ROYAL GOVERNMENT OF BHUTAN

DAM SAFETY GUIDELINES FOR HYDROPOWER IN BHUTAN

Department of Energy

Ministry of Energy and Natural Resources
Royal Government of Bhutan

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Abbreviations

AEP	Annual Exceedance Probability
ANCOLD	Australian National Committee on Large Dams
BEA	Bhutan Electricity Authority
CME	Controlling Maximum Earthquake
CSR	Comprehensive Safety Review
CDSR	Comprehensive Dam Safety Review
DBE	Design Basis Earthquake
DCF	Dam Crest Flood
DGPC	Druk Green Power Corporation Limited
DHPS	Department of Hydropower and Power Systems
DSCP	Dam Safety Critical Plant
DSHA	Deterministic Seismic Hazard Assessment
FDSR	Formal Dam Safety Review
FEMA	United States Federal Emergency Management Agency
FERC	United States Federal Energy Regulatory Commission
FY	Financial Year
ICOLD	International Commission on Large Dams
IDSR	Intermediate Dam Safety Review
GLOF	Glacial Lake Outburst Flood
IDF	Inflow Design Flood
MCE	Maximum Credible Earthquake
MCL	Maximum Control Level
MDE	Maximum Design Earthquake
NZSOLD	New Zealand Society on Large Dams
OBE	Operating Basis Earthquake
PGA	Peak Ground Acceleration
PFMA	Potential Failure Modes Analysis
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PSHA	Probabilistic Seismic Hazard Analysis
RGOB	Royal Government of Bhutan

SDSR	Special Dam Safety Review
SEE	Safety Evaluation Earthquake
SPF	Standard Project Flood
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation

Note on Guideline updation (July 2024)

The Ministry of Finance (MoF) has proposed to the World Bank's (WB) in 2023 for accessing the contingent financing line of credit called, Climate and Disaster Resilience Development Policy Credit with a Catastrophe Deferred Drawdown Option (Cat DDO) that will provide immediate liquidity to Bhutan to address shocks related to natural disasters. The facility serves as early financing while funds from other sources such as bilateral aid or reconstruction loans are being mobilized. The Cat DDOs enhance a country's financial resilience by providing quick access to funds needed for emergency response and recovery efforts following natural disasters, once a drawdown trigger is met. The Cat DDO drawdown period is set for three years with possible extension to a maximum of six years once approved by the WB's Board slated in September 2024.

In order for the country to be eligible for a Cat DDO, it must put in place an adequate macroeconomic policy framework and a satisfactory Disaster Risk Management program which the Bank will monitor periodically during the project implementation period. As Cat DDO is a Development Policy Financing instrument, the preparation required due diligence in the form of prior actions (PAs) that will strengthen the capacity of the RGoB to manage the risk of climate change and natural disasters. This was to be achieved by supporting reforms under three pillars:

i. Climate and disaster resilient infrastructure and cities;
ii. Strengthening early warning systems for hydrometeorological hazards and forest fires; and
iii. Strengthening financial protection of vulnerable households and properties.

The PAs were aimed to help Bhutan address a large spectrum of hazards it faces, with a focus on seismic resilience, landslides, floods including glacial lake outburst floods (GLOF), and adaptive social protection. As part of the PAs required under the Cat DDO concerning the energy sector, the Department with support of WB reviewed and updated the Guidelines for Development of Hydropower Projects-2018 and the Dam Safety Guidelines-2020 through its consultants. This revision was found crucial for enhancing the resilience and sustainability of hydropower infrastructure against climate change and natural hazards. Climate change is said to increase the risk of natural hazards, posing serious threats to hydropower infrastructure where for instance, the July 2023 flash flood had damaged part of the 32 MW Yungichhu hydropower project.

In the process, the Consultants carried out the gap analysis of the two Guidelines from March-June 2024 to examine the interplay between hydropower infrastructure and climate change and, provided recommendations for incorporation whereby their recommendations were drawn from the WB's Good Practice Note on Dam Safety including its similar works in Nepal and the stakeholder consultations which included the private sector. The critical updates included the incorporation of the Integrated Geohazard Assessment (IGA) framework, which shifts the focus from a site-specific to a catchment-wide perspective, addressing the interrelated risks of natural hazards, such as earthquake, GLOFs, landslides and flash floods, which are exacerbated by climate change. Based on the recommendations, the Guidelines were updated by an inter-agency team from DoE, DGPC, DGM, NCHM & ERA which was approved by the Ministry for adoption.

These updated guidelines are expected to support the development of resilient hydropower infrastructure & disaster risk management which are key pillars of the Cat DDO operation under MoF.

Preface

Bhutan is endowed with hydropower resources. In Bhutan, 100% of electricity is generated from hydropower. To date 2,335MW has been harnessed and over 2,930MW is under development, with more than 10,000MW in various stages of planning. The Government of Bhutan has identified that hydro-electric power development has two important roles to play in the socio-economic development of Bhutan:

i) to provide safe, reliable, affordable and abundant electricity to improve the lives of all Bhutanese and drive industrial growth, and
ii) for exporting surplus power to enhance Government revenue and achieve positive balance of payments.

To date there has not been a national level dam safety guideline in effect in Bhutan. Meanwhile, the Government of Bhutan requires hydropower developers and operators to provide assurance that the dam is designed and constructed with dam safety considered and then operated using accepted dam safety practices.

Dam Safety Guidelines are present in many countries to assist in the application of dam safety in the investigation, design, construction and operation phases of a dam's life cycle. Major hydropower developments in Bhutan have, to date, involved international partners and designs which have commonly used international guidelines for design and construction. International guidelines may be generally suitable, but may not be consistently applied across projects and do not necessarily recognise Bhutan's unique and complex geology and natural hazards.

Bhutan has long been at the forefront when it comes to implementing international best practices in hydropower development and dam safety. Current international best practices for dam safety policy go beyond the traditional hydrological assessment including Probable Maximum Precipitation (PMP) / Probable Maximum Flood (PMF), and rainfall-runoff simulations. There is an increasing recognition and application of risk- informed approaches to dam safety assurance including geo-hazards assessment in the upstream catchments and providing a range of various methods for carrying out risk analyses, ranging from qualitative to fully quantitative methods. The World Bank publication: "Good Practice Note on Dam Safety", 2020, provides guidance on using a risk management approach to dam safety and applicable risk analysis tools. More emphasis is placed on building capacity within the borrower to deal with social and environmental aspects by offering broader and more systematic coverage of risks. The World Bank Environmental and Social Standard, Annex 1, addresses the safety of dams and introduces a comprehensive risk management approach in line with Good International Industry Practice.

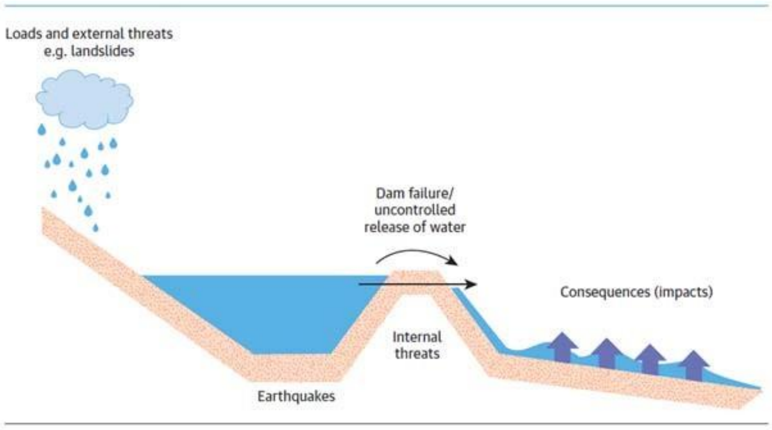

Figure 1.0 Conceptual Diagram of Threats/Loads, Dam Response/Performance, and Consequences

In the context of dam safety, risk is defined as a measure of both the likelihood and consequences of an adverse event on downstream communities, environment, assets, and infrastructure. Expressed as the expected value of risk calculated as the product of likelihood of dam failure and the consequences of subsequent flooding. The likelihood of dam failure can be further broken down to the probability of occurrence of (a) threats to, and loads upon, a dam (for example, storm, earthquake, and so on) and

(b) the probability of the dam structure/reservoir performance or response leading to dam failure because of the threats and loads (see figure 1.0). Consequences represent negative effects resulting from an uncontrolled release of a large amount of water—not necessarily involving failure of the dam body but caused by failure or mis-operation of spillway gates and so on—in terms of loss of life and other social, environmental, and economic impacts.

