing Dam Safety Issues).

4.3.4 Inspection, maintenance and testing of other dam and reservoir safety systems

There is a range of other systems that may contribute to dam and reservoir safety and therefore should be inspected, maintained and tested at frequencies appropriate to the consequences of their failure (non- operation or inappropriate operation).

Examples of other systems that fulfil dam and reservoir safety functions include:

- Pump systems – that remove foundation drainage water from a dam gallery. Pump systems should be sufficiently reliable to minimise the risk of pump failure and the consequent development of uplift pressures in a dam or its foundation.
- High or low water level detection systems – that indicate when reservoir levels are outside set limits (e.g. the maximum normal operation level). In some instances these may be built into spillway watchdog/ failsafe systems as a method of automatic control. High water level detection systems are crucial for pumped storage reservoirs and usually have multiple levels of redundancy.
- Flood and earthquake alert systems – that provide alarms when floods or earthquakes exceed set trigger levels.

As outlined for gate and valve systems, dam system analysis, event tree analysis, fault tree analysis, Failure Modes and Effects Analysis (FMEA), Failure Modes and Effects Criticality Analysis (FMECA) and reliability assessments completed by suitably qualified and experienced engineers can assist Owners in developing testing programmes for other systems that contribute to dam and reservoir safety.

4.4 Intermediate dam safety reviews

4.4.1 Objectives

An Intermediate Dam Safety Review (IDSR) is a dam performance review that is intermediate in the sense that it fits between Routine Surveillance and the Comprehensive Dam Safety Review in frequency and in its level of detail. The IDSR is largely based on a visual inspection by a Technical Adviser, in the company of the Owner's operational and surveillance staff, as well as a close examination of surveillance, operation, maintenance and testing records. If concerns are raised the review may require some additional analyses, tests or investigations.

The IDSR should identify any dam safety issues and categorise them into physical infrastructure issues, potential or confirmed dam safety deficiencies, and non-conformances (refer Module 7: Lifecycle Management). In some cases the Owner may also require the IDSR to identify and/or recommend potential actions to resolve identified issues.

For High and Medium PIC dams IDSR's should be completed annually by a Technical Adviser external to the Owner's organisation. For Low PIC dams IDSR's should be completed every 1 to 2 years by an external Technical Adviser, or competent technical personnel within the Owner's organisation. The regulatory requirements for IDSRs are discussed in Module 1: Legal Requirements. The dam Owner and Technical Adviser should consider IDSR inspection timing with respect to reservoir level variation to support observation of the dam's condition and performance under a range of load conditions. High reservoir level is most beneficial due to the higher load condition, however, periodic low reservoir level inspection may support observation of features that would otherwise be under water.

4.4.2 Scope

The detail and scope of the IDSR should reflect the PIC of the dam and its complexities. Generally, the scope should include:

- An on-site inspection of the dam and appurtenant structures with the Owner and their operational and surveillance staff.
- A review of operation, surveillance, maintenance and testing records.
- An evaluation of the performance of the dam as indicated by the on-site inspection and operation, surveillance, maintenance and testing records for the period since the last IDSR.
- A report that identifies any dam safety issues, any changes to monitoring or visual inspection frequencies, or any additional items to be monitored.

On-site inspections should be systematically organised so that the status of all critical aspects of the dam can be accurately recorded and evaluated. Repeatable field inspection checklists should be used, and recent surveillance records and previous IDSR and Comprehensive Dam Safety Review (CDSR) reports should be reviewed in preparation for the site inspection.

Gates and valves that fulfil dam or reservoir safety functions are not necessarily tested; however, maintenance and testing records should be available for review.

4.4.3 Report

The findings of each IDSR should be recorded in a written report. The focus of the report should be on confirming safe dam performance and identifying dam safety issues.

Generally, IDSR reports for Medium and High PIC dams should include:

- Observations during the site inspection.
- Photographs taken during the site inspection.
- The identification of any significant events since the previous IDSR (e.g. floods, earthquakes), operational events (e.g. inappropriate operation, spill events, gate/valve testing), or dam safety incidents, and the responses and results of any such events or incidents.
- The identification of the completion of any maintenance and the resolution of previously identified dam safety issues, or the status of those issues.
- A review of surveillance data and other salient information.
- An evaluation of the performance of the dam and related structures/equipment, in the context of expected performance, characteristic behaviour and potential failure modes, using previous IDSRs and the previous CDSR as reference points.
- An outline of the status of instrumentation maintenance, including a comment on its adequacy.
- A summary of gates and valves that fulfil dam or reservoir safety functions, and an outline of their dam and reservoir safety functions.
- A comparison of planned and actual maintenance and testing activities for gates and valves that fulfil dam or reservoir safety functions (in the period since the previous IDSR), and comment on the adequacy of the completed maintenance and testing activities.
- The identification of any dam safety issues during the inspection and review, including any potential or confirmed dam safety deficiencies.
- The categorisation of any identified dam safety issues into physical infrastructure issues, potential or confirmed dam safety deficiencies, and non-conformances (refer Module 7: Lifecycle Management).
- A summary of the status of previously identified dam safety issues.

As a minimum, IDSR reports for Low PIC dams should include:

- Observations during the site inspection.
- Photographs taken during the site inspection.
- The identification of any significant events since the previous IDSR (e.g. floods, earthquakes), operational events (e.g. inappropriate operation, spill events, gate/valve testing), or dam safety incidents, and the responses and results of any such events or incidents.
- The identification of the completion of any maintenance and the resolution of previously identified dam safety issues, or the status of those issues.
- A review of surveillance data and other salient information.
- A summary of gates and valves that fulfil dam or reservoir safety functions, and an outline of their dam and reservoir safety functions.
- The identification of any dam safety issues during the inspection and review, including any potential or confirmed dam safety deficiencies.
- The categorisation of any identified dam safety issues into physical infrastructure issues, potential or confirmed dam safety deficiencies, and non-conformances (refer Module 7: Lifecycle Management).
- A summary of the status of previously identified dam safety issues.

4.5 Comprehensive dam safety reviews

4.5.1 Objectives

A Comprehensive Dam Safety Review (CDSR) is a comprehensive, periodic, independent review of the design, construction, operation and performance of a dam, and all systems and procedures that affect dam and reservoir safety, against current dam safety guidelines, standards and industry practice.

The CDSR should identify any dam safety issues and categorise them into physical infrastructure issues, potential or confirmed, dam safety deficiencies, and non-conformances (refer Module 7: Lifecycle Management). In some cases the Owner may also wish for the CDSR to identify and/or recommend potential actions to resolve identified issues.

CDSRs should be completed every 5 years for High and Medium PIC dams. Formal CDSRs are also recommended for Low PIC dams to preserve the asset value or earning potential of the dam. These Guidelines recommend that CDSRs should be completed for Low PIC dams on first filling and subsequently every 10 years. The regulatory requirements for CDSRs are discussed in Module 1: Legal Requirements.

If a dam enters a dam safety deficiency management phase and if the Owner is following a Special Dam Safety Review (SDSR) procedure (refer section 4.6), then the next regularly scheduled CDSR can be postponed until the dam is back in normal service.

The following sections provide guidance for the completion of CDSRs. The material focuses on key points but does not cover every detail.

4.5.2 General requirements

The CDSR scope should reflect the dam type, complexity, PIC, condition and performance. It should also reflect whether the review is:

- An 'initial' review of an old dam for which there are poor records.
- A follow-up review after corrective action has been taken.
- A regularly scheduled review of a modern or modernised dam which has been well documented.

Records of the dam's history are important information sources for a CDSR, particularly if they contain details of the Designer's intentions, the characteristics of the materials used, construction records and the history of the dam's performance since commissioning. Data books for each dam, which should be kept by the owner, are a good way to compile and retain relevant information on the history of dams and are a valuable source of records on the dam for the CDSR. Key information typically includes:

- Investigation data and reports.
- Design reports and drawings.
- As-built drawings, construction photographs and construction reports.
- Commissioning reports.
- Operation, maintenance and surveillance procedures.
- Surveillance records and relevant operation and maintenance records.
- Event or incident reports and records of any changes to components or operations.
- Previous inspection and safety review reports.

Often much of this data is almost non-existent in the case of older dams and, either as a precursor to the first CDSR, or as part of it, considerable effort has to be put into collating whatever data may be available. Developing and maintaining these records is a key element of an effective DSMS. As stated previously in section 3.4, where an FMEA has not been completed for a Medium or High PIC dam it should be carried out prior to or during the completion of the CDSR. After the completion of the initial FMEA for an existing dam, subsequent CDSRs should review the results of the FMEA and highlight any identified shortcomings in the FMEA report as well as any changes to the dam system that should be reflected in an FMEA update. Refer to section 3.4 for further detail on completing FMEAs.

The independence, experience and qualification of the CDSR reviewers is an important requirement. The reviewers for the first two CDSRs should not have had any direct prior design, construction or operations involvement in the dam and should be in a position to undertake the review independently and without prejudice. The Owner's technical personnel (internal or external) should not be reviewers, and a reviewer should not complete two consecutive CDSRs for the same dam. Most importantly, CDSR reviewers must apply their ethical judgement as professional engineers to determine their competence for the type, complexity and PIC of the dam being reviewed.

In completing the CDSR, it is important that the Owner's dam safety, surveillance, operations and maintenance personnel accompany the review team during the site inspection and provide or obtain answers to relevant questions from the review team.

4.5.3 Personnel requirements

The following lists the key personnel that should be involved in a CDSR, outlines their roles or responsibilities, and recommends skill or experience requirements for the CDSR personnel:

Owner

The Owner should take all necessary steps to understand the requirements for CDSRs, plan and budget for their implementation, and ensure they take place. After taking any necessary advice, the Owner should draw up the brief for the CDSR, facilitate the CDSR, and consider and address any dam safety issues identified in the CDSR within an appropriate timeframe.

Owner's engineers, surveillance staff and operators:

On behalf of the Owner, these technical and operational personnel should provide all available data and relevant information to the CDSR review team, facilitating on-site inspections, providing safety briefings and inductions for on-site inspections, operating gates and valves that fulfil dam and reservoir safety functions, and responding to questions from the CDSR review team.

CDSR review team

The CDSR review team should complete the review and report in accordance with the Owner's Brief and to a high standard of professional practice. Each member of the team should be appropriately experienced and senior in the area to be covered and, while past experience may be of considerable value, it is important that each person is also technically up to date, because a fundamental part of a CDSR is to assess the dam in the light of the current dam safety guidelines and current dam engineering practice. The Owner needs to appreciate that if the team is not appropriately qualified and experienced, the review may not identify important dam safety issues. Members of a dam's original design team may assist by clarifying matters, but should not be included in the CDSR team for the first two reviews to ensure an independent review of dam safety is completed.

The composition of the team will vary depending on the situation; however, most dams will require an appropriately experienced and qualified civil engineer with specialist support for specific areas. Large and/or complex dams usually require:

- A specialist dam engineer able to evaluate the civil structures and components, and the overall safety of the dam and appurtenant structures.
- A specialist engineering geologist or geotechnical engineer to review the geology, foundation conditions and other geotechnical issues that could affect the safety of the dam or reservoir (e.g. existing landslides adjacent to the dam or reservoir).
- A specialist mechanical engineer able to evaluate relevant mechanical components that fulfil dam and reservoir safety functions, such as spillway and/or low level outlet gates and valves and their New Zealand operating systems, including documented procedures for their operation, maintenance and testing.
- A specialist electrical engineer to evaluate power supplies, communication systems, and control and protection systems that fulfil dam and reservoir safety functions.
- In some cases, where wider expertise may be necessary to evaluate aspects that are inadequately documented or understood, the CDSR team may be widened to include:
  - Seismologists.
  - Hydrologists and hydraulic engineers.
  - Dam structural analysts or designers.
  - Rock mechanics specialists.

Peer reviewers

While a CDSR is a form of peer review in itself, some Owners may require peer review of the CDSR team's work. This may apply particularly during initial CDSRs where there may be a lack of relevant information for the dam. The need for such a review depends on the particular circumstances of the dam, but peer review is recognised as a sound concept. Peer Reviewers need to have appropriately wide experience at least equal to that of the CDSR team members and generally will be drawn from the most senior practitioners available.

4.5.4 Scope and procedures for High and Medium PIC dams

CDSR requirements are similar for High and Medium PIC dams; however, the scope of the review and the specialist skills required will depend on the dam type and level of inherent risk.

Every dam is unique and as such it would be inappropriate for these Guidelines to prescribe exact procedures for individual reviews, and therefore the skills and experience of the dam industry should be drawn upon for specific advice. When preparing Briefs for the completion of CDSRs, Owners who do not have sufficient expertise directly available should obtain advice from persons recognised in the industry as having appropriate expertise.

Following the selection and briefing of the CDSR team by the Owner, the completion of a CDSR for a Medium or High PIC dam usually involves:

- Review of all available relevant information including data books, reports and surveillance records.
- Review of known and potential hazards and dam safety threats.
- Review of the dam's PIC.
- Review of the outputs from the FMEA, the identified potential failure modes and their key performance indicators.
- Detailed on-site inspection of the dam and appurtenant structures.
- Site inspection and witnessing of testing of gates and valves that fulfil dam and reservoir safety functions (including their operating equipment, power supplies and control, protection and telecommunication systems). Testing may not be necessary if the Owner has completed and documented recent tests that adequately satisfy the test requirements; however, the operation and performance records for the tests should be reviewed in depth.
- Assessment of the adequacy of the dam and its appurtenant structures, including all gate and valve systems that fulfil dam and reservoir safety functions, to safely perform to current acceptability criteria for all loading conditions. The reviewers are unlikely to reanalyse the dam but may identify that there is a lack of analysis, design or assessment for an element of the facility and identify this as a dam safety issue.
- Review of the DSMS, and operating, surveillance, maintenance and testing procedures and records, including clarifying matters of detail with operations, dam safety and surveillance staff.
- Review of the organisation of operational resources and infrastructure.
- Review of emergency preparedness including procedures, training, exercises, facilities and equipment.
- The completion of a report covering the review which includes:
  - comments on the appropriateness of the PIC
  - comments on the outputs of the FMEA, the potential failure modes and their key performance indicators
  - comments on dam performance
  - a discussion of any issues related to monitoring and surveillance, and any changes that should be made to monitoring and surveillance processes
  - an assessment of the safety of the dam with respect to current acceptability criteria
  - comment on the appropriateness of the DSMS
  - a discussion on any dam safety issues identified in the inspection, testing and review, including potential or confirmed dam safety deficiencies
  - the categorisation of any identified dam safety
  - issues into physical infrastructure issues, potential or confirmed dam safety deficiencies, and non-conformances (refer Module 7: Lifecycle Management)
  - comment on previously identified dam safety issues and either the adequacy of their resolution, or whether there are impediments that prevent their resolution.

4.5.5 Scope and procedures for Low PIC Dams

As discussed previously, CDSRs for Low PIC dams, while ostensibly not essential, are still important to any Owner from a dam safety perspective and are thus recommended in these Guidelines. In addition, an Owner may require a detailed safety review for asset management or reinsurance purposes, particularly where a dam failure could lead to a major loss of revenue.

If the recommended IDSRs are undertaken by appropriately skilled and experienced personnel, significant aspects related to dam safety should be identified as a matter of course. Where a CDSR is undertaken for a Low PIC dam, the procedures should be much the same as outlined above for Medium and High PIC dams, with the scope or level of detail set to reflect the Owner's level of concern about asset protection and the potential effects of a dam failure.

4.6 Special inspections and dam safety reviews

4.6.1 Special inspections

Special dam safety inspections should be carried out following unusual events, observations or emergencies. In the interests of time, these may be undertaken by the Owner or appropriate personnel with any anomalies referred to the Technical Adviser or, where practical, undertaken directly by the Technical Adviser. Such events and emergencies should be evaluated to determine whether they have resulted in any noticeable changes, damage that requires attention, whether any special safety measures or follow-up investigations need to be implemented, and whether the dam performance was in accordance with design expectations.

Unusual events, observations and emergencies may include:

- Adverse surveillance observations or instrument readings.
- Large rainfalls or floods.
- Strong winds.
- Earthquakes.
- Landslides into the reservoir.
- Volcanic eruptions.
- Man-made damage.

In addition to unusual events and emergencies, special dam safety inspections may be necessary to examine a particular feature of a dam that has been identified as having a potential or confirmed dam safety deficiency (e.g. from surveillance evaluation and safety reviews), or which has been subjected to abnormal loading conditions or remedial works.

Special inspections should be well documented and archived as an important part of the dam's long term record.