Broad risk management approaches are increasingly being used to inform dam safety assurance, which is likely the result of increased stock of aging dams around the world and more frequent dam safety incidents because of non-structural and contextual causes that are not well-captured by the traditional standard-based approach. There is also greater societal demand for full transparency, higher safety levels, better justification of the use of public and private funds, and the need to prioritize remedial action in reducing risks to acceptable levels, as defined by dam safety practice.

Risk management approaches to dam safety assurance typically include the following process:

(a). risk analysis,
(b). risk assessments,
(c). decision making for risk control and reduction measures, and
(d). monitoring and evaluation.

There is an important feedback loop in this approach—when the results of risk monitoring and evaluation are fed back into risk analysis and assessment, as well as any decisions needed on risk control and reduction measures. Robust operation and maintenance mechanisms should be established and maintained to keep effective risk management system in place throughout the life cycle of the project. This Risk-Informed Decision Making (RIDM) approach emphases a comprehensive decision-making process, not based solely on numerical risk estimates but also on deterministic analytical results and other relevant factors.

RIDM can be broadly defined as a method of dam safety evaluation that uses the likelihood of loading, dam fragility, and consequences of failure to estimate risk. This risk estimate is used, along with standards-based analyses, to decide if dam safety investments are justified or warranted. This approach has many benefits including an improved understanding of the safety of the dam and identifying dam safety vulnerabilities that have not been identified using standards-based evaluation techniques.

It is important to keep in mind that the risk is not static and will change depending on the condition of the dam and during the project cycle and so on including the impacts of a warming climate. The consequences of dam failure and subsequent flooding can also change for various reasons, such as growth in the population and assets in downstream areas of a dam.

In addition to hazards arising from dam failures on the downstream riparian communities, it is important to consider hazards from upstream which may impact the reservoir and/or dam, and the consequences arising therefrom. To ensure that such hazards are properly considered, it is recommended that an Integrated Geohazard Assessment (IGA) of the development be carried out and methodologies for this are referred to in this updated version of these Guidelines.

Bhutan has developed regulations and guidelines for some stages of the dam life cycle, for example Guidelines for Development of Hydropower Projects (DHPS, 2018) and Druk Green Power Corporation’s Dam Safety Guidelines (Druk Green, 2015) for inspection of operating dams. Dam owners have access to many international guidelines and manuals on specific topics to supplement the above references. However, the currently used guidelines do not comprehensively address all dam safety activities necessary for safe management of dams throughout their full life cycle.

It is important to recognise that the benefits of undertaking and updating IGAs applies to all stages of hydropower development and the earlier in the process an initial IGA is undertaken the greater will be the benefits throughout the entire dam development and operation cycle. This will in turn increase the safety and resilience of the dam to hazards

This “Bhutan Dam Safety Guidelines” is intended to be an overarching document for dam safety management of hydropower in Bhutan, whether the dam is in the development phase or in operation. While it is written for the hydropower sector, almost all the contents are also applicable for dams intended for other purposes.

There are three modules to the Dam Safety Guidelines:

1. Module 1: Dam Safety Management: Describes the principles and performance criteria fundamental to dam safety.
2. Module 2: Investigation, Design and Construction: Provides overview of the important dam safety considerations during the development and first reservoir filling phases of the dam life cycle.
3. Module 3: Dam Safety Performance: Covers dam safety practices in operations, maintenance and emergency management; i.e. the operational phase after first reservoir filling.

Module 1 will enable non-technical persons to understand the overarching dam safety objectives and principles, while Modules 2 and 3 provide technical guidance to those involved in the investigation, design, construction and operation of dams.

Module 1 identifies the legal requirements for dam safety in Bhutan. Dam classification provides a method to group dams according to the risk they pose if they were to breach. Two methods are used in Bhutan, one for the project development phase based on reservoir height and volume, and one for the operational phase based on downstream consequences. Both methods are expected to give common outcomes for the consequence class but each dam needs to employ both methods. The size (height and volume) classification links to the performance criteria and design loads for use in dam design (Module 2). The consequence classification links to the dam inspection, reviews and monitoring requirements during the operational phase (Module 3). Module 1 also outlines the operations and maintenance planning which needs to start early in the dam life cycle. This includes testing and maintenance of outlets and associated dam safety critical equipment which should be understood in the design phase to ensure the discharge facilities are specified with operation in mind.

Potential Failure Modes are common to all phases of development and operation of a dam. Potential Failure Modes Analysis (PFMA) outlined in Module 1 is a process to systematically identify, describe and evaluate ways a dam and its dam safety related appurtenant structures could fail under all postulated loading conditions. The methods go beyond the limitations of conventional analysis used in dam design. The results also apply to the selection of monitoring and surveillance procedures and instrumentation, and the scope of dam inspections during first reservoir filling and operation phases. The PFMA process should be carried out before first reservoir filling and reviewed on completion and at the frequency of dam safety reviews.

Module 2 applies to the investigation, design and construction period, including first reservoir filling. However, Module 2 is also relevant when undertaking a dam safety review during the operational phase. Detailed step-wise procedures for dam development of concrete and embankment dams are found in the DHPS guidelines and international reference documents. However, some aspects of this phase of the project are not covered in the DHPS Guidelines, including first reservoir filling. This Guideline has expanded on the missing topic areas.

Module 3 covers dam inspections, monitoring of instrumentation, safety reviews, identifying and managing dam safety issues and planning for emergencies. The frequency of inspection, monitoring and testing emergency plans will vary from dam to dam depending on the type of dam, its condition, the hazard posed by the structure and associated reservoir (i.e. its classification). Guidance is given for the dam owner to consider when setting these frequencies. Dam safety issues are those which could impact safe dam operation and can occur at any time in a dam’s life cycle. For clarity when managing issues, these are divided into physical infrastructure issues, dam safety deficiencies (potential or confirmed) and non-conformances. It is important that dam safety issues are managed in a time frame related to the dam’s consequence category, its condition and the probability of the issue leading to further problems.

The guidance material contained in this document will in places be more relevant to some entities involved in Dam Safety, compared to others. This is entirely appropriate as different modules and sections within the Guidelines are targeted to those most involved in that aspect of Dam Safety.

1.0 Module 1: Dam Safety Management

This module will enable all involved in dam safety including non-technical persons to understand the overarching dam safety objectives and principles. The purpose, objective and principles described below provide a common foundation on which all guidance is formed. Modules 2 and 3 provide technical guidance to those involved in the investigation, design, construction and operation of dams.

This module outlines legislation of Bhutan that influences the development and operation of dams. Both legislation and supporting regulations change over time. Participants responsible at each stage of development and operation of dams for dam safety need to maintain awareness of the current laws and regulations.

Classification systems are used in many countries to understand the hazard that the dam poses. Dam breach or unexpected or uncontrolled major discharge poses a major risk to communities and the environment downstream of the dam. Classification systems that apply in dam design and dam operation are summarised in this module.

Control of the reservoir is critical to safe operation of the dam. This means dam designers and operators need to focus on discharge facilities throughout the dam life cycle. Maintenance and testing of these facilities are included in this module.

Maintenance of accurate and reliable records is also important in design, construction and operation of the dam. Transfer of knowledge from one phase to another is important for understanding the dam's behaviour and maintaining safety of the dam.

1.1 Governance, Roles and Responsibilities

Responsibilities and processes during dam development and ownership in Bhutan is defined in legislation, supported by regulation. Current practice tends to have different governance at each phase of development; investigation, design, construction and first reservoir filling, and finally operation. This is described in the following sections.

1.1.1 Regulatory

Hydropower dam development and operation in Bhutan is regulated under the Electricity Act (2001) [1]. Other Acts that also impact dam safety management are the Water Act (2011) and Disaster Management Act of Bhutan (2013).

Regulatory frameworks can change with time. Meanwhile, current Acts that incorporate dam safety aspects are:

Electricity Act (2001)

Electricity Act (2001) influences dam safety practice in Bhutan with the following provisions:

- The requirement to licence hydropower plants, and the mechanisms for licensing and regulating the operations of power companies.

- The creation of the Bhutan Electricity Authority (BEA). The Act states that BEA is to protect the interests of the general public, and that BEA will lay down the standards, codes, and specifications of the electricity supply industry. This includes:
    - issuing Regulations for safety of dams,
    - defining the roles and responsibilities of suppliers to the electricity industry,
    - issuing licences for generation, transmission, system operation, export, import, distribution and sale of electricity, and
    - determining performance standards, including minimum technical and safety requirements for construction, operation and maintenance of generation facilities.

<u>Application and Approval of Licences and Monitoring of Licensee Performance</u>

The Electricity Act authorises BEA to set requirements for Licensees' application, reporting, accounting and issuance of information to the Authority. The Act includes:

- The form of the licence application, including requiring licensees to submit the following:
    - a technical and economic description of the project,
    - the impact of the project on public interests and possible mitigation,
    - a summary and conclusions of assessments and studies, including environmental impact assessment,
    - impacts of the project on private interests, including the interest of affected landowners, and
    - any other documents required by the Regulator.

- Considerations that the Regulator is to cover when approving a Licence. These include:
    - the impact of operation on the social, cultural and recreational life of the community,
    - the needs to protect the environment,
    - the ability of the applicant to operate in a manner designed to protect the health and safety of users or other members of the public who would be affected by the operations,
    - the technical, economic and financial capacity of the applicant, and
    - other public and private interests affected by the operation for which the licence is required.

The Electricity Act requires BEA to monitor the performance of Licensees and their compliance with the Act, Regulations, Standards, Codes, Licences and contracts approved by the Authority and contained in concession agreements;

Water Act (2011)

The Water Act (2011) provides for State ownership of water. Relevant to dams, the Act includes the following:

- Bhutan Electricity Authority holds authority as the “Competent Agency” for hydropower. In this case the Act requires the Competent Authority to set criteria for the safety of dams and monitor the safety of dams.
- Environmental requirements for water use, including setting minimum environmental flows for watercourses.

Disaster Management Act of Bhutan (2013)

The Disaster Management Act of Bhutan (2013) has the following provisions:

- Establishes the Disaster Management Authority (DMA) chaired by the Prime Minister.
- Requires approval of the National Disaster Management and Contingency Plan
- The Disaster Management Office can direct agencies to include risk reduction in their development plans, policies, programmes and projects.
- Authorises the DMA to accept international assistance if necessary.

Regulations

As outlined above, Bhutan Electricity Authority is required to develop regulations covering dam safety. Draft Regulations have been developed but are yet to be approved for implementation.

Guidelines

Technical guidelines and requirements for the development of hydropower is detailed in the Hydropower Guidelines – 2018.

1.1.2 Hydropower Project Developer and Owner

In Bhutan the following key roles are involved in the development and operation of hydropower dams:

- Department of Hydropower and Power Systems (of the Ministry of Economic Affairs): DHPS is the policy advisor for development of new hydropower projects. DHPS is the nodal agency for according approval of the Detailed Project Report (DPR) on behalf of the Royal Government of Bhutan.

- Special Purpose Vehicle (SPV) or Project Authority: The SPV/Project Authority is typically the Developer of the project responsible for design, construction and first reservoir filling of the project. It is sometimes a joint venture between a developer/financier and the Royal Government of Bhutan. The SPV/Project Authority will appoint a Contractor and Designer for the development phase of the project.

- Druk Green Power Corporation (DGPC): DGPC is the Government owned power utility. Ownership of the newly developed power project usually transfers to DGPC within 2 years following completion of first reservoir filling. DGPC has internal engineering resource for operations and maintenance or uses consultants as technical advisors.

- As stated earlier, Bhutan Electricity Authority (BEA) is the Electricity Regulator approving licences, setting domestic tariffs, setting standards and requirements for dam safety etc.

- The Disaster Management Office (DMO) administers emergency management for Bhutan. The dam owner is required to cooperate with this office.

1.1.3 Communities

Communities are important stakeholders in the operation of dams. Downstream communities that could be impacted by dam failure or mis-operation must be considered in the emergency planning process. They must also be considered in the design phase, where the dam classification system is used to recognise the hazard posed by the presence of the dam to anyone at risk from a dam disaster and incorporate dam design practices to avoid dam failure. These communities require total confidence in the dam safety management provided by the project designers, contractors and operators to maintain their support of the project.

Downstream communities will also be affected by power station discharges during normal operation. Fluctuations in flow may impact community life, but unexpected large changes in dam discharge could be a public safety risk to the people in the vicinity of the river. Consideration of risks to the communities downstream should be made when setting ramping (flow change) limits for the power station. Warning systems may be necessary to notify people in the downstream river area.

1.1.4 Experts

Technical experts may be located inside Government organisations, contractors and private sector consultants. Expertise in dam engineering is developed through gaining experience from design and operation of similar projects. Designers need to have experience of the dam type under construction as do engineers undertaking dam safety reviews. Contractors need to have experience building the type of dam. The level of experience and expertise of those involved should relate to the hazard of the completed dam and complexity and geotechnical risk relating to the specific project. For high hazard dams, dams on complex foundations or with high seismic hazard, the lead Designer should have more than 20 years' experience in dam engineering, including the type of dam being developed. The Contractor's project team should include engineers who have constructed the same type of dam.

Pre-Qualification Criteria for selection of designer and contractor should be included in the tender document. Based on the qualification, the contractor is selected. If the necessary expertise is not present, then the Developer should re-consider selection of designer and contractor or add suitably qualified and experienced advisors to the project.

Similarly dam safety expertise during operation requires experience in dam engineering or dam safety management. Training should be provided for dam operators, inspectors and engineers responsible for dam safety instrument data analysis.

Independent experts are recommenced for some activities, such as review of dam design and Comprehensive Dam Safety Reviews (CDSR). Independence ensures that external perspective is applied to the safety of the dam. Independent experts should also have 15 to 20 years' experience or more in their field of expertise.

An independent Panel of Experts (PoE) is strongly recommended for design and construction of high hazard dams on complex foundations or high seismic zones. A PoE should include experts with more than 20 years' experience in design or construction of the type of dam, especially complex dam projects. Each Panel member would be expected to contribute a different speciality of dam expertise relating to the risks involved with the project. A Panel of

Experts may also be valuable to resolve a dam safety deficiency identified at an operating dam.

1.2 Purpose, Objectives and Principles

Regardless of how an individual, government authority or organisation is involved in dam safety, it is important that all do so with a common understanding of purpose, objectives and principles related to dam safety. A lack of consistency in the understanding of purpose, objectives and principles is a common reason for poor performance of systems. This in turn increases the risk to people, property and the environment.