4.6.2 Special dam safety reviews

Special Dam Safety Reviews (SDSRs) may be required following an unusual event, observation or emergency, or when a potential or confirmed dam safety deficiency has been identified. The management processes for SDSRs should follow those outlined in Module 7: Lifecycle Management for the management of dam safety issues.

The scope of an SDSR will be specific to the nature of the dam's condition and any potential or confirmed dam safety deficiency that has been identified, and may include:

- A review of records and reports from investigation, design, construction and surveillance.
- Site inspections and investigations (e.g. exploratory geotechnical or geophysical investigation by excavation, drilling, density testing, or shear wave testing).
- Natural hazard assessments (e.g. flood, seismic, geologic, reservoir landslides).
- Stability and performance assessments (e.g. structural, flood passage, rock mechanics, erosion, scour).
- New or updated Failure Modes and Effects Analysis (FMEA).
- Dam-break modelling and consequence assessment.
- The identification of preliminary remedial actions or mitigating measures (structural or non-structural).
- The completion of a report covering the review which includes:
  - any dam safety issues investigated and/or identified in the review, including potential or confirmed dam safety deficiencies
  - possible interim risk reduction measures and long-term risk reduction options, and comments on time drivers for their implementation
  - the categorisation of identified dam safety issues into physical infrastructure issues, potential or confirmed dam safety deficiencies, and non-conformances (refer Module 7)
  - comment on previously identified dam safety issues and either the adequacy of their resolution, or whether there are impediments that prevent their resolution.

When undertaking SDSR's the Owner should employ appropriate specialist expertise relevant to the dam and foundation type, natural hazards, any particular features, any potential or confirmed dam safety deficiencies, and the consequences of failure. These Guidelines recommend an appropriate level of peer review where the consequences of failure are high.

4.7 Emergency preparedness

Emergency preparedness, and its role as part of a DSMS, is mentioned for completeness in this module. However, it is of sufficient importance that it is covered separately and in full in Module 6: Emergency Preparedness.

4.8 Identifying and managing dam safety issues

Identifying and managing dam safety issues, and its role as part of a DSMS, is mentioned for completeness in this module. However, it is of sufficient importance that it is covered separately and in full in Module 7: Lifecycle Management.

4.9 Information management

4.9.1 Philosophy

In the context of a dam's lifetime, and the rigour that must be applied to its ongoing safe management, the importance of careful record keeping and preservation of all dam information cannot be overstated.

Whether paper-based or computer-based, it is vitally important that all dam information is filed and managed in a way that it can be easily located by future users, including those that may not know it exists. Dam information should also be backed up and stored at an alternative location to the primary copy.

A robust and defensible information management system will safeguard an Owner against the risks of institutional knowledge being lost through staff turnover. Activities that are planned using reliable knowledge and good records will likely save the Owner considerable time and money. For example, when investigating a dam safety deficiency, historic records may avoid the need for intrusive (and unnecessarily risky) dam investigations.

4.9.2 Relevant information

The types of information that are important to a dam and its wider DSMS are many and varied. Material to be included in an information management system for the effective implementation of a DSMS should include:

- A dam inventory/register that captures the details of an Owner's dam portfolio including key dimensions and attributes such as (but not limited to) dam types, heights, appurtenant structures, PICs, surveillance frequencies, potential failure modes and key performance indicators.
- The DSMS and supporting documentation.
- Process and procedural documents relating to implementation of the DSMS (e.g. surveillance procedures, operation and maintenance procedures, gate/valve testing procedures, reservoir operating rules during normal and flood conditions).
- All historical documents and drawings relating to investigation, design and construction. These are sometimes compiled into a data book.
- All historical performance information including records of surveillance (including reservoir levels), maintenance, gate and valve operations and tests, significant events and incidents.
- All dam related investigations, studies, reviews, upgrades (including new drawings) and changes to operating conditions or systems (e.g. a change to the reservoir operating rules and/or a change to the spillway gate control system).
- An instrumentation inventory and supporting information such as as-installed drawings, technical specifications, calibration certificates, operation and maintenance requirements, and records of maintenance.
- An auditable database of dam safety issues (e.g. those made during IDSRs and CDSRs) including tracking of their status and associated decisions.
- All dam safety governance, oversight and status reporting prepared for the internal and external communication of issues (including communications with Regulators and local authorities).
- Training schedules and records for all dam safety related staff including managers, engineers, operators and surveillance inspectors.

4.10 Audits and reviews

Audits and reviews of a DSMS allow an Owner to maintain a pathway of continuous improvement and provide assurance that dam safety risk is being appropriately managed. Audits and reviews provide the best value when they are undertaken as a complementary mix of introspective self-assessment and external assessment.

4.10.1 Audits

Audits of DSMSs are largely for the purpose of ensuring defined processes and procedures are being followed. They do not necessarily need to be carried out by a Technical Adviser, but rather by someone who is able to recognise governing processes and procedures, and question to an appropriate level of detail when looking for supporting evidence. There is not a prescribed frequency for such audits; however, an Owner may choose to complete annual or two-yearly audits, depending on the nature of their organisation and dam portfolio. Internal audits may assist the Owner to identify preparedness for external audits such as the regulatory dam safety assurance programme (DSAP) certification and audit (by a Recognised Engineer) described in Module 1: Legal Requirements.

4.10.2 Reviews

Reviews of DSMSs are aimed at identifying opportunities for technical and strategic improvements based on recognised dam safety practice (e.g. is the existing DSMS appropriately and effectively managing dam safety risk?). Such reviews are usually performed by a highly experienced and external Technical Adviser (or Technical Specialist) in conjunction with the Owner and their key dam safety personnel. There is not a prescribed frequency for such reviews; however, an Owner may choose to complete 2-yearly to 5-yearly reviews, depending on the nature of their dam portfolio and organisational governance arrangements. As a minimum a DSMS review should be completed as part of a Comprehensive Dam Safety Review (CDSR) for High and Medium PIC dams. Regulatory requirements for the review of dam safety assurance arrangements for High and Medium PIC dams are provided in Module 1: Legal Requirements.

An Owner of a Low PIC dam, for which a DSMS exists, may choose to adopt seven- yearly to ten-yearly reviews.

Indicators of an effective DSMS include (but are not limited to):

- An Owner's dam safety policy/statement/standard exists and the objectives conform to relevant dam safety regulations, guidelines, dam safety practice, and the Owner's goals and values.
- Governance arrangements for the DSMS, including oversight and enabling, are in place and are effective. Dam safety issues and risks are well recognised by the Owner.
- Roles, accountabilities, responsibilities and delegated authorities are clearly assigned.
- Personnel with dam safety accountabilities and responsibilities clearly understand their roles, accountabilities and responsibilities.
- The DSMS is well resourced, implemented and documented.
- Surveillance, operation, maintenance and testing activities that affect dam and reservoir safety are carried out and documented with a high level of quality assurance.
- Dam safety issues and incidents are managed appropriately including escalation, reporting, investigation and resolution.
- Potential and confirmed dam safety deficiencies are identified, investigated and resolved in a timeframe and manner that is appropriate to the level of risk.
- Risks are well understood.
- The DSMS is responsive/adaptive to changing environment or operational conditions.
- Capability, knowledge and succession requirements are planned for and implemented.

5. Change management and improvement

5.1 Philosophy

It is important for an Owner to stay abreast of developmental, environmental and operational changes, both within and outside of their organisation, which may affect the operation of their dam systems. The establishment and maintenance of effective communications with key stakeholders are important. Stakeholders may include local and Regional Authorities, neighbouring industries and landowners, emergency authorities and local communities.

An Owner should ensure that its mode of reservoir operation and the contents of its DSMS remain current and appropriate to their situation at any given time.

5.2 Common aspects that change

The most common aspects that change with time and may require amendments to the mode of reservoir operation and/or the DSMS are:

- Changes in upstream reservoir/river/catchment use including the operation of other dams, de-forestation, recreational use, and development of the reservoir shoreline.
- Changes in downstream populations with development or increases in recreational use.
- Changes in climate and therefore inflows, reservoir levels, and flood management procedures.
- Seismic hazard changes
- Bush fire hazard changes
- Physical changes or threats that may be caused by geothermal activity, mining or quarrying (including blasting)
- Environmental concerns (e.g. algal blooms or fish habitats).
- Physical security and cyber security threats
- Public safety around dams and waterways
- Owner organisational changes
- Owner resource constraints during disruptions and prolonged events (e.g. pandemics, widespread natural events)
- Regulatory changes

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Society on Large Dams

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MODULE 6
EMERGENCY PREPAREDNESS

Abstract

Dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, operation, assessment and rehabilitation of dams in New Zealand are included in the Parent Document. The Parent Document also includes a glossary of terms used in these Guidelines.

This module provides a framework for the development of Emergency Action Plans (EAPs) to minimise the potential for dam failure through pre-planned or pre-conceived intervention actions should a dam safety emergency event arise and, in the event that a dam failure cannot be prevented, to limit the effects of a dam failure on people, property and the environment. The module includes:

- An outline of emergency preparedness planning and processes.
- Recommended procedures for the development of EAPs.

The intent in preparing the module is that it is consistent with the Coordinated Information Management System (CIMS) that is utilised by New Zealand's Civil Defence Emergency Management (CDEM) agencies and some dam Owners for the management of emergencies. While some of the terminology used in the module may be a little different from that in CIMS, it is consistent with the terminology used for the management of dam safety in other countries with similar jurisdictions to New Zealand and is consistent with the broad principles and objectives of CIMS.

The module includes limited discussion on the role of Regulators in dam safety, and reference should be made to Module 1 (Legal Requirements) for a more complete description of their role and responsibilities.

Notice to reader

While this module has been configured to be, as much as practicable, self-contained from a technical perspective, the reader should be conversant with the principles, objectives and limitations expressed in the Parent Document prior to considering the information provided in this or any other individual module.

Document history

Release	Date	Released with
Original	May 2015	Parent and all modules
2023	December 2023	Updates to Parent and Modules 1, 2 and 5

Contents

1. Introduction

1.1 Principles and Objectives

All dams should have emergency response procedures in place if emergency procedures could reduce the potential for dam failure, if there is a population at risk, or if implementation of emergency procedures could reduce the potential consequences of failure. Emergency response procedures are included in documents with a variety of names such as an Emergency Preparedness Plan (EPP), a Site Emergency Response Plan (SERP), or an Emergency and Civil Defence Plan (ECDP). In these Guidelines, emergency response procedures are included in an Emergency Action Plan (EAP).

The level of detail in the procedures should be adequate to ensure all necessary information and directions are conveyed, but not so verbose as to inhibit the reader from gaining a clear and definitive understanding of the actions to be taken. Principle 7 in the Parent Document states that:

Effective emergency preparedness and response procedures should be in place for dams.

The objectives of this module are to provide guidance for the development of dam specific emergency action plans, and outline appropriate testing and training programmes to confirm the ongoing effectiveness of dam specific emergency action plans.

Planning for a dam safety emergency is a necessary risk management task, especially for dam Owners where there is a potential for loss of life or heavy environmental damage and costly restoration in the event of dam failure. An Emergency Action Plan (EAP), that describes the actions to be taken by a dam Owner or Operator during a dam safety emergency, should be prepared for all Medium and High Potential Impact Classification (PIC) dams. Guidance on the classification of dams by PIC is provided in Module 2. Notwithstanding this, dam Owners may choose to prepare EAPs for dams that present a lesser hazard for their own organisational risk management goals and objectives.

Effective emergency management relies on the establishment of a clear emergency response plan and strategy that is understood by all involved in the dam safety emergency and is supported by the following:

- An EAP that details the actions the dam Owner or Operator will take in response to a dam safety emergency.
- A maintenance, testing and training programme to improve and confirm the ongoing effectiveness of the EAP.
- A local emergency plan developed by CDEM agencies, prepared in coordination with and using inputs from the dam Owner, for their own purposes to warn and evacuate residents in the flood plain should this be necessary.

1.2 Scope of module

This module provides guidance in emergency action planning for dams. It is specific to dam safety emergencies that have the potential to endanger the integrity of the dam, damage downstream property and result in loss of life. It is not relevant to other emergencies (e.g. a personal accident or an oil spill) or dam safety incidents, such as large flood events or observed departures from expected dam performance, which do not endanger the integrity of the dam, damage downstream property or result in loss of life. The module addresses:

- Potential dam safety threats and dam safety emergencies.
- Procedures for the development of EAPs.
- What should be included in EAPs.
- Sample EAP format.
- Responsibilities for maintaining and updating EAPs.

A list of reference documents is included at the end of this module to assist Owners in the development of EAPs.

2. Emergency Preparedness Planning

Emergency preparedness planning is planning that allows all involved with the dam and the potential consequences of dam failure, including the Police and CDEM agencies, to be prepared for the management of a dam safety emergency. It is an important component of a dam safety management system and includes the preparation and maintenance of an EAP, and regular training exercises to ensure that emergency management personnel are familiar with the EAP and their responsibilities and that they are able to fulfil their duties during a dam safety emergency.

2.1 EAP Documentation

Where appropriate, there should be an EAP for each phase of a dam's life cycle – during construction, first filling and normal operations, rehabilitation and decommissioning. EAPs should be controlled documents covered by appropriate procedures for distribution and the management of changes.

The EAP should be referenced in Operation and Maintenance procedures so that there is a seamless transition in the management between normal operating conditions to emergency conditions. This is particularly important with respect to Operations and Maintenance procedures for plant and equipment that fulfil dam safety functions.

2.2 Potential dam safety threats and dam safety emergencies

Potential dam safety threats can be initiated by a range of conditions that include:

- A flood.
- An earthquake.
- A landslide into the reservoir from the reservoir slopes, or from the abutments.
- The identification of abnormal behaviour (evidence of significant seepage, piping, spillway blockage, inoperable gates etc).
- Incorrect operation.
- Accidental damage.
- A volcanic eruption (lava flow, ash, etc).
- Sabotage.

Potential dam safety threats will vary depending on the hazards and risks, and the characteristics of the dam and its reservoir, and the EAP should reflect the particular site-specific hazards and risks, and the characteristics of the dam.

Once a dam safety emergency has been declared, it is important that it is classified using pre-defined criteria to trigger the appropriate emergency response. Typically, three levels of emergency response are defined, with increasing levels of urgency:

- **Internal event** – Only impacts on the dam Owner and the response can be managed internally.
- **Potential emergency** – Has the potential to affect external parties and the Police, CDEM, emergency services, and local and regional authorities should be notified of the situation.
- **Imminent failure** – An event that will affect external parties is underway. A dam failure has either occurred, is occurring or is obviously about to occur. The Police, CDEM, emergency services, and local and regional authorities should be immediately notified of the situation.

Note that dam Owners cannot declare civil defence emergencies; they can only be declared by people with specifically designated roles in accordance with the Civil Defence Emergency Management Act.

A simple flow chart showing a typical process for the management of a potential dam safety threat, or a dam safety emergency, is shown in Figure 2.1.