The purpose, objective and principles provide the common framework and understanding within which those involved can check that their approach is consistent with good practice.

Furthermore, it is important that there is consistency across all stakeholders that they share a common purpose, objective, and principles that include consideration of hazards from within upstream catchments on downstream infrastructure projects, not just hydropower schemes.

1.2.1 Purpose: Why are dam safety guidelines important?

A purpose defines the reason why an action, process or system is being undertaken. In this context the ***purpose of good Dam Safety Management*** is to;

> *Minimise the risk dams pose to people, property, the environment and infrastructure both now and into the future.*

The ***purpose of these guidelines*** is to;

> *Enhance national dam safety practices through the provision of guidance material that builds capacity, facilitates and the transfer of knowledge.*

1.2.2 Objective: What should dam safety guidelines achieve?

The objective defines what is desired to achieve though the adoption and implementation of a process or system being undertaken.

In this context the ***objective of good Dam Safety Management*** is to;

> *Continuously seek to identify and adopt good practice in investigation, design, construction and operation that collectively delivers safe and resilient dams based on juridical catchment-wide assessments.*

The ***objective of the guidelines*** is to;

> *Provide direction and guidance that facilitates the advancement of dam safety management as a fundamental goal integrated across all stages of dam development and operation, considering also the upstream catchment and which recognises and responds to hazards identified that could impact on any significant infrastructure downstream.*

1.2.3 Principles: Key Rules Under Which All Involved Should Operate

The key principles discussed below define the overall framework within which the purpose and objective lie. They form a broad checklist against which dam owners, regulators and individuals can access their own performance, systems and processes. In the absence of any specific guidance, the suitability of any process, system of action can be checked against these principles.

> ***Principle 1**: The consequence of an uncontrolled release of the content of a reservoir should be fully assessed and understood, and this understanding used to guide appropriate design, construction and operation of the dam.*

Understanding how the failure of a dam, or any uncontrolled release of reservoir content, impacts people, property and the environment is crucial. This understanding drives the level of design, construction and operational procedures that should be adopted.

> ***Principle 2**: All loading conditions, natural or man-made, that have the potential to threaten the integrity of the dam at any time in its lifetime, should be identified and assessed. It is important that loadings arising from conditions in the upstream catchment are included and to this end an Integrated Geohazard Assessment should be carried out at an early planning stage and updated throughout the life of the dam.*

The components of an Integrated Geohazard Assessment (IGA) are as follows:

1. Desk study
2. Gap analysis
3. Event mapping
4. Process identification
5. Neo-tectonic provinces and seismicity
6. Regional geological analysis
7. Landslide susceptibility mapping
8. Glacial hazard assessment
9. Hydrological analyses
10. Sediment management
11. Other analyses identified in gap analysis

Methodologies for each component are to be found in relevant literature including the paper “/8/ The role of integrated geohazard assessments in disaster risk management, J.M. Reynolds, Reynolds Geo-Solutions Ltd, UK, 44Hydropower & Dams - Issue One, 2023.

A clear understanding of the many loading conditions a dam will face is important both as inputs for design, but also for targeting ongoing performance monitoring and assessments throughout the dam’s lifecycle.

Conditions and situations that threaten the integrity of a dam are expected to change for each lifecycle stage of a dam. For example, a significant risk to the dam during construction may no longer be relevant during operation when it becomes superseded by other risks. All risks that arise during each lifecycle stage (construction, first reservoir filling, early and mature years of operation, and risks to aging structures) need to be identified and appropriately considered. Consideration should also be given to both, discrete risks (e.g. arising from a major flood) and combinations of lesser risks that collectively contribute to a significant risk, (e.g. loss of spillway capacity and hence flood capacity following a seismic event),

> ***Principle 3****: The various modes by which a dam might fail, under various loading conditions identified, should be assessed and defined.*

Understanding the ways in which a dam might fail, typically known as the dam's "failure modes" is important as these highlights, where greatest attention should be focused throughout the life of the dam.

Resilience in terms of design and ongoing performance during operation can then be aligned with these failure modes.

> ***Principle 4****: Dams and associated structures required for safe operations should be designed, constructed and operated to ensure they meet appropriate performance criteria commensurate with the consequence of dam failure.*

Having clear and relevant performance criteria, aligned with the consequences of failure, is crucial in ensuring that the risk to people, property and the environment is consistent between different dams and over time. Performance criteria provide a benchmark against which society can be assured that the nation's dams, both individually and collectively, are being manged to achieve an acceptable level of risk.

> ***Principle 5****: The dam owner is accountable for the safety of the dam and its operation.*

The dam owner is accountable for ensuring that the hazard to people, property and the environment, posed by the reservoir is appropriately managed. This includes during design and construction as well as normal operations and operation during emergency events.

Accountability must be with the dam owner as they are the ones in control of the dam as well as benefiting from the purpose of the dam. While other entities (e.g. government ministries, technical specialists etc.) often adopt some responsibility for aspects of safe dam management the dam owner still retains overall accountability. This includes ensuring how other entities are most appropriately involved to achieve the best outcome.

> ***Principle 6****: Governance, management systems and resourcing should be provided at a level commensurate with the consequences of dam failure.*

To achieve good dam safety performance requires consistent and integrated coordination of effort at all levels. Where one aspect of an integrated performance system is insufficient the effectiveness of all other aspects is compromised.

As well as consistency across all aspects of dam safety management, alignment against the consequences of dam failure means that the risks associated with dam failure is consistent irrespective of dam size or hazard.

> ***Principle 7****: All reasonable efforts should be made to prevent inappropriate or accidental releases from the dam or associated structures.*

Any abnormal, excessive or emergency release from a dam, including dam failure, has the potential to place people, property and the environment at risk. Focus should primarily therefore be on preventing such occurrences. This is achieved through; investigation, design, construction, operation and performance management that is appropriately aligned with the level of hazard posed by the reservoir contained by the dam.

> ***Principle 8****: An effective emergency preparedness, response and mitigation plan should be in place for each dam.*

The results from the IGA should be incorporated into the emergency preparedness, response and mitigation plan for the dam. Even where best practise is adopted and implemented across all aspects of a dam, there remains a residual risk of dam failure and inappropriate releases from the reservoir. Irrespective of how remote this likelihood might be, prepared emergency plans and associated procedures are necessary to further reduce the risk to people, property and the environment.

> ***Principle 9****: Due diligence should be employed at all stages of a dam's life cycle.*

Dams last for many generations during which their operation, use and hazard they pose may well change. Structural and operational components of the dam will also deteriorate, be upgraded, modified or replaced. Communities downstream will change and grow and social needs and risk tolerances change. Climate change, and changes in the catchment upstream will impact on catchment characteristics and hence threats to dam integrity.

This all means attention must be given to the implications of such changes overtime. These implications in turn need to be captured, assessed and prioritised through a programme of upgrade, enhancement and rehabilitation.

1.3 Classification, Criteria and Assessments

Dam classification (or hazard category) is used 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.

Performance criteria are key parameters for setting design loads and acceptable limits for safety evaluation of a dam. Fundamentally, the dam must retain the reservoir contents safely while withstanding the design loads, yet the structure may be damaged at the level of extreme loads. The link between dam classification and performance criteria is that when the dam poses a threat to life, the design requirements are greatest. Hence in Section 1.3.2 and 1.3.3 design criteria are tabulated against hazard category.

Potential Failure Modes are a key step in the evaluation of the safety of a dam. Design analysis does not necessarily cover every way that a dam can fail. The assessment process for determining Potential Failure Modes for a dam is likely to identify a mechanism that could lead to dam failure which is not evident from traditional analysis. The level of effort to assess Potential Failure Modes also relates to the hazard category for the dam.

Hazards, Risk and Vulnerability: The recommendations in the World Bank Good Practice Note on Dam Safety should be applied.

In relation to natural hazards which are of concern with respect to dam safety the concepts for Hazard, Risk and 'Vulnerability defined in the United Nations International Strategy for Disaster Reduction (UNISDR) should be applied:

- Risk is taken as the product of Hazard x Vulnerability, with the latter considered in terms of “the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards” (UNISDR 2009).
- Vulnerability is often taken as a function of Exposure and Probability of occurrence.
- ‘Exposure’ is defined as “the people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses” (UNISDR 2009).
- The probability of occurrence is determined statistically or qualitatively.

Hazards can be present, continuously or most the time (e.g. upstream Glacial Lake) or be intermittent (e.g. Earthquakes). A given **Hazard** can, however, induce more than one **risk** for the dam. A natural hazard such as a major flood, for example, can induce many vulnerabilities such as the potential to destroy critical upstream flood warning sites, destroy access to the dam, induce large debris and sediment loads, as well as directly impacting and overwhelming the dam through high inflows.

There are three options to reduce the probability of occurrence of hazards:

(a) Avoidance – do not construct a project in the most vulnerable location;

(b) Mitigation – upstream interventions may be feasible, such as lowering the water level in a glacial lake, or constructing debris-capture dams; and

(c) Engineering resilience of the infrastructure in response to likely hazard scenarios.

Aspects of all three approaches may also be applied.

Considering Hazards and Threats in this way helps guide dam safety processes such as Potential Failure Mode Assessments, implementation of control and mitigation measures, and, preparation of Emergency Action Plans (EAP).

1.3.1 Dam Classification

Dam classification categorises dams according to the hazard they pose to the community downstream. Ideally this would be assessed by a dam break consequence assessment that identifies the population at risk if the dam were to breach. This is a hypothetical scenario and has no correlation with the probability of the dam failing or experiencing a dam safety incident.

Consequence assessments which deliver dam break maps assist dam owners and operators:

- in emergency planning and preparedness,
- to thoroughly understand the risks posed by the presence of the dam, and
- in developing risk reduction measures to address unacceptable risks.

When developing the dam project, it is possible that the extent of flooding from a dam breach is unknown (especially if details of the dam are yet to be finalised). It is reasonable therefore to adopt an initial, simple, classification system to guide preliminary design. Once the dam design has advanced beyond a preliminary stage, the associated hazard represented by the storage is apparent, so classification based on consequence of failure should be adopted. Hence these guidelines allow the hazard category approach used in the DHPS Hydropower Guidelines to be used in the preliminary design phase. The consequence assessment method of Classification is to be applied from the time of first reservoir filling.

<u>Dam Classification for Preliminary Design Purposes</u>

The dam classification for preliminary design must be undertaken before the design process is progressed beyond a basic concept stage.

The dam classification for the purpose of defining dam safety performance criteria and design loading is based on the gross storage of the reservoir and the hydraulic height of the dam as shown in Table 1.1. These are applicable to all dam types during the design process. The designer must use this classification result when determining flood and seismic design loads on the dam and when following the design requirements for concrete dams or earth and rockfill dams set out in Section 2 of these guidelines.

Table 1.1: Dam Classification for Preliminary Design Purposes

Classification Title for Dam		Gross Storage (10^6 m^3)	Hydraulic Head (m)
DHPS	International		
Small	Low	0.5 – 10	7.5 – 12
Intermediate	Medium	10 – 60	12 -30
Large	High	>60	>30

The classification shall be the higher of the classifications obtained by considering the gross storage and hydraulic head separately.

The classification titles adopted in the DHPS Hydropower Guidelines (Small, Intermediate & Large) are shown against titles more commonly adopted internationally (Low, Medium & High).

Dam Classification for Operational Management and Emergency Management

A second classification method which applies to all operation, management and emergency planning functions is shown in Table 1.2.

This process for classification uses dam break flood maps to identify people, property and the environment that would be impacted by a hypothetical dam failure, or dam safety incident. Dam break flood maps are produced by hydraulic modelling software, with one-dimensional flow modelling in narrow river valleys and two-dimensional flow modelling where flow breaks out onto terraces or plains. There are several software packages available that deliver dam break flood routing.

Hence the hazard is defined by the consequences if the dam were to fail. This particularly helps operational dam safety management and emergency planning. The dam type is important when considering how the dam could fail and what the maximum discharge from the breach would be. For example, a concrete dam block failure would result in an almost instantaneous release of water whereas an embankment dam failure is more often gradual as the breach widens and deepens with corresponding increasing discharge as the embankment erodes.

The Dam Classification for operational management and emergency management must be determined early in the Design and Construction stage in order to define the level of hazard the reservoir presents to downstream communities so that operational and emergency management plans are complete before first reservoir filling.

This second classification is to be compared to the earlier classification for the preliminary design phase. Any difference in consequence categories should be reviewed and a decision made as to whether there is an impact on design.

Table 1.2: Dam Classification for Operational Management and Emergency Management

Consequence Category	Class of Dam	Affected Housing Units	Environment and Property	Infrastructure	Reservoir Production Structure/Equipment
Large (High)	4	>150	Large and irreversible damage on environment and property	Damage on heavy traffic roads or national grid or other structures, which are very important for life and health	Very large consequences for the society
	3	20-150			
Intermediate (Medium)	2	1-20	Large damage on environment and property	Damages on secondary roads, district grid or other structures important for life and health	Large consequences for the society
Small (Low)	1	0-1	Moderate damage on environment or property	Damage on minor roads, local grids and other structures that may have importance for life and health	Moderate consequences for the society
	0	0	Minor repairable environmental damages or damages on property	Minor damages on local roads and other structures without any consequences for life and health	Minor consequences for owner's company and production

These potential impacts can change with time. The Classification must be reviewed every five years from the time that reservoir filling is complete, and if the scale of dam hazard changes.

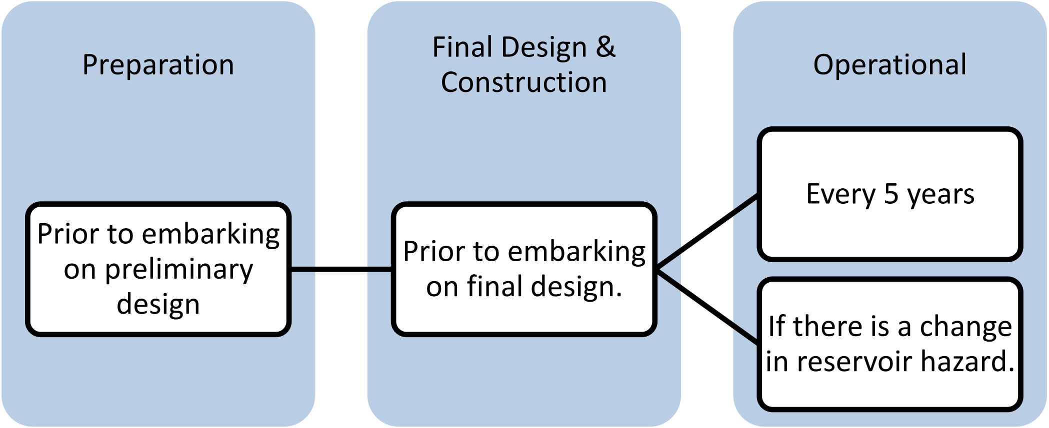

Figure 1.1: Times When Dam Classification Must Be Determined or Reviewed

1.3.2 Performance Criteria for Floods

Two inflow design floods are required to be considered for design purposes for Intermediate (Medium) and Large (High) Classification dams.

Check Flood.