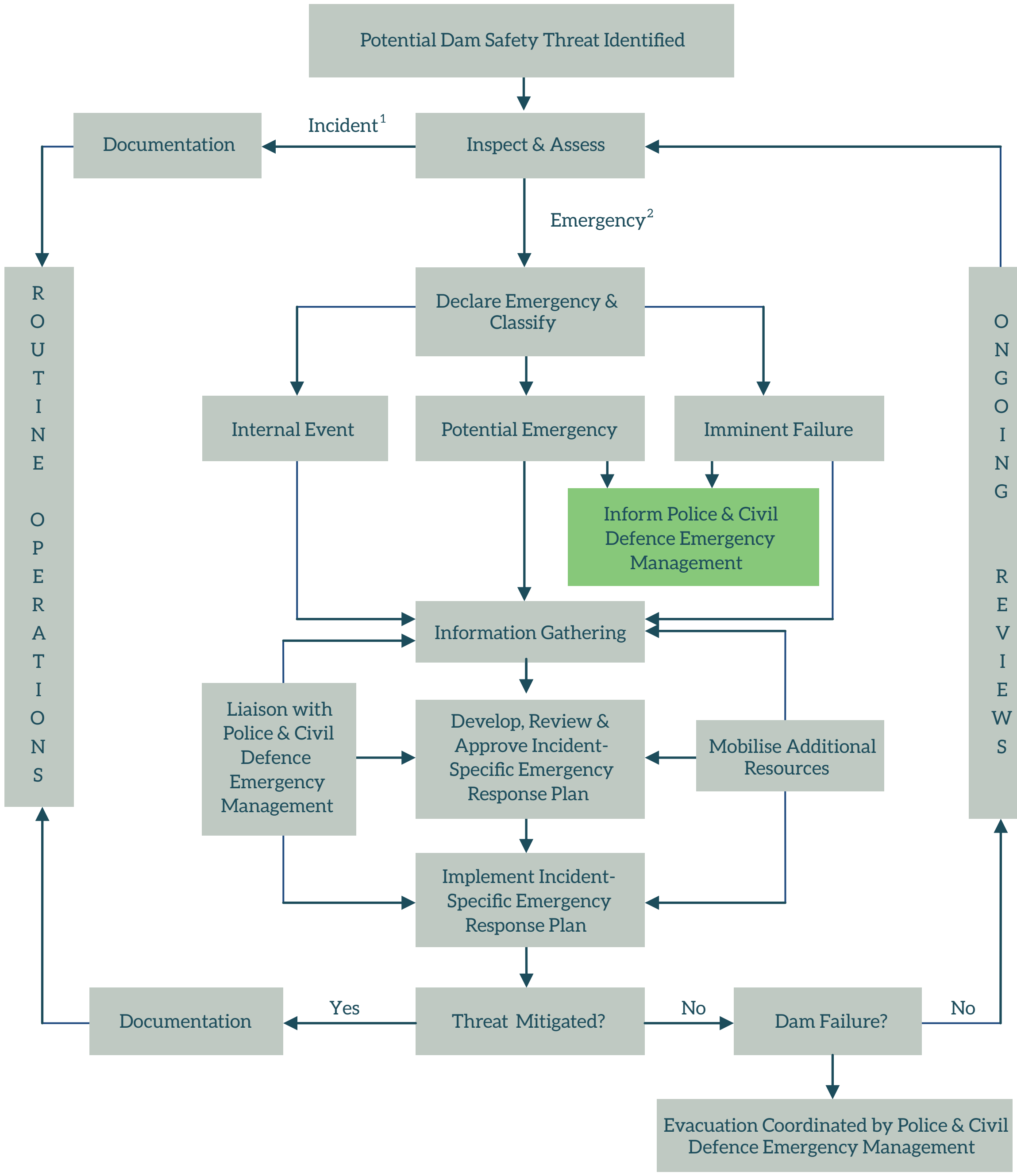

Figure 2.1: Typical Process for the Management of a Potential Dam Safety Threat or a Dam Safety Emergency

Notes

1. An incident is defined as an occurrence that requires a response from one or more agencies, but is not an emergency.
2. An emergency is defined as a situation that poses an immediate risk to life, health, property, or the environment and requires a coordinated response.

3. Emergency Action Plans

3.1 Development of an Emergency Action Plan

An EAP should detail the actions that the Owner and operating personnel should take in a dam safety emergency. The EAP should be specific to the dam and should include emergency procedures for each of the identified credible potential failure modes for the dam. Where a chain of dams is located on a river system, coordination is necessary to ensure that emergency actions taken at one dam do not jeopardize the safety of a downstream dam.

Where a single dam owner has a portfolio of dams, it may be appropriate to develop a generic EAP that details common company procedures and includes, within separate appendices or reference documents, site-specific information and procedures relating to each dam and its credible potential failure modes.

The development of an EAP requires coordinated planning with all involved parties. In this regard an EAP has two components:

- The internal procedures that the dam Owner or Operator carry out in the event of an emergency at the dam (who does what when).
- The information needed by external agencies so they can develop their own emergency plans (e.g. inundation maps, notification procedures).

The steps in developing an EAP are generally as follows:

- Identify those situations or events that may require the initiation of an emergency action. Reference should be made to potential failure modes for the dam (refer Modules 3 and 5) and the likely consequences of a dam failure (refer Module 2).
- Identify performance or surveillance indicators which may indicate that an emergency is developing.
- Identify key sources, agencies, and individuals who are able to supply information for input into the EAP.
- Identify all jurisdictions, agencies, and individuals who will be involved in implementing the EAP.
- Identify primary and auxiliary communication systems, both internal (between owner/operator personnel) and external (between owner/operator personnel and external agencies).
- Identify all persons and agencies involved in the notification process (by liaison with the local CDEM Group), and draft a notification procedure. Include who should be notified, in what order, and what other actions are expected of downstream agencies.
- Liaise with relevant Territorial and Regional Government agencies to ensure the EAP will have a good fit with wider community emergency plans.
- Develop a draft EAP.
- Discuss the draft EAP fully with all parties included on the notification list, seeking review and comment.
- Make any revisions, obtain any necessary approvals, and circulate controlled copies of the completed EAP to those who have responsibilities under the plan.

3.2 Integration with Territorial, Regional and Emergency Authorities

All dam Owners within Territorial or Regional authorities supplying potable water and those generating electricity are designated as Lifeline Utilities in the Civil Defence Emergency Management Act and are required to “make available to the Director in writing, on request, its plan for functioning during and after an emergency”. The supply of an EAP to the local CDEM Group (CDEMG) is considered to be consistent with this requirement. Other dam Owners should offer their EAPs to their relevant CDEMG for incorporation, as appropriate, within the local community emergency management plan.

A dam Owner’s EAP may include a lot of detail on internal operations that is of no interest to the CDEMG. In such cases the CDEMG may request elements from the Owner’s EAP, for example:

- A description of the dam.
- Notification procedures.
- Any warning systems.
- Inundation maps, including inundation tables.
- EAP testing and training programmes.

3.3 Contents of an Emergency Action Plan

An Emergency Action Plan (EAP) should include, or include references to, the following information and procedures:

- The purpose of the EAP.
- EAP responsibilities.
- Emergency contact lists.
- Identification, assessment and classification procedures.
- Notification procedures.
- Preventive and emergency actions.
- Emergency termination actions.
- Access to site, including site location maps and main and alternative access routes.
- Response procedures for any situation where access to the dam may be impaired (e.g. during periods of darkness, adverse weather, transport disruptions, road closures).
- Communication systems.
- Emergency power supplies.
- Sources of emergency materials, supplies and equipment.
- Technical and operational support resources.
- Warning systems (if used).
- EAP maintenance and training.
- Dam break inundation maps and tables.
- Any additional information required to ensure an appropriate response to a potential or imminent dam safety emergency.

3.3.1 Purpose of an EAP

The purpose of an EAP is to provide a pre-determined plan of actions that a dam Owner is able to implement if a dam safety emergency develops.

As such, an EAP should be designed to:

- Minimise the potential for dam failure should a potential dam safety emergency arise.
- Limit the effects of a dam failure on people, property and the environment In the event that a dam failure cannot be prevented.

An EAP should take into account the credible potential failure modes applicable to the dam and the potential downstream consequences of the breach discharges associated with those potential failure modes. It should define and prioritise the implementation of those actions that realistically may be achieved to minimise the potential for loss of life and damage to property and the environment.

3.3.2 EAP responsibilities

This section should specify the person(s) or organisation(s) responsible for the surveillance, maintenance and operation of the dam and the person(s) and or agencies responsible for implementing various stages of the EAP. Delegated authorities for key personnel should be specified.

The availability of emergency personnel to fulfil their responsibilities during a dam safety emergency can be affected by large natural events such as floods, earthquakes and volcanic eruptions. For example, nominated emergency personnel may be directly affected by a large earthquake and unavailable to assist in the management of a dam safety emergency that arises following the earthquake. It is therefore important that EAPs incorporate a level of resilience to ensure appropriate personnel are available to assist in the management of a dam safety emergency.

3.3.3 Emergency Contact Lists

The EAP should include an easy to find list that provides key emergency contact details.

The details should include names, roles, addresses and contact details (landline and mobile telephones numbers), and the details should be updated on a regular basis to ensure they remain current.

3.3.4 Identification, assessment and classification procedures

Potential threats which could endanger the safety of the dam and could require immediate action should be included in the EAP.

If detected early enough, potential dam safety threats can be assessed and preventive or remedial actions can be taken prior to the declaration of a dam safety emergency to avoid a dam breach or mitigate the size and extent of a dam breach. The EAP should contain clear procedures for taking action when a potential dam safety threat is identified.

A special dam safety inspection should be carried out as quickly as possible following the identification of a potential dam safety threat. Appropriate monitoring should take place during the assessment of the potential dam safety threat and continue until the threat has been resolved. A list of qualified dam inspectors and technical specialists, keyed to the type of dam safety threat, should be included in the key emergency contacts list included in the EAP.

The declaration of a dam safety emergency requires that a responsible person decides if and when an emergency should be declared and the EAP implemented.

Any hesitancy in declaring a dam safety emergency could affect the effectiveness of any emergency actions. Clear guidance should therefore be provided in the EAP on the conditions which require a dam safety emergency to be declared, who is able to declare a dam safety emergency, how the emergency declaration should be recorded, and what guidelines should be followed in classifying the emergency (internal event, potential emergency or imminent failure).

3.3.5 Notification procedures

The first step with regard to notification is the 'decision to notify'. This decision is particularly important for the evacuation of any population at risk and the notification procedures should detail who has the authority to make the decision to notify and how the decision should be made according to the timing of the event (day, night, weekend). Any hesitancy in making the decision to notify could affect the effectiveness of the evacuation of any population at risk.

The Police, CDEM, and local and regional authorities should be notified of any potential emergency and immediately notified of any imminent failure.

Notification procedures must be clear and easy to follow. The EAP should include a list of all persons to be notified in the event that a dam safety emergency is declared, and clearly indicate who is to make the calls and in what priority. The number of persons to be notified by each responsible individual should be kept to a minimum. The procedure, which is often best presented in a notification flow chart, should include notification to the Police, CDEM, Owner, Technical Advisers, Contractors, Territorial Authorities and Regional Authorities as appropriate. The procedure should also include individual names and position titles, office and home telephone numbers, and alternative contacts and means of communication. Copies of the notification procedure, or flow chart if prepared, should be available for all individuals having responsibilities under the EAP, and should be prominently posted at the dam and the Owner's emergency operations centre.

Early notification to the Police will allow them to determine if they have sufficient resources to respond, or if they will need to call in CDEM. The local CDEMG may or may not decide to declare a civil defence emergency.

The EAP does not necessarily need to include details of briefings for the news-media but procedures for these should be pre-planned. Consideration should be given to the use of a dedicated person, skilled in media briefings, to prepare statements and provide regular updates to the news-media.

3.3.6 Preventive and emergency actions

This section should detail preventive actions that can be taken both prior to and following the declaration of a dam safety emergency to remedy or mitigate the potential effects of a dam failure. In broad terms, such actions are likely to fall into one of the following categories; intervention to prevent dam failure, reducing the level of the hazard (lowering the reservoir level), slowing the rate of deterioration, or reducing the consequences of the failure. Depending on the dam safety emergency, there are likely to be potential actions available in more than one of these broad categories.

Actions taken prior to the identification of a potential dam safety deficiency, that can assist in the mitigation of a dam failure or minimise the downstream effects of a dam failure, include:

- Agreements with supporting third parties to respond at short notice with equipment, materials or expertise.
- The stockpiling of materials.
- The installation of warning systems to alert the population at risk.
- Establishing coordinated plans and procedures with Police and CDEM authorities.

Preventive or remedial actions taken prior to the declaration of a dam safety emergency may include reservoir drawdown (refer section 4), limiting inflows and outflows, placing material to staunch potential seepage erosion or piping discharges, placing material or sand bags at low spots on a dam crest, or controlled breaching.

Preventive actions taken following the declaration of a dam safety emergency may include initiating physical works to reduce the likelihood of dam failure, reservoir drawdown, or evacuating people from the likely inundation area.

The EAP should include events or indicators that would initiate implementation of the EAP. These may be based on the design criteria adopted for the dam, the historical performance of the dam, or the results of a completed Failure Modes and Effects Analysis (FEMA). The following factors and emergency response actions should be outlined in the EAP:

- Events and indicators that would initiate the EAP.
- The nature of the discharge (size, contents) that may potentially be released in a failure.
- Estimated times to respond to an adverse event (e.g. estimated time before failure, time for earthmoving equipment to reach site, available warning time for downstream population).
- Information from third parties (e.g. weather forecasts, river flows) that can assist in the timing of preventive actions.
- Details of any warning systems.
- Actions that can be taken to lower the reservoir, or limit reservoir inflows and outflows.
- Actions that can be taken to remedy or alleviate the dam safety emergency.
- Actions to mitigate the potential effects of a dam failure.

3.3.7 Emergency Termination Actions

The EAP should include procedures for terminating a dam safety emergency and notifying the emergency services that the dam safety emergency has been resolved. The emergency services are responsible for declaring an end to any public emergency response process.

Following the termination of a dam safety emergency, as determined by the dam Owner and/or his/her Technical Adviser, the dam Owner or Technical Adviser should fully document the emergency response in a report. The report should include discussion on:

- The event or condition that initiated the emergency.
- The response actions taken by the dam Owner and all emergency service agencies.
- The extent of any damage to the dam.
- The extent and effect of any downstream inundation.
- The justification for terminating the dam safety emergency.
- The strengths and weaknesses of the existing EAP including the emergency management procedures, equipment, resources and leadership.
- Corrective actions to address any identified weaknesses in the EAP.

3.3.8 Access to site

The description of access should focus on primary and secondary routes, the means for reaching the site under various conditions (e.g. road, foot, boat, helicopter, bulldozer), and the expected travel times.

Earthquakes and heavy rainstorms can result in landslides, tree falls and bridge washouts that prevent road access for days or weeks. Poor weather can also prevent helicopter access. It is therefore important that the accessibility of the site following a large natural event, and the effects of possible access constraints on the availability of equipment needed to manage a dam safety emergency, are given early consideration and that EAPs incorporate a level of resilience to minimise the adverse effects of access constraints. If access constraints are likely following a large natural event, it may be appropriate to store essential equipment at the site.

3.3.9 Response procedures where access to the dam may be impaired

The EAP should include response procedures for any situation where access to the dam may be impaired. Access could be impaired during:

- Periods of darkness, including those caused by power failures. Appropriate responses may include establishing emergency power and lighting, limiting areas of access or inspection, or waiting until daylight.
- Adverse weather, including extremes of temperature, snow, or storms. Appropriate responses may include temporary shelters, appropriate clothing and equipment, or video rather than manned surveillance.
- Transport disruptions.
- Road closures.

3.3.10 Communication systems

Full details should be included of the internal and external communication systems as they apply to the EAP. Commonly used communication systems (cell phone, land line telephone and email) are vulnerable to failure or overload in the adverse conditions that may lead to a dam safety emergency (e.g. earthquake, storm, heavy rainfall etc). As such, the robustness of the available communication systems should be assessed and, where appropriate, enhanced by additional communication systems.

Examples of additional communication systems are trunk radios, satellite phones and internet messaging.

3.3.11 Emergency power supplies

Details on the location and operation of emergency power supplies (e.g. portable generators, fuel) should be included.

3.3.12 Sources of emergency materials, supplies and equipment

The location and availability of emergency supplies (e.g. food for response teams) and materials (e.g. rip rap, filter and drainage materials) for emergency use should be addressed.

The location and availability of equipment (e.g. torches, cameras, emergency lighting, earthmoving plant) and local contractors that could be mobilised in a dam safety emergency should be included.

3.3.13 Sources of technical and operational support resources

In a dam safety emergency it may become necessary to obtain specialist technical support to consider dam performance trends and identify the need for any preventive actions or temporary support works. It may also become necessary to obtain additional resources for operation of the facilities (e.g. during a basin wide emergency that affects the operation of a number of dams).

Managing a dam safety emergency is demanding on staff and additional resources may be required if the emergency is likely to extend beyond 10 hours. In addition, resources from outside the affected area may be appropriate in some circumstances (e.g. following a large local earthquake on-site resources may be affected by family or other concerns).

The EAP should include a listing of technical and operational support personnel, together with their contact details.

3.3.14 Warning systems

Warning systems are sometimes installed to provide warnings to residents, camp grounds, and parks that are close to a dam. Where they are installed, full details of the warning systems and their activation, including who is responsible for any decision to activate the warning systems, should be included in the EAP.

3.3.15 EAP Maintenance and training

The dam Owner is responsible for issuing, maintaining and updating all registered copies of the EAP. It should be a controlled document.

The EAP should include provisions for appropriate review of the document, its procedures and communications systems for currency, relevance and operability. The review should be completed on a regular basis, at least annually, and include updating, as necessary, the names and contact details for all personnel with emergency management responsibilities. The EAP should also be reviewed during the completion of Intermediate Dam Safety Reviews and Comprehensive Dam Safety Reviews to verify that it is current and that the information, guidance and direction are consistent with the dam's condition and performance.