The check flood inflow (also known as the Inflow Design Flood in many international guidance documents) is required to be safely passed accepting sub-optimal hydraulic conditions and marginally safe performance characteristics assuming all gates in operation. The check flood is considered to be an extreme load condition.

Spillway Design Flood

The spillway design flood inflow is required to be safely discharged with fully acceptable hydraulic conditions and adequate freeboard below the dam crest. If the spillway is gated the design flood shall be passed with 1 spillway gate assumed to be inoperable. The spillway design flood is considered to be an unusual load condition.

The Probable Maximum Flood and Standard Project Flood are the Check Flood and Spillway Design Flood respectively for Intermediate and Large Classification dams as shown in Table 1.3.

Standard Project Flood (SPF)

The SPF is the flood generated by the most severe rainstorm on record yielding the highest rainfall depth over the catchment or in a meteorologically homogeneous neighbouring catchment.

Probable Maximum Flood (PMF)

The PMF is the largest flood that could conceivably occur at a particular location, estimated from probable maximum precipitation (PMP), and where applicable, snow melt, coupled with the worst flood producing catchment conditions.

Table 1.3: Required Design Floods

Classification	Check Flood IDF	Spillway Design Flood IDF
Small	Not Applicable-	1:100 AEP
Intermediate	PMF	Greater of SPF or 1:1000 AEP
Large	PMF + GLOF	PMF

Glacial Lake Outburst Flood (GLOF)

The Glacial Lake Outburst Flood is as estimated based on assessment of the risk of outburst from an upstream glacial lake (refer to DHPS Hydropower Guidelines).

Glacial Lake Outburst Floods (GLOFs) are a hazard in Bhutan and can have devastating effects on both the hydropower infrastructure and downstream communities. With climate change, both the frequency and magnitude of extreme geological and hydrological events such as GLOFs appear to be increasing. It is therefore important that upstream catchments, the physical processes that occur there, and how these may individually or in combination impact downstream hydropower schemes are considered. While there has been greater emphasis on undertaking Glacial Hazard Assessments in recent

years, the methods that have generally been used have proven to be inconsistent and unreliable. An objective method of assessment to review glacial hazards associated with Glacial Lake Outburst Floods can be found in “Glacial hazard assessments in the Himalayan Region, John M. Reynolds, Reynolds Geo-solutions Ltd.” It uses the latest developments in the use of Multi-Criteria Analysis, RGSL, 2003; Reynolds, 2023c; Racoviteanu et al., 2021 and is based on a long-established technique that has been adapted specifically for glacial hazard assessments and which have been tested on many hundreds of glacial lakes in South America and especially in the Himalayan Region.”. Where glacierised catchments lie upstream in regions to which access is restricted, suitable assessments of such areas can be undertaken using Remote Sensing techniques. Methods of dealing with transboundary assessments are also described variously within the above references as well as those for Integrated Geohazard Assessments.

1.3.3 Performance Criteria for Earthquakes

The dam and its appurtenant structures must be able to safely retain the reservoir and allow reservoir operation following an earthquake.

Three different earthquake levels are required to be considered for design purposes for Intermediate and Large Classification dams.

Operating Basis Earthquake (OBE)

The Operating Basis Earthquake (OBE) is the level of earthquake at which little or no damage occurs, and therefore dam operation should continue without interruption. Any damage will be minor and easily repaired. The OBE is typically represented by ground motions of 1:145 AEP (annual exceedance probability). If the risks associated with loss of reservoir operation, even temporarily, are considered too great at this relatively low return period, stronger ground motions of 1:475 AEP should be used.

Maximum Design Earthquake (MDE) or Safety Evaluation Earthquake (SEE)

The Maximum Design Earthquake (MDE) for new dams or Safety Evaluation Earthquake (SEE) for existing dams is the earthquake that produces the maximum level of ground motion for which a structure is to be designed or analysed. The MDE or SEE may be set equal to the Maximum Credible Earthquake[1] (MCE) or to an earthquake determined by a Probabilistic Seismic Hazard Analysis (PSHA).

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[1] *The MCE is regarded as the largest hypothetical earthquake that may be reasonably expected to occur along a given fault or other seismic source. A Deterministic Seismic Hazard Analysis (DSHA) is generally performed to identify the Maximum Credible Earthquake (MCE). The maximum earthquake for each identified fault is considered to identify the maximum ground shaking (i.e., largest seismic demand on the dam), and define the MCE scenario.*

Design Earthquake for Dams and Structures with Critical Dam Safety Functions

This design earthquake is the load to be considered for the dam and associated appurtenant structures to meet the performance criteria for the dam to safely retain the reservoir and allow reservoir operation following an earthquake. The dam may be damaged but there must be no uncontrolled releases of the reservoir.

Table 1.4 shows the Design Earthquakes for Small, Intermediate and Large Hazard dams and the structures and equipment with critical dam safety functions.

Table 1.4: Required Design Earthquakes for Dams and Structures with Critical Dam Safety Functions

Classification	OBE	MDE or SEE
Small	1:145 AEP	1:475 AEP
Intermediate	1:145 AEP	MCE or 1:2,500 AEP
Large	1:145 AEP	MCE or 1:25,000 AEP

Design earthquakes derived from the MCE are based on the hazard at the mean plus one standard deviation. Design earthquakes derived from probabilistic methods are based on the mean hazard.

Design Basis Earthquake (DBE) for Structures and Components that do not have a Critical Dam Safety Function

Structures which do not have a critical dam safety function or do not directly retain the reservoir (e.g. penstocks and power stations) can have a lesser design earthquake than the dam. For these structures and components, the DBE may be represented by ground motions of 1:475 AEP. If the power station is critical for electricity supply to an area of Bhutan, the DBE may be greater (say 1:2,500 AEP) in order to increase the reliability of electricity supply after an earthquake.

The implications of earthquakes on the catchment and especially the river valley both upstream and downstream of the dam shall also be considered. A downstream landslide could result in an impoundment behind a valley- blocking landslide dam, with the water inundating assets associated with the hydropower project. It could also affect transmission lines and the ability to evacuate power to markets. Landslides generated by a major earthquake may result in valley-blocking dams. The majority of such dams fail within a matter of weeks to months and can release massive volumes of water in Landslide Dam Outburst Flood (LDOF) events that can overwhelm even large dams (e.g., Sichuan earthquake in 2008 in China).

Design of new dams should employ defensive design principles as explained in the World Bank Good Practice Note on Dam Safety -Technical Note 3 on Seismic Risk, 2021.

1.3.4 Potential Failure Modes Analysis

A Potential Failure Modes Analysis (PFMA) is required to be performed for all dams with a Classification of Intermediate (Medium) or Large (High) during preliminary design. The PFMA is to be reviewed in the final design stage, before first filling of the reservoir. First filling is an important handover period to eventual dam operators and the PFMA provides an excellent opportunity to transfer knowledge and records from one phase to another. Following completion of first filling, the PFMA is to be reviewed at intervals of every 5 years.

A PFMA is a process to systematically identify, describe and evaluate ways a dam and its dam safety related appurtenant structures could fail under all postulated loading conditions or component and/or system failures during a loading condition.

PFMA is a valuable tool which can be used both during dam design and for existing dams to:

- identify the applicable potential failure modes;
- identify where additional defensive measures could reduce the likelihood of failure;
- identify key performance parameters and provide instrumentation to monitor them; and
- prepare operating, surveillance, maintenance and emergency preparedness plans that take account of potential failure modes.

PFMA can be carried out at a number of levels. The process for existing dams is described in Chapter 14 of FERC Dam Safety Performance Monitoring Program [2]. The ANCOLD publication *Guidelines on Risk Assessment* [3] has a useful discussion on types and levels of risk assessment. As an adjunct to the standards based engineering design, a screening or preliminary level, qualitative or semi-quantitative PFMA is suggested.