Provisions should also be included for the training of personnel involved in the activation and implementation of the EAP. This is to ensure all personnel nominated in the EAP are familiar with the elements of the plan and their responsibilities, and are able to fulfil their duties during a dam safety emergency. Training exercises can range from a limited table top exercise for a specific dam safety emergency to a full scale simulation of a dam safety emergency which includes multiple failures (domino effects).

The frequency and type of training exercises should reflect the consequences of failure and should be sufficient to maintain the dam Owner's readiness for a dam safety emergency. It should also reflect the level of turnover in personnel having emergency preparedness responsibilities. A frequency of two to three years would be appropriate in most instances. From time to time, Police and CDEM officers should participate in the training to maintain their readiness for a dam safety emergency and maintain coordination across all affected parties.

3.3.16 Dam break inundation maps and tables

Dam break inundation maps (refer Module 2) assist Police, CDEM, and Territorial and Regional Authorities in the development of management and evacuation plans. However, inundation maps are usually based on worst case dam failure scenarios and understanding the actual condition of the dam, and the most realistic dam breach scenarios, are important for communication of the risk to the downstream population.

Dam break inundation maps should be included or referred to in all EAPs prepared for Medium and High PIC dams. They should show inundation areas at scales sufficient for the identification of areas at risk and should include inundation tables which show at key locations:

- The arrival time of the first flood waters.
- The arrival time of the peak flood level.
- The peak flood elevation above mean sea level.

It may also be useful to express flood levels as relative depths at key locations (eg bridges) and the time at which key structures may become unusable. Regional Authorities have a responsibility for regional scale natural hazard information, including flood hazard maps. Where the estimated discharge that would result from a dam failure is similar to the flood size already mapped, the existing inundation information held by the Regional Authority may suffice.

3.3.17 Additional information

Additional items frequently incorporated as appendices in an EAP include:

- General site plans, drawings and photographs.
- Details and operating instructions for gates and valves that fulfil dam safety functions.
- Information for assessing reservoir dewatering options.
- Procedures for the recording of emergency situations (e.g. flood inspection check lists, post-earthquake check lists, emergency action log, emergency termination log).

3.4 EAP format

The effectiveness of an EAP can be enhanced by the adoption of a uniform format that ensures all information and procedures are included and easily understood.

While an EAP should be formatted in a way that is most useful to and consistent with the organisation involved in its implementation, the sample format outlined in Figure 3.1 for a Medium or High PIC dam should result in a user-friendly document that facilitates a timely response to a potential or actual dam safety emergency.

EMERGENCY ACTION PLAN

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Figure 3.1: Sample format for an Emergency Action Plan (Medium of High PIC Dam)

An EAP for a Low PIC dam need not be as detailed as that for a Medium or High PIC dam, but should be sufficiently detailed to meet the dam Owner's risk management goals and objectives.

4. Reservoir drawdown plans

For many dams, or canals, a primary response to a dam safety emergency may be to reduce the hazard by drawing down the reservoir. Depending on the characteristics of the dam safety emergency and the available drawdown facilities (e.g. spillways, low level sluices), the achievable drawdown may be limited to the normal operational range of the reservoir or it may be possible to drawdown the reservoir to the invert levels of the discharge facilities.

Reservoir drawdown plans should be developed for all Medium and High PIC dams that incorporate drawdown facilities, and the plans should either be referenced or incorporated within the EAPs. Because drawdown requirements in a dam safety emergency are often difficult to establish, drawdown plans should include sufficient flexibility to respond to changing conditions and contain sufficient information to assist decision makers in determining appropriate courses of action.

A reservoir drawdown plan might contain:

- Dam, or canal, safety conditions that could necessitate reservoir draw down.
- An outline of reservoir inflows and whether or not they can be controlled.
- An outline of the available drawdown facilities, their discharge capacities and their drawdown limitations.
- Limitations on the rate of drawdown to prevent serious damage to the dam, or canal, (e.g. a rapid drawdown failure of the upstream slope of an earth dam), and prevent instability in the abutments or the reservoir slopes including any dormant or suspected landslides.
- Limitations on the rate of discharge or discharge ramping rates to reduce downstream impacts.
- Alternative drawdown scenarios and drawdown procedures.
- Plots of reservoir level versus time, for the alternative drawdown scenarios and procedures, which reflect drawdown and discharge limitations and clearly show drawdown progress.
- Links to the EAP and emergency notification lists.

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MODULE 7
LIFE CYCLE MANAGEMENT

Abstract

Dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, operation, assessment and rehabilitation of dams in New Zealand are included in the Parent Document. The Parent Document also includes a glossary of terms used in these Guidelines.

This module discusses dam life cycle management issues beyond design and construction, and provides guidelines for managing dam safety issues and deficiencies, the rehabilitation of dams, sediment management, change of dam use, and the decommissioning of dams. The focus of the module is primarily related to issues that can directly affect dam safety (i.e. the uncontrolled release of reservoir contents); however, the module also provides guidance on the management of public safety around dams which is an important component of dam safety management.

This module includes limited discussion on the role of Regulators in dam safety and reference should be made to Module 1 (Legal Requirements) for a more complete description of their role and responsibilities.

Notice to reader

While this module has been configured to be, as much as practicable, self-contained from a technical perspective, the reader should be conversant with the principles, objectives and limitations expressed in the Parent Document prior to considering the information provided in this or any other individual module.

Document history

Release	Date	Released with
Original	May 2015	Parent and all modules
2023	December 2023	Updates to Parent and Modules 1, 2 and 5

Contents

1. Introduction

1.1 Principles and objectives

Dam safety is important through all stages of a dam's life cycle including initial design and construction, operation, rehabilitation, decommissioning and, in the case of tailings dams, long-term closure.

Principle 8 in the Parent Document states that:

Due diligence should be exercised during all stages of a dam's life cycle.

The focus of this module is on 'lifetime' issues that Owners may encounter on existing and new dams beyond design and construction. The module provides guidance for Owners and, if appropriate, Regulators in managing and addressing issues associated with public safety around dams, lifetime changes, dam safety issues and deficiencies, dam rehabilitation, sediment management, change in use, and dam decommissioning.

Public safety around dams is an important component of dam safety management. Beyond the hazard associated with the potential uncontrolled release of the reservoir, dams, their reservoirs and their associated hydraulic structures can incorporate a wide variety of other hazards that can affect public safety. Some controls considered necessary for the mitigation of public safety hazards may place constraints on dam operation which, in turn, may influence dam safety.

Dams typically have life expectancies that span several generations. It is almost inconceivable therefore that the environment within which a dam is situated, its use and societal priorities will remain unchanged over the life of a dam. Irrespective of normal wear and tear processes, Owners must be cognisant of such changes over time and how these may influence the safety of their dams. Even where little change has occurred over time that may influence dam safety, different operational requirements, technology advances and changes in performance expectations may necessitate the completion of significant modifications or upgrade works to a dam and/or its appurtenant structures.

As many aspects of life cycle management need to involve interaction with the public and interested parties, it is important for Owners to consider how stakeholder engagement and participation can be incorporated within their projects. Ultimately the management of dam safety deficiencies, modified operating procedures and potential decommissioning projects will involve the consideration of short and long-term risks and, as such, there will be a range of stakeholders who will be interested in both the manner in which risks are considered and the ensuing decision.

Owners may need to consider the necessity for rehabilitation works to ensure or restore appropriate levels of dam safety where:

- The Potential Impact Classification (PIC) of a dam has changed as a result of downstream development.
- The understanding of issues such as flood and seismic hazards, and dam performance change with time.
- Materials have deteriorated over time (e.g. contamination of filter and drainage systems in an embankment dam or alkali-aggregate reaction damage in a concrete dam).
- The dam's use changes.
- The public's dam safety expectations change.

In addition, if the costs of rehabilitation works are high or if a dam reaches the end of its economic life, Owners and Regulators will need to consider whether the dam should be decommissioned and removed, or modified for an alternative use or mode of operation.

1.2 Scope of module

There are many changes that can occur over a dam's lifespan that may require dam safety management. It is not the intent of this module to exhaustively explore the dam safety implications of all potential lifetime changes and how they might be addressed. Rather, a number of selected cases are illustrated to highlight some of the issues that Owners should be aware of and the processes that might be adopted for their management.

This module addresses the management of issues associated with identified deficiencies, rehabilitation, sediment management, decommissioning, change of use, and public safety around dams. The module addresses:

The management of public safety around dams including;

- Lifetime changes that may necessitate dam safety management.
- The management of dam safety issues.
- The investigation, assessment and treatment of identified dam safety deficiencies.
- Rehabilitation of dams.
- Sediment accumulation in reservoirs and its effects on dam safety.
- Changes in use, where the function of a dam is required to be different from its original function.
- Decommissioning of a dam and decommissioning procedures.

A list of reference documents is included at the end of the module to provide further assistance to Owners and their Technical Advisers.

2. Public safety around dams

2.1 Introduction

Beyond the hazard associated with the potential uncontrolled release of the reservoir, dams, their reservoirs and their associated hydraulic structures can incorporate a wide variety of other hazards that can affect public safety. The simple existence of a water body attracts the public. The construction of a dam often facilitates easier public access through the provision of roads and access points directly to the river or water body, and the provision of improved public access is often a consent condition for the construction of a dam. In addition, the demand for public access is increasing over time as is the range and nature of water-based recreational activities.

Public safety hazards that are typically encountered at, and in the vicinity of, a dam and reservoir include:

- Hazards associated with reservoir operation – changing water levels, submerged intakes, submerged structures which may be located just beneath the reservoir surface, and floating debris.
- Hazards associated with discharges from spillway and sluice facilities, or climbing on or traversing these facilities – physical drops, high water velocities and turbulence, unsecured deck gratings over sluice gate openings, and automatic or remote operation of spillway and sluice facilities.
- Hazards associated with approaching the spillway or intake facilities from the reservoir.
- Hazards associated with intake and conveyance facilities – physical drops, high water velocities, steep and slippery canal side slopes, and high undercurrents associated with inlets to conduits, tunnels, drop inlet structures and inverted siphons.
- Hazards associated with other discharge sources including power stations and surge relief facilities, sudden increases in flow, high water velocities, turbulence and vortices, and slippery shoreline surfaces at low tailwater levels.

While not directly related to the safety of a dam, the protection of the public and operating personnel from hazards associated with the presence of a dam, an appurtenant structure and a reservoir, and the operation of a dam and its associated hydraulic structures is an important component of dam safety management. Some controls considered necessary for the mitigation of public safety hazards may place constraints on dam operation which, in turn, may influence dam safety. For example, a constraint on the rate of spillway gate opening to reduce the risk to downstream river users could reduce the Owner’s ability to safely manage a large flood event.

Owners are obligated under the Health and Safety in Employment Act to ensure that dam workplaces are safe for operational employees and persons who enter the site.

The following subsections outline a recommended approach for the management of public safety at dams. The approach includes:

- Identifying and assessing potential hazards.
- Controlling the hazards by changing operational procedures, installing physical controls, or installing warning signs and devices.
- Managing the hazards through a documented public safety plan, inspection and maintenance activities, and continual review and improvement processes.

The material largely reflects recommended practices included in the Canadian Dam Association publication “Dam Safety Guidelines” (2007) and their associated “Guidelines for Public Safety around Dams” (2011).

2.2 Hazard identification and assessment

The initial step in the development of a site-specific public safety plan is the identification and assessment of hazards.

Unlike dam safety hazards, public safety hazards associated with dam operation may have little to do with the size of the dam and/or the volume of the stored fluid. Similarly, downstream populations that may be at risk from a dam failure may have little relevance to public safety hazards associated with the operation of the dam. For example, the public safety hazard of a small Low PIC weir, which is utilised by the public for recreational activities, may be much greater than the dam safety hazard.

The identification and assessment process should include:

- Consideration of the physical extent, both upstream and downstream, to which dam operation introduces potential hazards to the public and operating personnel.
- A discussion with site operating personnel to determine areas visited by the public, determine the nature of the visits, discuss hazards, and discuss past incidents or 'near misses' which may have occurred at the site.
- A site inspection with operating personnel to identify and assess hazards, and the appropriateness of existing barriers, warning signs and warning devices.
- A review of existing operating procedures for the safe management of hazards associated with the operation of hydraulic structures (e.g. spillway gates, sluice gates, generation plant).
- Consideration of any differences in the identified hazards that may arise through automatic, remote and local operation.
- A qualitative assessment of the identified hazards and a ranking of the hazards according to their potential to result in loss of life or injury.

In addition, it may be appropriate to meet with local authorities and recreational groups to obtain an improved understanding of public access to water bodies that are affected by dam operation.

2.3 Hazard controls

A variety of measures are available for the control of hazards. In a limited number of cases it may be practicable to eliminate the hazard (e.g. a stilling basin could be designed or modified to eliminate back eddies that could trap swimmers). In some cases hazards may be able to be mitigated by the adoption of alternative operating procedures while, in other cases, hazards may be best controlled by the installation of barriers, warning signs, rescue equipment or alarms.

Operating procedures which minimise sudden rates of change in water levels and flows can be very effective in the mitigation of hazards associated with the discharge of water from spillway, sluice and generation facilities. Wherever possible, operating procedures should include requirements for:

- Visual observation prior to operation.
- Audible and/or visual alarms prior to operation.
- Incremental gate or valve openings, or machine discharges to avoid sudden large increases in water levels and flows.

In some situations it may be appropriate to include time-specific operational controls. For example, a tighter constraint on the rate of change in a discharge may be appropriate during the summer months when numerous recreational activities are present in the downstream river.

If hazards cannot be eliminated or mitigated, physical control measures such as lake booms, barriers, fences, warning signs and warning alarms should be considered. Lake booms are usually installed upstream of spillway and intake facilities, barriers and fences are usually provided to protect against vertical falls (e.g. from the crest of a concrete dam) and prevent unauthorised operation of gate facilities, and warning signs and alarms are usually installed in areas where physical barriers are impractical (e.g. downstream of spillway and sluice gate facilities).

2.4 Hazard management

Where operation poses a risk to public safety, hazard management should include the preparation of a site-specific public safety plan, periodic inspection and maintenance activities, periodic review and updating of the plan to reflect any changes in the hazards, and a system of incident reporting.

Where warranted, a site-specific public safety plan should outline:

- The objectives of the plan.
- Individual responsibilities for public safety, the development and implementation of the plan, the training of operating personnel in the requirements of the plan, and the reporting of public safety incidents.
- A summary of the identified hazards and the results of the hazard assessment.
- A description of the physical control measures installed at the site and a plan showing their locations.
- A reference to the operational procedures for spillway and sluice gate operation, surge facility operation and machine start-up.
- Procedures for the inspection of hazards and the maintenance of physical control measures.
- Procedures for the reporting and evaluation of public safety incidents, including both 'near miss' and actual events.

Records should be kept of all inspection and maintenance activities and all incident reports.

3. Lifetime changes

There are many changes that can occur over a dam's lifespan that may influence dam safety management. These may include changes and modifications initiated by the Owner, and external influences to which the Owner has no control over but needs to be aware of. Change in dam use is discussed separately in section 4.

Some potential lifetime changes that may influence dam safety management are:

- Upstream catchment changes – land use changes upstream can result in changes in flood risk, sediment and debris inflows and changes in water quality. All these can influence the ability of the dam to meet safety requirements. Additional dams built upstream may also represent a change in risk for the existing dam.
- Reservoir changes – sedimentation, land use changes along reservoir boundaries, recreation accommodation, and the potential instability of reservoir slopes due to erosion or drawdown operations all require dam safety management
- Dam use and operation – this will almost certainly change overtime in response to changes in use or demand. This could mean an existing use is discontinued and replaced by a new use, or the addition of multiple uses (e.g. recreation) over time. Constraints may also be imposed though resource consent conditions that may influence operational flexibility and how the dam can respond to extreme events.
- Progressive deterioration – despite regular prescribed maintenance, some dam components will deteriorate. This will lead to the need for periodic replacement, upgrades or rehabilitation to maintain an acceptable level of dam safety.
- Sudden deterioration – this may occur following a major event, during which the dam performed as intended but not without incurring damage that required repair (e.g. spillway channel or stilling basin erosion) or operational modifications to maintain an acceptable level of dam safety. In an extreme case decommissioning may be necessary.
- Legislative changes – these may result in changes to acceptable dam safety thresholds. As legislation can be considered to represent the expectations of society, these changes reflect the evolving acceptance of risks by communities.
- Health and safety considerations – dam safety management typically incorporates a range of physical measurements to verify performance. Where measurements rely on personnel accessing structures, future health and safety requirements may limit access and necessitate the introduction of alternative measurements or systems to verify dam performance.

- Downstream changes – the population and/or value of the environment and infrastructure, located within the potential dam-break flood inundation area, will almost certainly change with time. While this is likely to be a progressive evolution it will probably manifest itself in a series of step changes in dam safety requirements appropriate to the PIC of the dam.
- Technological advances and standards of practice – technological improvements and an improved understanding of dam performance may result in a corresponding shift in dam safety requirements, even if the dam, its use, and the environment in which it is located remain constant.
- Public safety considerations – dam operation during normal, unusual and extreme loading conditions can result in risks to public safety. Future changes in the level of risk considered to be acceptable by the public could necessitate operational changes that have a consequential effect on dam safety.

4. Identifying and managing dam safety issues

4.1 Philosophy

The identification and management of dam safety issues is an essential part of dam safety management for any dam, and should be addressed with established processes and procedures in all dam safety management systems.

Dam safety issues are defined as a broad set of issues that affect dam safety including physical infrastructure issues, dam safety deficiencies (potential or confirmed) and non-conformances (refer section 4.2 for detailed definitions). Dam safety issues should be identified through the following dam safety management activities (refer Module 5: Dam Safety Management):

- Surveillance.
- Inspections.
- Gate and valve system testing.
- Dam safety reviews.
- Failure Modes and Effects Analysis (FMEA) workshops.
- Investigations.
- Emergency Action Plan tests.
- Dam safety management system audits and reviews.

4.2 Dam safety issue categories

When managing dam safety issues it is helpful to place them in categories so that:

- Clarity of the different issues and their relative importance can be achieved.
- The significance of issues can be better understood.
- An appropriate response to the issues can be identified.

These Guidelines recommend the following dam safety categories, as shown in Figure 4.1 and described in sections 4.2.1, 4.2.2 and 4.2.3.

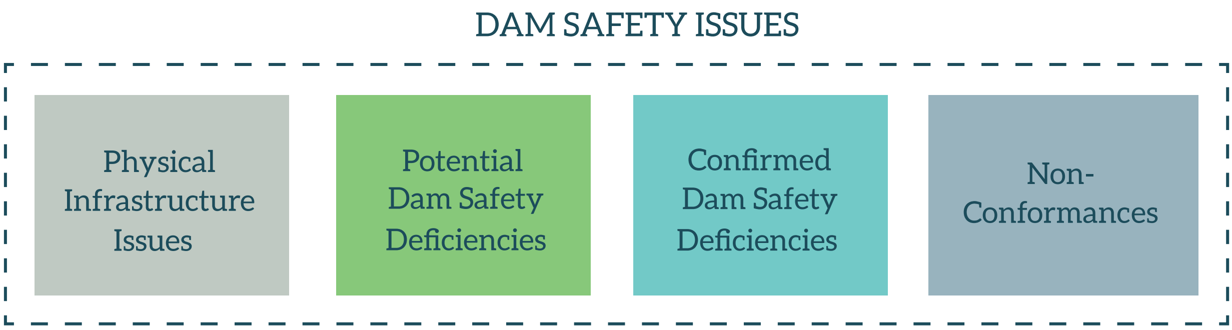

Figure 4.1: Dam Safety Issue Categories

4.2.1 Physical infrastructure issues

Physical infrastructure issues are where equipment, access, instrumentation, communications or maintenance is insufficient to verify satisfactory dam performance. The following examples are provided:

- Inadequate or unsafe access preventing surveillance and monitoring observations at the dam site.
- Vegetation on a dam embankment or abutments preventing visual observation.
- Dam performance monitoring instrumentation is inadequate, out of calibration or requires maintenance.
- Instrument telemetry links are not functional.
- Surface or internal relief drain maintenance is required.
- Wave or surface runoff erosion requires repair.
- Concrete requires surficial repair.
- Spillway walls or chute joints or waterstops require maintenance.
- Operating procedures or instructions are not provided at the local gate control facility.
- Gate and valve equipment maintenance is required (e.g. paintwork, grease winch ropes).

Physical infrastructure issues are usually considered as part of normal asset management and thus may be suitable for prioritising and planning responses based on their anticipated impact on normal business operations. However, in some cases this approach may be inappropriate as certain physical infrastructure issues must be responded to immediately and there may not be a clear distinction between some physical infrastructure issues and dam safety deficiencies.

4.2.2 Potential or confirmed dam safety deficiencies

Dam safety deficiencies include potential dam safety deficiencies, where particular performance requirements may not be met (unknowns exist and further investigation and/or assessment is required), and confirmed dam safety deficiencies where adverse performance has already been observed, or will definitely come to pass under realistically expected loading conditions. They are usually where a fundamental flaw (design, construction or previously unrecognised condition) or vulnerability exists that may develop, under certain circumstances or loading conditions, into an identifiable (and credible) potential failure mode. The following examples are provided:

- Embankment dam material compatibility and filter criteria are not met.
- Foundation or abutment defects were not treated during dam construction.
- The capacity of the spillway is less than the recommended performance criterion.
- The dam does not meet structural performance criteria.
- High foundation uplift pressures beneath a concrete dam, or high internal piezometric pressures in an embankment dam or its abutment.
- Internal erosion has initiated or is in progress.
- The gate or valve system does not meet functional performance requirements.
- The gate or valve systems are inappropriately operated.
- The gate or valve system operators are not adequately qualified and trained.
- Reservoir shoreline instability exists and could initiate dam overtopping.

Dam safety deficiencies can be very complex and take time to investigate, assess and resolve effectively and safely. Through appropriate investigation and/or assessment, potential dam safety deficiencies may be resolved as either not a dam safety deficiency or a confirmed dam safety deficiency. This process should be completed in conjunction with appropriately experienced Technical Advisers and thoroughly documented. Dam safety deficiency and risk management is discussed in detail in section 4.4. Risk-informed decision making, discussed in section 4.5, is a valuable tool that can assist in the prioritisation and management of dam safety deficiencies.

4.2.3 Non-conformances

Non-conformances are where dam safety management system processes and procedures have not been followed, or established dam safety practices have not been implemented. The following are example non-conformances:

- The dam safety management system does not exist or is inadequate.
- The dam safety management system is not adequately documented.
- The dam safety management system processes, procedures or plans are not followed.
- Appropriate dam safety governance, oversight and enabling arrangements do not exist.
- Dam safety management system roles and responsibilities are not adequately defined and understood.
- The dam safety management system is not implemented by appropriately experienced and qualified personnel.
- The surveillance inspectors are not adequately qualified and trained.
- Dam safety issues are not escalated, recorded and tracked appropriately.
- Dam safety issues are not resolved in a timeframe appropriate to the level of risk.
- Dam safety management system record-keeping or information management is inadequate (e.g. design, construction, operation, maintenance, surveillance or testing records are limited or unavailable).
- An Emergency Action Plan does not exist, is inadequate, or is not tested.
- Dam safety regulatory requirements are not met.

Non-conformances are dealt with by taking appropriate corrective actions to achieve conformance with the Owner's procedures and processes, the regulations and established dam safety practice.

4.3 Dam safety issue recording, prioritising and tracking

An Owner should have a systematic and auditable approach to recording, updating and tracking their dam safety issues. The following should be clearly identified for each issue and available for update and review:

- The nature of the issue.
- When the issue was identified.
- Supporting references and information.
- The verified category of the issue (physical infrastructure issue, potential dam safety deficiency, confirmed dam safety deficiency, or non-conformance).
- Who is responsible for addressing the issue.
- The priority of the issue (updated as the understanding of the issue has developed).
- The planned investigation, assessment and resolution process.
- Progress and decisions in the investigation, assessment and resolution process.
- Overall tracking and reporting on the status of the issue.

The importance of the above, as an effective recording and tracking tool and as evidence of prudent dam safety issue management, cannot be overstated.

4.4 Dam safety deficiency and risk management

4.4.1 Philosophy

It is important to recognise that dam safety deficiencies, potential or confirmed, can arise from internal influences, such as physical changes or processes that can affect dam safety, or external influences such as changes in land use and consent requirements that can affect dam safety. A dam safety deficiency can therefore be associated with:

- Inadequate design and construction, where the performance of the dam is inconsistent with the design assumptions. Such deficiencies may be identified within one to two years of commissioning, but this is not always the case as some deficiencies may take many tens of years to materialise.
- Deterioration in the performance of a dam, or appurtenant structure, which cannot be addressed through normal maintenance. Deterioration is typically associated with gradual changes that occur over time, but can include sudden changes that result from equipment failures, major floods or large earthquake events.
- The development of engineering practice and design criteria. This might include advances in techniques for assessing natural hazards and advances in the understanding of phenomena relating to dams, such as internal erosion processes.
- A change in the physical and social environment in which the dam operates. Environmental changes can include development in downstream flood plains, increases in downstream populations, and operational constraints imposed though the renewal of resource consents.

Guidance for the investigation, assessment and resolution of dam safety deficiencies, including the use of risk informed decision making, is provided in the following sections. Where a confirmed deficiency indicates an elevated likelihood of dam failure, interim risk reduction measures (such as reservoir level restrictions) and Emergency Action Plans (EAPs) may need to be initiated. Interim risk reduction is discussed later in this module. Guidance for the preparation and maintenance of EAP's is included in Module 6 (Emergency Preparedness).

4.4.2 Dam safety deficiency management process

A dam safety deficiency essentially represents a dam safety risk to the Owner, the public, downstream property or the environment, where the risk is the product of the likelihood of an adverse event (that results from the dam safety deficiency) and the consequences of that event. These Guidelines recommend that Owners manage their dam safety deficiencies using a risk management process that includes the steps shown in Figure 4.2.

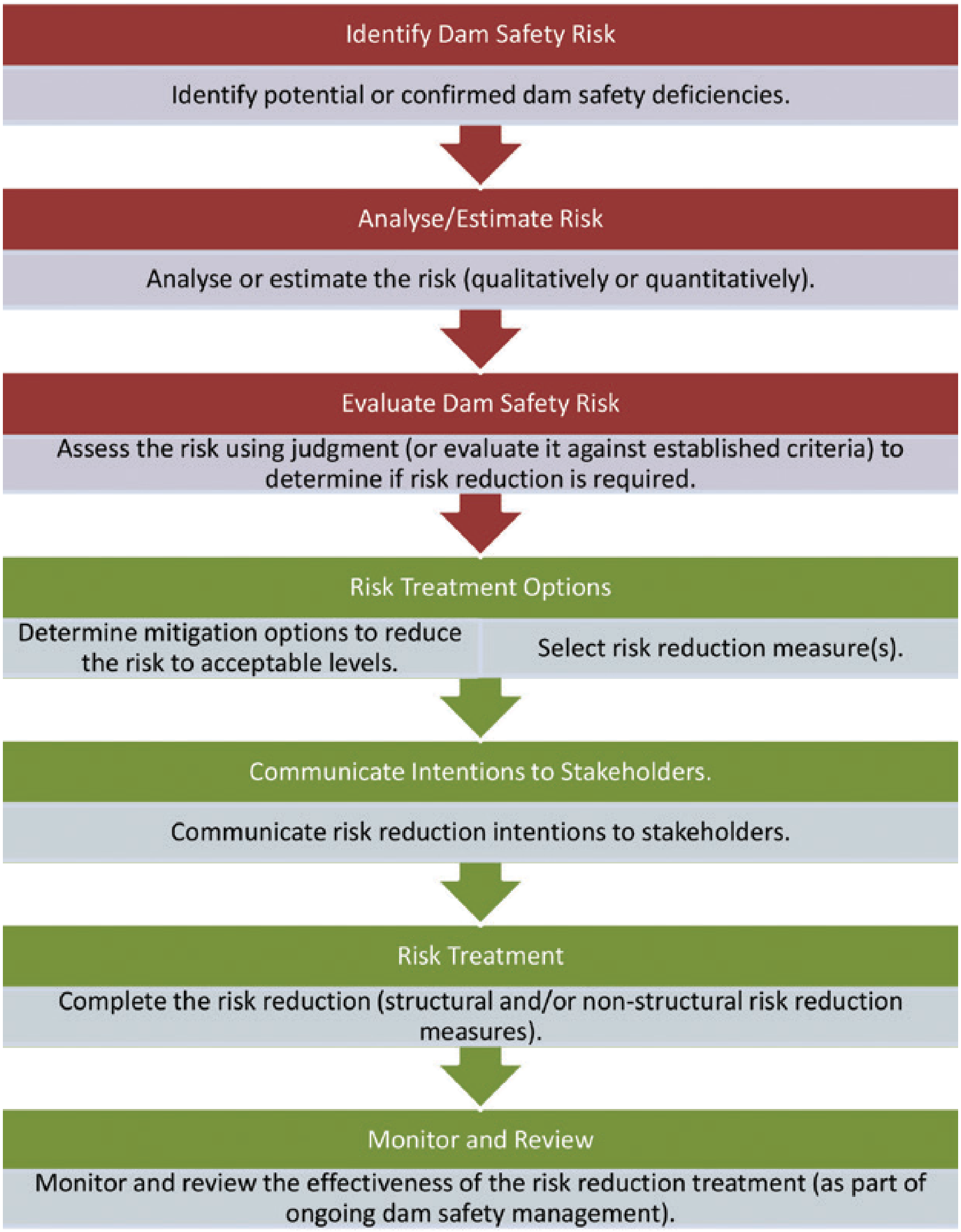

Figure 4.2: Dam Safety Risk Management Process

4.4.3 Procedures for investigation, assessment and resolution of dam safety deficiencies

Owners should have clear and defined procedures (in their dam safety management system) for the investigation, assessment and resolution of dam safety deficiencies, and all Owners should be able to demonstrate that their dam safety deficiencies, whether they are potential or confirmed, are being addressed in a prudent manner. Where an Owner has a number of dams, deficiency management may be undertaken on a portfolio-wide basis to maximise risk reduction achieved as deficiencies are addressed.

Deficiency management procedures should be designed to ensure an effective and efficient deficiency/risk evaluation process. The procedures should address the selection of a team to investigate and assess the deficiency, the determination of appropriate dam safety acceptance criteria and risk levels, the completion of appropriate independent reviews, the decision-making processes and the provision of feedback to key stakeholders. It is also important that the procedures are sufficiently flexible to allow deficiencies to be managed in a manner and within a timeframe appropriate to the level of the risk, and redefinition of the scope of the deficiency assessment in response to the receipt of new information.

The procedures for deficiency management should include:

- An initial assessment of an identified potential deficiency to confirm whether a deficiency exists and whether risk reduction measures are necessary. If the initial assessment of the suspected deficiency indicates that a deficiency does not exist then establish parameters for continued monitoring and review of the issue.
- Where necessary, the identification and assessment of remedial options.
- The design and implementation of the preferred remedial option.
- Continued monitoring and review of the remedial treatment through the dam safety management system.

Usually, the Owner will require specialist advice and/or expert review throughout this process. However, the level to which this is required will depend on the nature of the dam safety deficiency, including its complexities and the consequences of failure.

4.5 Risk-informed decision making

For some dam safety deficiencies, 'standards-based' acceptance criteria may be available from design manuals, guidelines, standards or regulations and, if the safety requirements expressed as design requirements are not met, structural or non-structural improvements must be implemented for the dam to be in compliance with the design requirements recognised by industry or required by regulation. In such an assessment the gap between actual performance and the design requirement determines whether improvements are required to address a deficiency. Module 3 (Investigation, Design and Analysis) provides advice on elements of dam design that can be assessed using a 'standards-based' approach.

However, some potential dam safety deficiencies cannot be assessed by comparing actual performance against design requirements for a number of reasons:

- Design requirements do not exist for the failure mode identified.
- Formal computation may not adequately represent the failure mode.
- Uncertainties in the parameters are significant.
- The existence of the deficiency may be difficult to establish or relies on expert judgement rather than measured data.

An Owner may find it useful to develop a risk-informed decision making framework that allows the organisation to manage its dam safety deficiencies. 'Risk-informed' implies using risk assessments as an input to decision making. Risk-informed decision making can account for a wider range of parameters and utilise risk assessment in its broadest sense as an input to determine the benefits from risk reduction. Expressing deficiencies in risk terms allows the comparison of risks posed by deficiencies at one dam or the comparison of risks across a portfolio of dams. Therein a reasoned approach to prioritising deficiencies can be developed and the basis for risk reduction communicated to stakeholders.