Outline of PFMA Process during Dam Design

The PFMA process is used to identify potential failure modes for the dam, spillway, foundations, abutments and low-level outlets. Credible potential failure modes are those with enough significance to warrant continued awareness and attention to visual observation, monitoring and remediation as appropriate. This leads to identification of opportunities for risk reduction, possible investigations or analyses, and means for monitoring/inspecting for the development of potential failure modes.

The following steps of the PFMA are to be followed:

1. Collect all data, studies and information on the investigation and design and, where applicable, construction. A listing should be made of the data available for review.
2. Prepare a Supporting Technical Information Document (STID) that covers all system components.
3. Form a diverse PFMA team from experts that adequately cover all relevant technical disciplines involved in the analysis, and with sufficient specialized expertise. A core team of minimum 4 persons (composition shown in Table **1.5** below) should conduct the PFMA exercise.

Table 1.5: Makeup of PFMA Team

PFMA Core Team Member	Main Tasks
Facilitator - international expert familiar with the PFMA process	Site inspection, Facilitator of the PFMA session
Independent Dam Safety Specialist – international expert in dam safety evaluation and familiar with dam failure mechanisms.	Site inspection; expert input to PFMA
Engineer geologist/ geotechnical engineer – national expert	Site inspection, provide site specific knowledge during PFMA
Hydrologist/ hydraulic engineer – national expert	Site inspection, provide site specific knowledge during PFMA
Hydro-mechanical Engineer – national expert	Site inspection, provide site specific knowledge during PFMA re flow discharge equipment

Attendance at the PFMA workshop should also include:

- Dam operators;
- Representatives of the dam designer
- Representative of the dam contractor
- Operators of other dams which can impact the operation of the dam undergoing PFMA;
- Representatives of stakeholder institutions.

4. Key PFMA participants need to visit the project site to look for potential failure modes and the conditions that might lead to one occurring. The site visit should consider structural and geologic conditions, review proposed operations, and interview owners/operators for their input on potential failure modes.
5. Review all the background information for general understanding and with these specific questions in mind:
    - How could this dam fail? (Consider site-specific geology, loadings, structure condition, and project past and anticipated operations),
    - What would happen if the dam fails?
    - Are the identified potential failure modes recognized and being appropriately monitored by visual surveillance or instrument monitoring?
    - What actions (immediate or long term) can be taken to reduce dam failure likelihood or to mitigate failure consequences? These actions could include any of the following: data collection, analyses or investigations, operational changes, communication enhancement, monitoring enhancement and structural remediation measures.

6. Systematically identify potential failure modes for normal, flood and earthquake conditions. The dam site should be assessed as a number of discrete components and analysed one at a time.

7. Brainstorm potential failure modes and failure scenarios at the PFMA workshop. The team most familiar with design, analysis, performance, and operation of the dam should lead this assessment.

8. Specifically identify possible performance monitoring enhancements for each potential failure mode.

9. Document the analysis by recording the major findings and understandings from the brainstorming session. Records of findings will include: the identified potential failure modes, the reasons why each potential failure mode is likely to occur and identify any possible actions, related to each mode of failure that could help reduce risk (monitoring enhancement, investigation, analysis, and remediation).

10. Prepare summary tables that include key parameters related to the following elements:
    i. Potential Failure Mode;
    ii. Scenario/Initiating Events/Sequence/Consequences;
    iii. Negative Factors affecting the likelihood of the PFM;
    iv. Positive Factors reducing the likelihood of the PFM;
    v. Monitoring/Risk Reduction Opportunities/Data & Analysis;
    vi. Gaps/Emergency Plans;
    vii. Action Items, and
    viii. Categorization of the PFM according to the FERC system as shown in Table **1.6**:

Table 1.6: Potential Failure Mode Categories

Category	Characterization	Description
I	**Highlighted PFM**	Considers potential for occurrence, magnitude of consequence and likelihood of adverse response (physically possible, fundamental flaw or weakness identified, conditions reasonable and credible).
II	**Potential PFM considered, not highlighted**	Of lesser significance and likelihood that Category I.
III	**More information or analyses needed to classify**	Lacked information for confident judgment and since action may be required, these may be highlighted.
IV	**PFM ruled out**	May be that physical possibility does not exist, information eliminated concern, or so remote a possibility as to be non-credible or not reasonable[2].

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[2] Sometimes the technical subject experts are called to make judgments on extremely low probabilities. In most cases it is a single person, or maybe two, who make such judgment but the responsibility is hidden behind the PFMA team. For this reason, it may appropriate to require that the report states who exactly ruled out the failure mode and on what basis.

1.4 Operations and Maintenance

An Operations and Maintenance (O&M) Manual must be prepared for all dams.

Dam safety relies on a combination of systems and physical components working when they are needed. This need is often very infrequent due to the extreme events dams are typically designed to endure.

It is therefore vitally important that components and systems are well maintained and are in a state of readiness. The maintenance, testing and review processes adopted to provide this certainty is commonly contained in an Operations and Maintenance Manual.

The purpose of an O&M manual therefore is to document the maintenance, testing and review requirement for all dam components that contribute to dam safety and performance.

It should be noted that, for many dams and their associated uses, operations and maintenance systems and manuals include many aspects not relevant to dam safety. The scope of this guideline is limited to components and systems relevant to dam safety and performance.

1.4.1 Operations Manual Content

The exact content and detail contained in an O&M manual will depend on the type and Classification of the dam, the environment in which it is formed, and specific components relevant to dam safety (often termed ‘dam safety critical plant’ DSCP).

Depending on the preference of the owner, the O&M manual can be structured to consider either;

- address one component at the time with all the detail and requirements relating to that component, or
- break the manual down in to sections that cover each O&M topic for all components at once.

This later approach has been adopted in the example contents provided in Table 1.7 below.

Table 1.7: Contents of an O&M manual

Section	Contents
Preface	***Describe*** the purpose of the document.
Dam Safety Components	***Describe*** each relevant aspect and component, its key specifications and statistics and it purpose in terms of contributing to dam safety. ***Define*** the operational states of each component. These indicate what successful operation is, and hence any deviation from these states could be considered a malfunction or failure. Example, the states for a gate may be; open, closed, or adjusting under control. Any other situation – such as closing by itself, would indicate a malfunction.

Section	Contents
Performance Data and Records	***Define*** what information and data is required to monitor and confirm a component performance and what performance criteria and limits are applicable. This may change depending on the nature or relative risk level of threats. Example, during wet months more frequent data recording and review may be conducted.
Operational Criteria	***Define*** what operational limits, criteria and procedures exist for each component. This might include physical, operational and environmental based criteria. These may also be continuous or periodic constraints. Example, different seasonal gate operating limits. ***Identify*** any interdependence between components particularly where issues with one component may reduce effectiveness of another. ***Identify*** any cross linkages with emergency preparedness planning (Refer: Module 3, Section 3.4). Example, if reservoir level exceeds Elevation X.X overtopping occurs and this is managed in the EAP.
Maintenance issues, testing and review	***Describe*** the nature of typical or unusual issues that impact operation of the component. Example, debris blockage, sedimentation. ***Define*** routine and preventative maintenance requirements. ***Provide***, where applicable, a summary of key historical maintenance and repair requirements particularly where this relates to identified performance issues. ***Define***, testing and review requirements to verify performance.
Out of service Considerations	***Describe*** issues that need to be considered if the component is taken out of service for repairs and maintenance. This would typically be associated with a formal 'change management' process. Example; taking a spillway gate out of service reduces capacity by 33% (1 of 3 gates). This increases overtopping risk.
Procedures	***Provide*** specific procedures, process and templates relevant to a given component or maintenance task. These may be contained within computerised asset management systems with examples appended to the O&M manual.