However, dam safety risks do not often align with normal business risk management models because of the very low probability of the consequences, which are extreme compared to normal business risks and, in the case of potential loss of life, it is considered morally unacceptable to assign a monetary value to the loss of a life. Furthermore a dam failure resulting in the loss of a life could have criminal consequences for the Owner that cannot be captured in a business risk model. While these differences need to recognised by Owners, a risk-informed dam safety framework will allow Owners to understand the nature and levels of risks, prioritise risks, target resources effectively, and demonstrate a prudent approach to reducing risks associated with their dams.

Risk-informed decision making is an additional tool for the management of dam safety deficiencies. It is not, however, a means for Owners to avoid mitigation measures that should be completed at their dams. Risk concepts are outlined in the following subsections.

4.5.1 Risk definitions

Definitions of risk terminology are contained in New Zealand Standards (2009) and ICOLD Bulletin 130. They are included in the Glossary in the Parent Document and are repeated here for convenience:

- Risk – a measure of probability and severity of an adverse effect to life, health, property or the environment. In the general case, risk is estimated by the combined impact of all triplets of scenario, probability of occurrence and the associated consequence. In the special case, average risk is estimated by the mathematical expectation of the consequences of an adverse event occurring (that is, the product of the probability of occurrence and the consequence, combined over all scenarios).
- Risk requires an understanding of:
  - the probability of the scenario (e.g. the failure mode)
  - the probability of an adverse response to the scenario (e.g. the probability of an uncontrolled release of water due to the scenario occurring)
  - the consequences given that the adverse event occurs.
- Probability – a measure of the degree of confidence in a prediction, as dictated by the evidence, concerning the nature of an uncertain quantity or the occurrence of an uncertain future event. It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event. This measure has a value between zero (impossibility) and 1.0 (certainty).
- Consequence – the outcome or impact of an event.
- Uncertainty – result of imperfect knowledge concerning the present or future state of a system, event, situation or population under consideration. The level of uncertainty governs the confidence in predictions, inferences or conclusions. In the context of dam safety, uncertainty can be attributed to (i) inherent variability in natural properties and events, and (ii) incomplete knowledge of parameters and the relationships between input and output values.
- Because of the unique nature of every dam, its setting and the hazards faced, uncertainty exists in most dam safety assessments. Uncertainty is present in all three of the above risk parameters.
- Risk Analysis – the use of available information to estimate the risk to individuals or populations, property or the environment from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification, and risk estimation.
- Risk Assessment – the process of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases.
- Risk Criteria – the terms of reference against which the significance of a risk is assessed.
- Risk Reduction – actions taken to lessen the likelihood of an occurrence or its adverse consequences, or both.
- Residual Risk – the remaining level of risk at any time before, during and after a programme of risk mitigation measures has been taken.

4.5.2 Dam safety risk assessment

Risk assessment methods applicable for both dam safety and more general use are addressed in a number of publications and standards listed in the references at the end of this module. These include New Zealand Standard (2009), ICOLD Bulletin 130, ICOLD Bulletin 154, ANCOLD (2003) and Gillon (2006).

The commonly accepted risk assessment process (Figure 4.2) has three main steps:

- Risk Identification
- identify hazards
- determine failure scenarios.
- Risk Analysis
  - identify existing controls
  - determine consequences
  - determine likelihood
  - determine level of risk.
- Risk Evaluation
  - compare against criteria or other issues
  - set priorities.

Risk Uncertainty

Uncertainty is an important factor to recognise in risk assessment. Uncertainty may be present in:

- Risk estimates for which we know or can assume a range of outcomes and their likelihoods, but we don't know the specific value within the range.
- Risk estimates where there is variability in the nature and extent of exposure or in susceptibility.
- Risk estimates where we either don't know all the possible outcomes, or their likelihoods, or both.
- Risk estimates where 'we don't know what we don't know'.

Risk Analysis Methods

Risk analysis can be qualitative, semi-quantitative or quantitative depending on the information and level of detail available.

Qualitative analysis uses descriptions rather than numerical means to define a level of risk. The consideration of probability and consequences results in a word description of the risk. This can be displayed on a colour grid (Figure 4.3) with axes of likelihood (from improbable to almost certain) and consequence (from minor to severe or catastrophic).

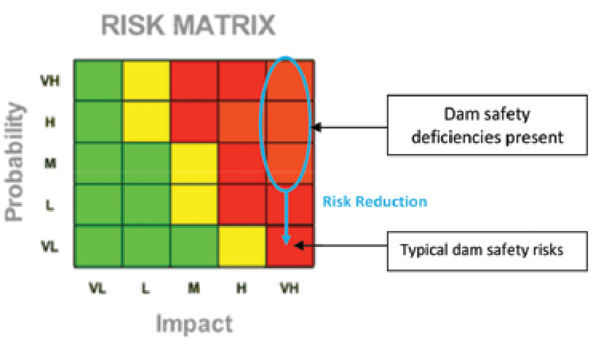

Figure 4.3: Displaying Qualitative Risk Results

Semi-quantitative and quantitative methods use numerical data. The data might be from databases or expert judgement. Fully quantitative analyses should use recognised methods such as event trees and fault trees to systematically and consistently formulate all possible failure scenarios.

Dam Safety Risk Presentation
Many corporate business risk models will use similar displays but scaled for normal business risks. Impacts or (consequences) are commonly expressed in dollars. Often the business risk heat maps (e.g. Figure 4.3) describe an extremely low probability/high consequence event to be a more moderate risk compared to a higher probability event. However, dam failure (or even major incidents) can financially cripple a dam Owner or result in regulatory penalties that prevent the Owner from continuing to operate. Furthermore, it is considered morally unacceptable to place a financial value on life safety risks to enable a comparison with other business risks. Hence, as previously stated, dam safety risks do not always fit well in a common business risk presentation framework.

Quantitative risk results can be displayed for life safety on an F-N type plot (Figure 4.4). The vertical axis F is the cumulative probability of experiencing N or more fatalities from the failure event. Societal risk data and criteria are more commonly expressed in terms of cumulative probability. The probability is expressed in likelihood of occurrence per year.

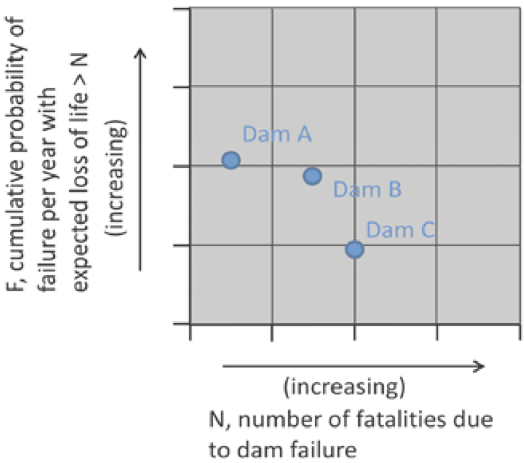

Figure 4.4: Example F-N Plot showing Cumulative Probability of N or More Fatalities

4.5.3 Risk acceptance criteria

Understanding the level of dam safety risk in the context of the need for risk reduction, or conversely in terms of general tolerable risk, may be useful to an Owner in choosing an appropriate response to an identified dam safety deficiency (e.g. continued monitoring or mitigation).

Where a risk assessment process is being used only to prioritise risk reduction across a number of dams, risk acceptance criteria may not be necessary. However, where a risk assessment process has been used to evaluate a specific dam safety deficiency, there is likely to be a desire to decide if the risk posed does or does not require some form of action to reduce the risk. Zero risk decisions may not be practicable or affordable so typically a trade-off between the costs of various alternatives for reducing the risk and the benefits from risk reduction needs to be made.

Tolerable and Acceptable Risk
There is no defined or regulated level of tolerable or acceptable risk for dam management in New Zealand. Further, it is recognised that a risk estimate made as part of the risk assessment process is based on engineering judgements and, as such, is not an ‘absolute’ value but rather a relative value. Thus, in choosing a course of action on a dam safety deficiency that has been identified and assessed, the Owner needs to determine and provide decision rationale to stakeholders as to whether:

- Spending on a risk reduction alternative (enhanced monitoring or mitigation) is reasonable.
- Spending on risk reduction is disproportionate to the benefits of managing the risk.
- The risk can be considered insignificant.

Evaluation of a dam safety risk will likely result in it being assigned into one of the following risk categories:

- Broadly acceptable, indicating that no risk reduction measures are needed.
- Tolerable, only if risk reduction is impractical or if its cost is grossly disproportionate to the improvements gained.
- Unacceptable, indicating that the risk cannot be justified except in extraordinary circumstances. Risk reduction measures should be implemented regardless of cost.

Two fundamental tenets that drive acceptance of risk are described in ICOLD Bulletin 130:

- Equity: The right of individuals and society to be protected, and the right that the interests of all are treated fairly. In the case of dams this is especially true with respect to those individuals not receiving the benefit from the presence of the dam.
- Efficiency: The need for society to distribute and use available resources so as to achieve the greatest benefit.

These tenets are often competing but demonstrate that in matters of life safety, the public have a say in risk-based decision making that affects their safety. Owners should note that affordability in implementing risk reduction measures is unlikely to be considered as a factor when the risks are deemed unacceptable.

The level of acceptable risk in each country, and within a country, will differ depending on societal values, cultural and environmental values, political interests and legal systems.

Some international risk guidelines provide tolerable limits based on a probability of failure that they deem acceptable to society. Note that these differ between countries and organisations that use tolerable limits. Other Guidelines choose not to publish tolerable limits on the basis that insufficient social research has been completed to substantiate the setting of limits. Further, as noted above, the estimation of the risk is subjective and thus not wholly amenable to comparison to a strict measure. The sometimes quite large uncertainties in the various factors considered in a risk analysis (both in determining the likelihood and the consequence) really demonstrate that assessing risk against a single target value has the potential to be quite misleading. Accordingly, these Guidelines do not recommend using a prescribed societal tolerable risk limit to dictate risk-based decision making until social research provides guidance on public limits of tolerability in New Zealand.

As Low As Reasonably Practicable (ALARP) Principle

These Guidelines recommend application of the principle 'As Low As Reasonably Practicable' (ALARP) when considering measures to manage dams in the 'tolerable if' range (refer Figure 4.5). The adoption of this approach negates the need for discussion on absolute tolerable societal risk limits.

ALARP is a principle established in Common Law that risks should be reduced to the point where the cost of reducing the risk is grossly disproportionate to the improvements gained. Both the level of individual risks and societal concerns caused by the presence of the dam should be taken into account when deciding if risks are acceptable, tolerable or unacceptable. The extent of the ALARP demonstration should be proportional to the risk being considered. Higher risks will require more rigorous and extensive demonstration than lower risks. The extent of analysis and its rigour should be increased when the consequences are higher, both in terms of life safety and business interruption or loss of amenity impacts.

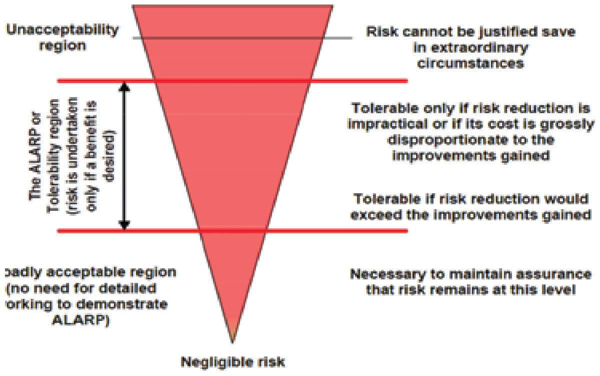

Figure 4.5: Acceptable and Tolerable Risk Framework (ICOLD Bulletin 154)

Application of ALARP can be demonstrated by risk reduction in terms of lower probability of occurrence or a reduction in the number of lives that could be lost (Figure 4.6). Some Guidelines (ANCOLD 2003 and Canadian Dam Association 2007) display tolerable risk limit lines on their F-N plots. Figure 4.6 demonstrates the effects of risk reduction on life safety; the effects of risk reduction on economic or environmental values can be evaluated in a similar manner.

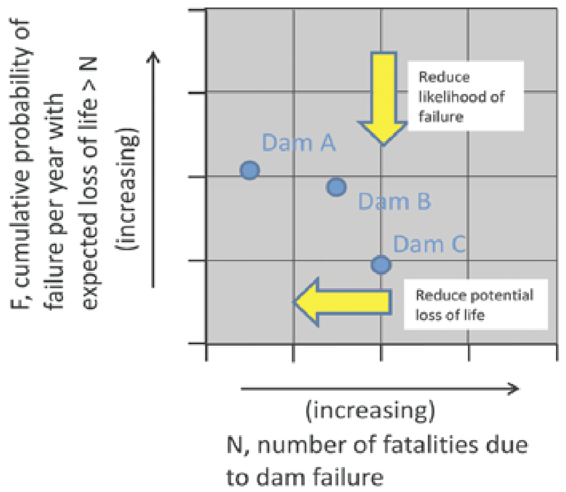

Figure 4.6: Risk Reduction Measures on Example F-N Plot

4.5.4 Time frame for risk mitigation

Timeframes for addressing dam safety deficiencies, following their identification are typically not prescribed in standards or regulations. The unique nature of each situation requires evaluation; nevertheless, the dam Owner has a duty of care to act in a timely manner if downstream consequences and in particular public safety risks are increased. A timely response to a dam safety deficiency may also minimise any adverse effects on a dam Owner's business that result from a reduction in asset availability.

An appropriate timeframe for action to be taken on an identified and confirmed dam safety deficiency on a specific dam could be immediate or could range from months to years, depending on the nature and significance of the deficiency. Both components of the risk equation (likelihood and consequences) need to be assessed. Consequences can include life safety, third party damages, loss of service provided by the dam, or financial losses to the Owner.

When dealing with a portfolio of dams, where an Owner has conducted a dam safety evaluation across the entire portfolio, it is recognised and generally accepted that it is not possible for an Owner to address all identified dam safety deficiencies at one time.

The Owner should follow a two-step process to demonstrate defensible diligence in dam safety risk management:

- Implement an interim risk management plan that will effectively provide protection through elevated management actions (e.g. reservoir restrictions, intensive monitoring, warning systems, etc). This includes taking immediate action on any dams where the identified dam safety risk is recognised as imminent or extremely serious.
- Once the interim risk management plan is in place, develop a deficiency investigation and risk reduction plan based on a risk-based or risk-informed prioritisation timeframe, set in the context of the wider constraints on the dam safety effort as dictated by regulation and economic pressures. The risk reduction plan (priorities and schedule) must address all of the deficiencies in a way that takes account of the various risks and constraints.

Partial risk reduction, rather than the ideal risk reduction, may be an economic and timely risk reduction approach under an ALARP management process, on the basis that significant improvement in the risk position can be achieved and this is better than no action at all.

4.5.5 Interim and non-structural risk mitigation

Where potential dam safety deficiencies relate to rare events, such as extreme earthquakes or floods, detailed and systematic studies may be required to confirm the extent of the potential deficiency and whether or not an actual deficiency exists. Such studies can take time (in some instances several years) and so a preliminary estimate of risk should be completed to determine what, if any, interim risk reduction measures are necessary. Appropriate interim risk reduction measures could include:

- Increased surveillance and monitoring.
- Changes to operational procedures (including lowering the reservoir level).
- Warning systems.
- Improved emergency planning and preparedness.
- Stockpiling materials.
- Temporary buttresses.

There may also be situations where the above non-structural risk reduction measures may achieve an acceptable longer term risk reduction and may remove the need to undertake structural works to address the dam safety deficiency. However, this will depend on the nature of the deficiency and the ability to demonstrate how the risk will be reduced. Owners should consult appropriate Technical Advisers and stakeholders in making such decisions.

5. Dam rehabilitation

5.1 Introduction

Dam rehabilitation is synonymous with remedial work considered necessary to restore a dam to an appropriate level of dam safety. It may become necessary for a wide variety of reasons that include design and/or construction deficiencies, material degradation, wear of equipment critical to dam safety (e.g. lifting gear for a spillway gate), damage from flood or earthquake events, damage from vandalism, changes in operating conditions, changes in flood and earthquake loadings, changes in the PIC of a dam, and legislative requirements.

The following subsections discuss the management of rehabilitation works and outline conditions that can necessitate the completion of rehabilitation works at concrete dams, embankment dams and appurtenant structures. ICOLD Bulletin 119 outlines possible remedial measures to address identified dam safety deficiencies and includes many examples of rehabilitation works that have been completed.

5.2 Rehabilitation considerations

5.2.1 Dam safety

Dam safety considerations which must be addressed during the completion of any dam rehabilitation project include:

- The safety of the dam in its existing condition.
- The safety of the dam during the completion of the rehabilitation works.
- The safe passage of flood events during the completion of the rehabilitation works.

The urgency with which rehabilitation works should be completed should reflect the nature of the identified dam safety deficiency and the level of risk it presents. For example, for a Medium PIC embankment dam, an inability to safely pass a 1 in 100AEP flood event should be urgently addressed but an inability to safely withstand the effects of a 1 in 2,500AEP earthquake event could be addressed over a longer timeframe.

In many cases the safety of a dam prior to the completion of rehabilitation works can be increased by enhanced surveillance and monitoring of the identified deficiency or by lowering the reservoir to reduce the loads on the dam. Increased warning systems for downstream areas at risk may also be suitable as an interim measure. In some cases the best solution may be to stage the rehabilitation project so that the risk is reduced progressively through the completion of initial temporary works, that are quickly undertaken to address a particular deficiency, and the completion of the full permanent solution at a later date.

The safety of a dam should not be adversely affected during the completion of a rehabilitation project. The Designer and Owner must be satisfied that the proposed methodology for the construction of the rehabilitation project does not result in unacceptable dam safety margins and that appropriate management systems are in place for monitoring the performance of the dam throughout the construction process.

The safe passage of flood events during the construction of rehabilitation works requires careful consideration. For example, a requirement to rehabilitate a spillway gate or a spillway facility must be carefully planned to minimise the potential for incoming flood events to exceed the available spillway capacity. Planning must consider operational constraints, the flood event to adopt for the design of the rehabilitation works, and how the flood event will be safely managed during the construction of the rehabilitation works. It may be necessary to complete the rehabilitation works at a time of the year when high flood events are less likely to occur, to lower the reservoir to provide flood storage, and/or to complete the rehabilitation works in a way which minimises the reduction in spillway capacity during the construction of the rehabilitation works.

A dam may fulfil an important public safety function, such as bulk water supply or flood management, and the rehabilitation project will need to consider how the function can be practically managed through construction. Such matters can often influence or even dominate the final design solution. In some cases it may be necessary to adopt a more expensive solution, such as a complete replacement structure, to effectively manage the risks during the implementation of the rehabilitation works.

5.2.2 Design, construction, commissioning and handover

The completion of dam rehabilitation projects, particularly significant projects, requires processes not dissimilar to those for new dams. In fact, in many cases rehabilitation projects are more complex as the existing and potential flood loadings on the dam, and the operations associated with the dam and reservoir, need to be managed throughout the rehabilitation work.

The design, construction, commissioning and handover of any dam rehabilitation works should be completed in accordance with the procedures outlined in Modules 3 and 4; however, special attention should be paid to the following:

- The rehabilitation principle of 'do no harm' should be present throughout the risk reduction process including the selection of the preferred rehabilitation solution, and the design and construction of the preferred solution. A significant number of well-intended dam rehabilitation projects have resulted in dam failures or serious dam incidents. Paradoxically, a number of these projects were rehabilitation projects directed toward addressing very unlikely events.
- The original design and construction records that relate to the proposed rehabilitation works. The records should be carefully reviewed to obtain a clear understanding of the original design assumptions and the structural integrity of the existing works. Where these are unavailable or are considered to be unreliable, extensive testing may be required in order to establish existing details.
- The methodology for constructing the rehabilitation works and its effects on the safety of the dam. Construction methods can have significant effects on dam safety. For example, the removal of a portion of the downstream shoulder of an embankment dam to install filter and drainage facilities could result in a significant short-term reduction in embankment stability.
- The consequences of the rehabilitation works on the overall safety of the dam. For example, a raising of the dam crest to obtain additional freeboard could lead to an increase in hydraulic load and a reduction in dam stability.
- The need for re-analysis of the complete structure. If the rehabilitation works incorporate substantial modifications, or if the design assumptions are significantly different from the original design assumptions, the complete structure should be reanalysed.
- The revision of operating procedures and dam safety management systems, and the training of personnel with operation and dam safety management responsibilities. Rehabilitated dams and appurtenant structures may have different operational requirements, particularly during extreme events, than the original structures. In addition, different surveillance and monitoring procedures may be necessary for monitoring the performance of rehabilitated structures.
- The need for instrumentation to monitor the performance of the completed rehabilitation works. Rehabilitation works often provide good opportunities to upgrade existing instrumentation or install new instrumentation for the monitoring of dam performance.

Many of the items listed above can benefit from the use of risk assessment techniques as discussed above and in Modules 3 and 5. The dam Owner and their Technical Advisers should complete an assessment covering the above matters to demonstrate adequate consideration of the risks relating to the rehabilitation itself, as well as the original dam safety deficiency. This should include aspects covering safety in design.

5.3 Rehabilitation work on concrete dams

Conditions that can necessitate the completion of rehabilitation works on concrete dams include ageing processes associated with the foundation and the body of the dam, the adoption of different design criteria arising from a change in the PIC of the dam, an improved understanding of flood or earthquake hazards, and damage incurred during extreme flood or earthquake events.

Such conditions can include:

- A loss of foundation strength or stability, resulting from reservoir saturation and the change to the foundation's hydraulic regime, changes in the groundwater regime adjacent to the foundation, or chemical and physical alteration of the foundation rock.
- Foundation erosion, resulting from the erosion of rock joint materials by high hydraulic gradients and solution processes where dams are founded on soluble rocks (e.g. limestone).
- Degradation of grout curtains, resulting from inadequate design or construction, deformation during or following lake filling, or erosion of the foundation leading to increased hydraulic gradients.
- Degradation of drainage facilities, resulting from inadequate design or construction, or insufficient or inappropriate maintenance.
- Degradation of concrete, resulting from alkali-aggregate reaction and the action of sulphates on concrete and mortar.
- Cracking of concrete, resulting from shrinkage and creep.
- Cracking of concrete, resulting from an inability of the structure to withstand actual loadings.
- Degradation of dam faces, resulting from chemical reactions between the concrete and the reservoir, and from freeze and thaw effects.
- Deterioration of structural joints, resulting from inadequate design and construction, deformation or waterstop damage.
- Loss of post-tensioned force in cable anchors, resulting from corrosion.
- Insufficient flood passage capacity.
- Inadequate structural stability under normal, flood or earthquake load conditions.

5.3.1 Rehabilitation measures

Inadequate performance or factors of safety under all loading conditions, or the adoption of different design criteria, can necessitate the completion of rehabilitation works to improve dam performance or stability. Dam performance and stability can be improved by:

- Increasing the vertical force by enlarging the profile of the dam, adding ballast, or installing post-tensioned cable anchors.
- Increasing the resisting horizontal force by the construction of a downstream buttress.
- Draining the dam and its foundation to reduce uplift.
- Grouting or the construction of shear keys to provide additional friction along sliding surfaces.
- Installing an upstream waterproof membrane to reduce dam leakage.
- Installing an upstream staunching blanket to reduce foundation seepage.
- Installing a crest wall and/or raising the spillway chute walls and/or providing additional spill measures to increase flood capacity.
- Toe protection works to prevent erosion of the foundation.

5.4 Rehabilitation work on embankment dams

As for concrete dams, conditions that can necessitate the completion of rehabilitation works on embankment dams include ageing processes associated with the foundation and the body of the dam, the adoption of different design criteria arising from a change in the PIC of the dam, an improved understanding of flood or earthquake hazards, and damage incurred during extreme flood or earthquake events.

Such conditions can include:

- Observation of material transport through the dam, along conduits, or through the foundation related to backward erosion piping or seepage erosion.
- The potential for backward erosion piping or seepage erosion.
- Observation of slumps, depressions or deformation of the dam or the abutments.
- Identification of potentially liquefiable materials in the dam or its foundation.
- Identification of a low permeability core (or similar element) not constructed high enough to assure dam safety during normal or flood operating conditions.
- The lack of filter protection for the full height of the core, where a filter is necessary for the prevention of internal erosion or piping.
- An improved understanding of material performance under normal, flood or earthquake loading conditions (e.g. erodibility, permeability, liquefaction).
- Insufficient flood passage capacity.
- Inadequate structural stability under normal, flood or earthquake load conditions.

5.4.1 Erosion effects

Erosion effects can include internal erosion of the embankment, its abutments or its foundation initiated by inadequate material compatibility and seepage control, and external erosion initiated by wave attack on the upstream face or overtopping of the embankment. While external erosion of the upstream face can threaten the safety of an embankment dam, it can be readily identified through visual surveillance and if it is repaired within an appropriate time frame it should not become a dam safety deficiency. In contrast, internal erosion may not be observed for a long time and, if it is not addressed promptly, it can quickly become a significant dam safety deficiency. Internal erosion or an unacceptable risk of internal erosion can occur in the embankment, in the foundation, of from the embankment into the foundation, and can be initiated by:

- A lack of filter and drainage protection or inadequate filter and drainage protection for seepage control.
- Internal instability of broadly graded embankment materials (e.g. a glacial till).
- Hydraulic fractures in areas of low stress (e.g. through core trenches and adjacent to conduits).
- The presence of preferential seepage paths along conduits or in the foundation, or the development of preferential seepage paths over time due to backward erosion piping in the dam or through infilled joints in the foundation.
- Dispersive clays.

5.4.2 Deformation Effects

Deformation effects that can seriously threaten dam safety include differential settlements, slope instability initiated by inadequate shear strengths and liquefaction of the embankment or its foundation during a large earthquake. Differential settlements can encourage the development of hydraulic fracturing, cracking, and low confinement pressures at interfaces between embank–ment dams and hydraulic structures, with subsequent increased seepage and internal erosion. The loss of shear resistance in the embankment dam or foundation materials due to saturation, creep, or liquefaction can cause slope instability and can result in sufficient crest deformation to initiate an overtopping failure. Other deformation effects resulting from consolidation of the foundation and fill materials, or variations in the reservoir level, usually result in small reductions in freeboard and are less significant to dam safety.

5.4.3 Rehabilitation measures

Inadequate performance or factors of safety under all loading conditions, or the adoption of different design criteria, can necessitate the completion of rehabilitation works to improve embankment stability or performance, or increase freeboard provisions during a large flood event. Embankment dam performance can be improved by:

- • The placement of toe buttresses and/or the provision of additional drainage facilities to reduce piezometric pressures in the downstream shoulder.
- • The installation of filter and drainage zones, that meet modern criteria, to provide protection against internal erosion and piping. This might involve temporarily removing the downstream shoulder, if possible, and installing replacement filter and drainage materials against the core. Additional weight may also be added to the replaced shoulder; these are sometimes termed filter-buttress upgrades. If the replacement of filter and drainage materials against the core is prohibitively expensive or impractical, then new filter and drainage materials placed downstream of the core and supported by a buttress may be a viable alternative.
- • Increasing the freeboard to safely accommodate an extreme flood event by raising the dam crest, by constructing a concrete wave wall along the dam crest, and/or by increasing the existing spillway capacity.

5.5 Rehabilitation work on appurtenant structures

Appurtenant structures are structures at the dam site, other than the dam itself, that are designed and are required for the safe containment and control of the reservoir contents and reservoir discharges. They frequently incorporate gate and/or valve systems (with their associated power supplies, and control and communication systems) that fulfil dam and reservoir safety functions. In Module 5 these are termed "gate and valve systems".

A primary driver for the rehabilitation of appurtenant structures, which include spillway and outlet facilities together with their gate and/or valve systems, is the effects of ageing and deterioration of mechanical and electrical equipment. Other primary drivers include a requirement for additional capacity (e.g. spillway capacity, generation capacity), additional diversity and redundancy in power supply and/or control systems, and damage to the civil works by appurtenant structure discharges (e.g. cavitation damage in surface spillways, abrasion damage in low level outlet structures, scour immediately downstream of discharge facilities).

The reliability of mechanical and electrical equipment and components installed in appurtenant structures that fulfil a dam and reservoir safety function is critical to dam safety. The installed equipment usually has a significant shorter life than the associated civil works and replacement is usually necessary within 30 to 40 years of installation. Shorter lifespans can result from the combined effects of corrosion, erosion, excessive vibration and poor maintenance, and communication and control systems can become outdated and unsupported within a few years. Regular inspection, maintenance and testing, as recommended in Module 5, are essential for the identification of poor performance and the programming of rehabilitation works.

5.5.1 Rehabilitation measures

Sufficient spillway capacity and reliable spillway performance are essential for the safe passage of extreme flood events. Any increase in flood estimates for the dam or the PIC of the dam since its original design and construction could necessitate the provision of additional spillway capacity, either by enhancing the performance of the existing spillway or by providing an auxiliary spillway, or a reduction in the normal operating level of the reservoir to provide additional flood storage. Higher spillway discharges and higher reservoir levels can also sometimes necessitate the completion of additional downstream works to ensure safe discharge of extreme flood events (e.g. increased wall heights to ensure the spillway chute walls are not overtopped, abrasion damage at energy dissipating structures). The scope of the downstream works should reflect the characteristics of the spillway and its operational requirements during an extreme flood event. For example, some damage to the downstream facilities may be acceptable during an extreme flood event in a small catchment, when the duration of the event is short and the resulting damage would not affect the safety of the dam. Alternatively, damage to the downstream facilities may be unacceptable during an extreme flood event in a large catchment, when the duration of the event is long and the resulting damage would affect the safety of the dam.

The rehabilitation of low level outlet facilities can frequently be very difficult. In some cases dewatering of the reservoir will be possible and the rehabilitation works will be able to be completed in dry conditions. In other cases, dewatering of the reservoir may not be possible and completion of the rehabilitation works may necessitate a programme of underwater construction to provide a means of dewatering the outlet facility. Clearly, low level outlet facilities should be regularly tested, as recommended in Module 5, to ensure they are not affected by debris blockages, component deterioration or failure, and to identify unacceptable performance.

6. Sediment management

Sediment accumulation in reservoirs is usually considered to be an environmental effect that should be addressed in the resource consent application lodged for a dam. However, sediment accumulation in reservoirs can also have dam safety implications which include the potential for:

- Overloading of concrete dams, due to the increased loading from saturated silt adjacent to the upstream face of the dam.
- Blocking of spillway or sluice gates.
- Abrasion damage in appurtenant structures.
- Depletion of live storage volumes and the consequential reduction in flood attenuation by reservoirs.
- Increased flood levels towards the upstream ends of reservoirs.

Sediment accumulation in reservoirs can also result in reduced sediment loads in river systems downstream of dams, degradation in downstream river systems, reduced groundwater levels adjacent to downstream river systems, and river channel instability.

While such factors may have been addressed during the investigation and design of a dam, they should also be assessed during the life of a dam to ensure that the effects of sediment accumulation remain within the design assumptions. Such assessments should be incorporated within dam safety management systems but, where there is the potential for significant effects on dam safety, Owners should consider the development of a separate sediment management plan.

For many dams, measures to mitigate the effects of sediment accumulation on dam safety may not be required until some decades after commissioning. However, it may take considerable time and expense to implement mitigation measures, particularly if they require variations to operational consents (e.g. reservoir lowering for sediment flushing), and in some cases it may be appropriate to develop sediment management plans well before sedimentation begins to affect dam safety. Typically, where required for dam safety, sediment management plans should include:

- Monitoring requirements to establish the characteristics of sediment accumulation in the reservoir (e.g. locations, deposition rates).
- Regular assessments of the potential effects of sediment accumulation on dam safety.
- • Mitigation measures to ensure sediment accumulation does not adversely affect dam safety.
- • Appropriate timelines for obtaining any necessary variations to operational consents and implementing the mitigation measures.

ICOLD Bulletin 115 provides guidelines and a number of case studies for sediment management.

7. Change in use

A change in use is where the function of a dam is different from its original function. For example, a dam constructed primarily for hydropower generation or primarily for water supply could, if it was no longer required for its original function, be modified for use as a recreational asset. Such a change in use would likely result in a change in reservoir operation.

Many dams offer a level of flood control, and infrastructure and communities may have developed downstream of a dam partially in response to the level of flood protection provided by the dam. In such a case, maintaining and changing the use of the dam would be unlikely to change the level of flood protection provided by the dam. The alternative of decommissioning and removing the dam could result in an inadequate level of flood protection for the infrastructure and communities downstream of the dam.

The Resource Management Act 1991 includes no requirements relating to change of use; however, resource consents for the storage and use of the stored contents would be required and the consents would be required to be renewed at the frequency required by the Act. Given that the purpose of the Act is to "promote the sustainable management of natural and physical resources", consents under the Act would probably be necessary for any change of use that would result in adverse effects on the environment.

The Building Act and the Building (Specified Systems, Change the Use, and Earthquake-Prone Buildings) Regulations 2005 include specific requirements relating to change of use. The requirements included in the legislation relate to the use of spaces or dwellings for crowd activities (e.g. cinemas, grandstands), sleeping activities (e.g. hospitals, hotels, houses), working, business or storage activities (e.g. factories, business premises, warehouses), and intermittent occupation or providing intermittently used support functions (e.g. car parks, locker rooms). While no requirements are included in the current legislation that relate to a change in use for dams, any demolition activities or modifications to an existing dam necessary for a change in use would require a building consent.

A change in use may also necessitate the identification of an alternative Owner with an interest in maintaining the dam for the alternative use. In assessing whether a change in use is a viable option, Owners will need to consider:

- Who will be legally liable for the ongoing safety of the dam.
- Future ownership options.
- Whether an alternative Owner can be identified with an interest in maintaining the dam for an alternative use.
- Who will be responsible for the ongoing surveillance, operation and maintenance of the dam.

From a dam safety perspective, it is important that any change in use incorporates an appropriate dam safety management system. The recommendations included in Modules 5 and 6 should be followed.

8. Dam decommissioning

8.1 Introduction

Decommissioning of a dam may become necessary because the dam has outlived its usefulness, or it requires rehabilitation works which the Owner cannot afford or which render the operation of the dam uneconomic. Unless emergency action is agreed by the Regional Authority as being necessary, the decommissioning of large structures will typically require consents under the Resource Management Act and Building Act. Investigation, design and decommissioning procedures should generally follow those outlined in Modules 3, 4 and 6, with a focus on controlling the risks during the decommissioning process and leaving them acceptably low on completion.

A decision to decommission a dam should be based on the careful evaluation of a wide range of alternatives to resolve issues associated with dam safety, high rehabilitation costs, high operation and maintenance costs, environmental effects, sedimentation issues, and long-term function and ownership. Such evaluations need to consider issues arising from either retention or decommissioning of the dam as there will be effects and consequences with either approach. In some cases full removal may be necessary to resolve critical issues, while in other cases partial removal may provide a satisfactory long-term solution. The following subsections provide guidelines for the consideration of dam decommissioning as a project alternative. The guidelines are restricted to the consideration of issues related to dam safety – they do not address environmental, legal, social, economic, ownership and political issues, all of which could have significant effects on the identification of a preferred decommissioning option. The guidelines do not apply to tailings dams.

8.2 Decommissioning considerations

8.2.1 Dam safety

The Building Act and Building (Dam Safety) Regulations require dams to meet current dam safety criteria as recommended in these Guidelines. If the criteria are not met Owners would likely consider a number of questions including the following:

- What rehabilitation works are necessary to address the identified dam safety deficiencies?
- What is the estimated cost and time for the completion of the rehabilitation works?
- How would the completion of the rehabilitation works affect my commercial operation?
- What are the costs of decommissioning and is it economically viable for me to complete the rehabilitation works?
- What alternatives are available if it is uneconomic for me to complete the rehabilitation works?
- What are the issues associated with the alternatives and what alternatives would likely be acceptable to the consent authorities?

Decommissioning could become necessary if it was uneconomic for an Owner to complete the rehabilitation works necessary to address a dam safety deficiency. Complete removal of a dam would usually be unnecessary to satisfy current dam safety criteria and, in most cases, partial removal would be sufficient. Partial removal could include reducing the dam height or breaching the dam to permanently reduce the loads on the structure, and removing all ancillary structures (e.g. gates, pipelines, pump stations, powerhouses). Total removal would generally only become necessary to address issues unrelated to dam safety.

8.2.2 Decommissioning process

A proposed process for the decommissioning of a dam is shown in Figure 8.1.

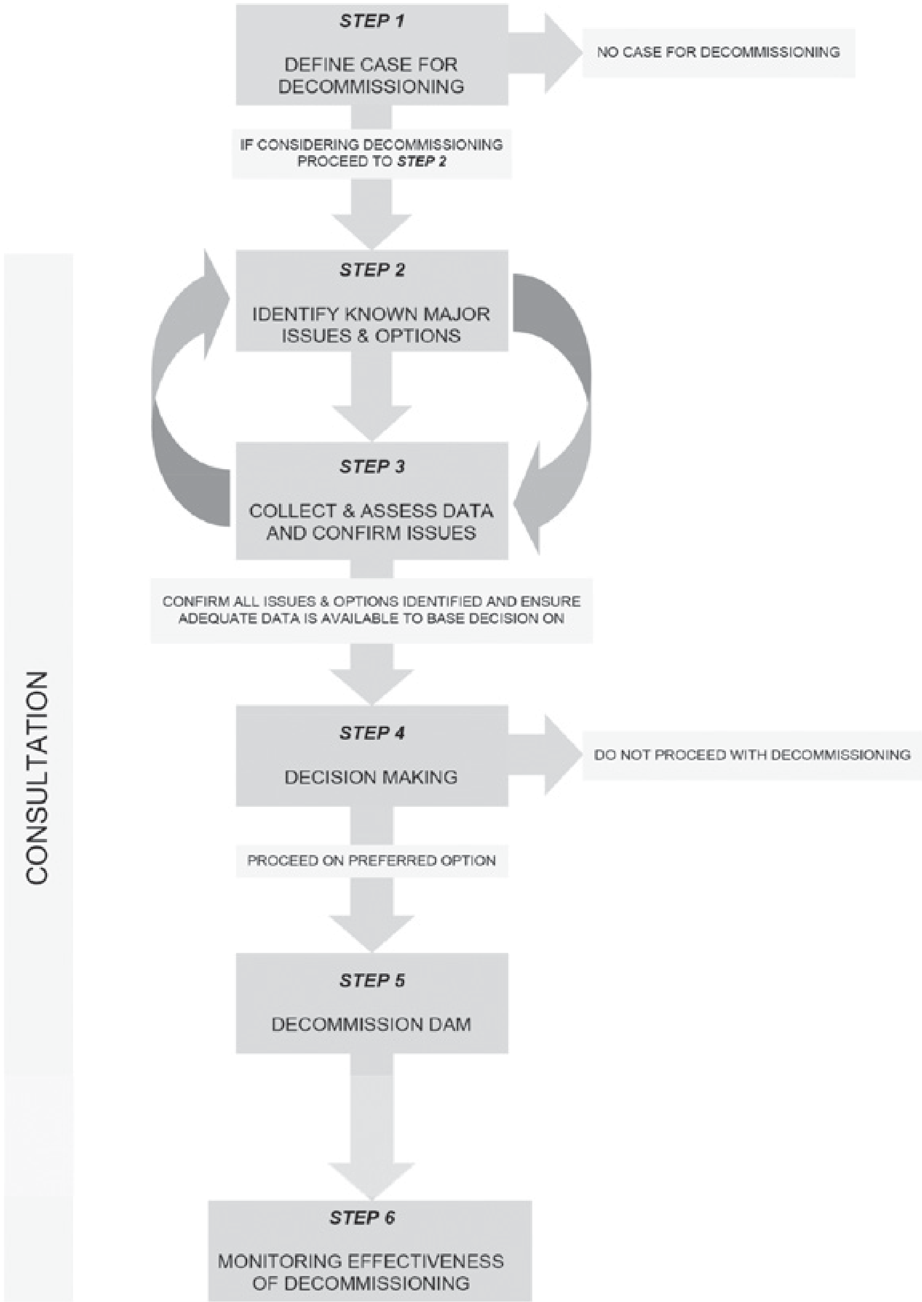

Figure 8.1: Dam Decommissioning Process

The process should include the careful evaluation of a wide range of decommissioning options that include complete removal, partial removal, changes in reservoir operation and change of use. A wide range of issues will be associated with each decommissioning option; some will be common to many of the options while others will be specific to a single option. The use of independent advice from technical specialists and stakeholders is an essential component in the identification of a preferred decommissioning option.

Stakeholder participation in the decision making process and stakeholder support of a preferred decommissioning option will usually be essential for a successful project outcome. Obtaining consents for a preferred decommissioning option will be very difficult, if not impossible, to achieve without support from community and environmental interest groups.

8.3 Decommissioning design and removal

Dam decommissioning projects require careful design and a comprehensive understanding of the existing structures is essential to the success of a decommissioning project. In some cases there will be sufficient documentation available to confidently establish the characteristics of the existing structures while, in other cases where documentation is scarce, a programme of field work may be necessary to confirm site conditions.

The design and removal processes should generally follow the recommendations included in Modules 3 and 4. However, experience in dam decommissioning projects is very limited in New Zealand and, depending on the scale of the decommissioning project, specialist design and contractor support may be necessary to achieve a successful outcome. Important engineering issues that will require careful consideration during the design and removal processes include:

- The structure removal limits necessary to achieve an appropriate level of dam safety.
- The long-term management of accumulated reservoir sediment (e.g. removal and disposal, removal by the river, flushing and release in to the downstream river or re-contouring and re-vegetation) and other environmental issues.
- Reservoir drawdown capabilities and limitations on drawdown rates.
- Flood management during decommissioning.
- The methodology for decommissioning the dam (e.g. removal sequence, demolition and removal methods, disposal, site restoration).
- The long-term safe passage of flood events.
- The long-term surveillance, operation and maintenance requirements for ongoing dam safety.
- Long-term public safety considerations where partial structures remain and are able to be accessed and used by the public.

8.4 Dam performance monitoring

A programme of dam performance monitoring would normally be necessary to quantify and evaluate effects that accompany the demolition and removal of a dam and, if partial removal is adopted, to monitor the ongoing safety and public safety of the completed project.

A dam performance monitoring programme during demolition and removal should address the dam safety objectives of the programme, monitoring requirements and frequencies, acceptable performance criteria for the elements being monitored and reporting and evaluation requirements. Mitigation measures and an Emergency Action Plan (refer Module 6) should also be in place to address any dam safety concerns that could arise during demolition and removal.

If partial removal is adopted and the completed project incorporates a permanent reservoir, performance monitoring may be necessary to enable verification that the completed works are performing as intended and to identify developing or changing conditions that could affect the safety of the decommissioned dam. Post-decommissioning performance monitoring programmes should reflect the PIC of the decommissioned dam and the procedures recommended in Module 5 should be followed. Although unlikely, given that the dam is decommissioned, there may be some residual dam safety risk that requires an Emergency Action Plan to be in place to address any emergencies that arise following the decommissioning of the dam. In such a case the recommendations included in Module 6 should be followed.

9. Operational floods

Section 4.2 in Module 3 discusses the topic of Flood Hazards and appropriate Inflow Design Floods for dams. This is in the context of dam safety with associated links to Emergency Preparedness as discussed in Module 6.

Particularly for Medium and High PIC dams, more frequent but smaller floods will be comfortably passed by the available spill capacity with minimal dam safety risk. This section briefly discusses some of the considerations relevant to smaller operational floods. While these may not be of measurable relevance to dam safety they may be relevant to individual dams, and hence owners, in terms of flood management.

9.1 Consequence of floods

While smaller, more frequent flood events, may be of little consequence to a dam in terms of dam safety considerations, these same events may be significant or even catastrophic for communities and other infrastructure.

There will be, in many cases, a range of design standards applied to infrastructure, unrelated to the dam, which could be impacted by a flood event. Typical flood standards are in the range 1 in 50 AEP to 1 in 200 AEP for structures such as stopbanks, bridges, roads and industry. It is therefore highly probably that, during flood events that are moderate from a dam design viewpoint, significant damage and associated consequences can arise elsewhere in the catchment.

For example, stopbanks protect property and potentially lives from flood hazards. Their design capacity means that at a particular scale of flood, there is a relatively rapid increase in the probability of stopbank failure with associated consequences. Similarly at some design flood level a bridge may be destroyed or be unserviceable. The consequence of floods, and hence risk, does not therefore follow some progressive relationship as flood magnitude increases. Rather there is almost always a sequence of steps in consequence. This is demonstrated on Figure 9.1.

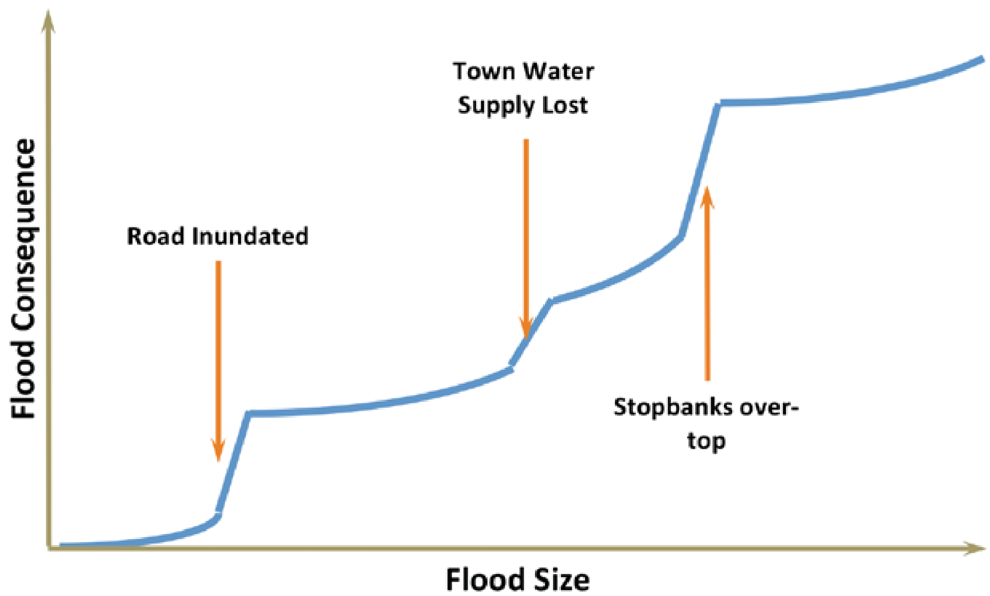

Figure 9.1: Flood Consequence vs Size

9.2 Flood management

There is always a desire from communities for dams to actively reduce the impact of flood events. The ability for a given dam to influence flood events is a function of a range of considerations dominated by the:

- Degree of forewarning of a flood that is available
- Volume of the reservoir in comparison to flood volume
- Physical constraints associated with discharge
- Operational constraints such as resource consents.

As flood magnitudes increase a given dam will therefore have less ability to reduce the impact of the flood. This issue is often difficult for communities to comprehend as they may have experienced the dam providing significant benefit during small flood events and as such the expectation is that it should have a similar or even greater beneficial impact on larger events. Clearly the opposite is true.

Flood management, and the ability to partially mitigate flood risks is unique to each dam and as such there is no single methodology. Further, given change over time, it is likely that flood management options will also change with time.

It is also not simply a case of seeking to reduce the maximum flood flow although this may be a desirable outcome. Depending on a range of interrelated sensitivities, the timing, duration and rate of change in flow may also need consideration when managing flood events. In assessing flood management options therefore the following may need to be considered:

- Flood magnitudes and levels critical to other infrastructure or communities. These will induce the steps in consequence compared to flood magnitude.
- Potential tidal or storm surge influence. Tides and storm surges will impact downstream levels and as such may change the rate of flow that the river can cope with before a given consequence is likely to arise.
- Timing of release (eg day vs night) and any change in vulnerability that may arise. It may be important to try to reduce flood releases during the hours of darkness when communities are more vulnerable.
- Environmental impacts of releases. Issues such as erosion and sediment movement may have environmental consequences.
- Financial consequence of draining reservoirs. If a reservoir is lowered to facilitate greater flood storage this will have a financial and potentially societal impact in terms of for example reduced water supply security, reduced recreational benefits and reduced energy supply.
- Public safety. Considerations such as spilling water in advance of a flood to gain reservoir storage can have public safety implications. Particularly in larger catchments, there may be little indication lower in a catchment that a flood is pending. Early spill releases may induce greater public safety risk than the flood itself.
- Time available to adjust reservoir level prior to a flood event. If greater time is available, actions, and hence possible impacts, can be more subtle. Improved warning times is a valuable tool in improving flood management options.
- Precedent flood events. Past flood events are useful in verifying dam flood performance and the response of downstream river systems. Dam flood capacity cannot be commissioned at the end of construction like other dam components. Performance during actual flood events provides partial verification and the ability to learn how larger events may be handled. Precedent flood events can also be useful in defining when flood management should be escalated. If it is known that minimal risks arise from up to certain magnitude events, then these can be considered normal operation.

Many of the points above are in conflict with each other. In optimising dam operation for a given consideration there will almost always be compromises to others. Flood management, and associated procedures need to consider these trade-offs and should never result in a compromise in dam safety.

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