1.4.2 Gate Testing

Performance monitoring and testing must be carried out on components, such as gates and valves that fulfil a dam safety purpose.

Gates and their contribution to dam safety can be very significant as they form a primary control mechanism against threats to dam integrity. They are frequently complex systems relying on many inter-reliant components each of which has its own requirements, risks and reliability. These inter-related components also often consist of a combination of civil, mechanical, electrical and communications and control. The reliability of the overall system is not only a function of the least reliable component but also the potential combination of partial malfunction across multiple components.

Not only is there a need to achieve the highest overall certainty that gates will be able to be operated when needed, they should not operate without cause. Inappropriate operation of gates is classified as a dam safety incident as the unexpected and unplanned discharge could have significant consequences to the downstream area and population.

<u>Testing</u>

An important aspect of verifying gate performance is testing. Such tests should seek to verify the performance of the overall system as well as all core components. If a single component malfunctions during a test and is repaired, this does not mean that the system is now reliable as another component may be at the point of failure but was not tested because of the first component failure.

The ability to test gates may be restricted by limited storage in the reservoir. It may also be restricted to reduce the impacts that the test discharge would have on the downstream area. For these reasons the purpose of the testing needs to be carefully considered and should cater for the specific risks posed to the dam, gates and environment.

Formal and routine testing of gates, under a range of scenarios, provides confirmation of current gate performance. Over time, repeat testing can highlight common weaknesses and issues that need to be incorporated into maintenance regimes and upgrades. It also provides an overall trend of reliability that highlights if reliability is changing overtime.

The types and frequency of tests, depending on the gate function is provided in Table 1.8 (with reference to NZSOLD [4]).

Table 1.8: Gate Testing Schedule including Minimum required and Preferable Frequency

Gate/Valve Dam or Reservoir Safety Function	Backup Power Source Test	Unbalanced Head (Flow) Test	Balanced Head (No Flow) Test
Passage of Floods (refer Note 1)	Preferable: **Monthly.** Minimum Requirement **Bi-Monthly.** Minimum Opening (refer Note 2).	Preferable; **Annual.** Minimum Requirement **2 Yearly.** 15% opening, or, one full rotation of moving parts (refer Note 3). Initiated by normal and backup power supplies and all control modes.	Preferable; **5-yearly.** Minimum Requirement **10-Yearly** Full range. Initiated by normal and backup power supplies and all control modes.
Reservoir Dewatering (refer Notes 1 and 4)	Preferable; **Six-monthly**. Minimum Requirement **Annual.** Minimum opening (refer Notes 2 and 5).	Preferable; **5-yearly.** Minimum Requirement **10-Yearly** 15% opening, or, one full rotation of moving parts (refer Note 3 and 5).	Preferable; **10-yearly.** Minimum Requirement **10-Yearly.** Full range (refer Note 5).

Gate/Valve Dam or Reservoir Safety Function	Backup Power Source Test	Unbalanced Head (Flow) Test	Balanced Head (No Flow) Test
	Initiated by backup power source (i.e. battery and motor start-up checks).	Initiated by normal and backup power supplies and all control modes.	Initiated by normal and backup power supplies and all control modes.
Machine or Water Supply Intake (refer Note 6)	N/A	Preferable; **5-yearly.** Minimum Requirement **10-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 or valve open and demonstrate operation of the backup power source.*
3) *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.*

Because gates are expected to operate in the wet season, annual tests shall be undertaken before each wet season.

As well as formal testing, event-based testing provides additional performance details that can often provide scenarios difficult to replicate by formal tests. For example, during a moderate natural flood one of the spillway gates (assuming there are multiple) might be intentionally 'tripped' to close. The benefit of this example would be that the test that the control system responds and re-apportions flow across the remaining gates. It also tests larger gate opening and hydraulic performance that may be impossible to replicate in a test regime.

To make 'event-based' testing of greatest value, additional data recording might need to be installed to allow full system performance to be reviewed. This might include;

- Loads on lifting mechanism & motors.
- Recording of automatic control system decisions.
- Recording manually induced interventions to test responses

Hydraulic performance of the spillway needs be checked during event-based testing to ensure asymmetric flow conditions in a spillway channel with a gate closed remain acceptable and does not result in a dangerous condition developing.

1.4.3 Gate Maintenance

The overall consideration of maintenance is provided earlier in Module 1 Section 1.4. Gates need to be maintained so they are reliable and are continuously ready for use. Gate maintenance also has specific considerations that warrant specific discussion.

Maintenance typically requires the removal of the component from service. This is for practical as well as health and safety reasons. For gates this reduces discharge capacity and therefore the resilience the dam has against many threats that can impact on dam safety and integrity. Careful planning of maintenance is important to reduce exposure to threats while the gate is out of operation.

The ability to undertake adequate and timely maintenance on key components such as gates should be part of the design process for the dam (refer Module 2 Section 2.4). It is unlikely however that there will be spare capacity or permanent alternatives provided as part of a design so that maintenance can be undertaken without impinging on capacity. Consideration must be given to;

- The different types of service outage and what maintenance can be undertaken under each of these types. Different service outages might include;

Disabled.	*Control system disabled but gate fully functional.*
Disconnected.	*Lifting gear disconnected or removed*
Hydraulically Isolated	*Stop logs installed, no discharge possible*
Removed	*Gate fully removed, no operation possible.*

- The reinstatement time for each of the outage types.
- The capacity reduction caused by the out of service gate.
- Any additional control measures (e.g. reservoir drawdown).

1.4.4 Modern Instrumentation / Automation of Gates and Valves

The progressive improvement in instrumentation in conjunction with being more cost effective allows greater understanding of the performance of components and as such helps target maintenance. It also potentially allows refined operation to achieve enhanced control of the reservoir.

For example, spillway discharge may have historically been based on a simple lake level vs discharge relationship, the higher the lake level, the greater the discharge. Modern instrumentation and control systems could allow predictive discharge ahead of approaching flood events, thereby providing greater attenuation of the flood within the reservoir.

Similarly, instrumentation can highlight areas of the system that are deteriorating and at risk of compromising reliability. Maintenance could therefore be targeted to address those components showing stress.

Nevertheless, care must be exercised before historical simple but reliable control systems are replaced to ensure dam safety risks are not increased by complex technology. Furthermore, routine maintenance must not be replaced by an asset management strategy to operate to components to imminent failure before maintenance. Some components will be difficult to replace and have long lead times to obtain.

This does not mean avoiding the opportunities provided by modern control and monitoring for maintenance. Rather it should be seen primarily as an enhancement on simple and reliable approaches.

For example, a predictive flood discharge control system could be adopted but the existing simple and robust lake level discharge control should also be retained. Both operate continuously with whichever control system requests the larger discharge setting the gate outflow. Even where gate operation is manual, a predictive control could be added, but rather than directly operating the gate, it suggests to the operator a gate setting.

Similarly, increased monitoring for maintenance can inform personnel if routine maintenance needs to be advanced or could be deferred for a period of time. More importantly it can indicate issues with components that are not normally part of routine maintenance or are examined only infrequently.

Considering automation and increased maintenance monitoring as enhancements to existing practises (rather than replacing historical methods) does not mean that financial benefits often claimed to be achieved from automation, are lost. Better control of spill flows can reduce the impacts of debris, sediment and erosion and hence rehabilitation costs. Likewise, improved indication of component performance can avoid unforeseen and costly forced repairs.

1.5 Knowledge Management

A Knowledge Management System is required for each dam (or portfolio of dams where a dam owner owns multiple dams).

Dams will exist and continue to operate for many generations. Therefore, there is a need to adopt a long-term strategy on knowledge management that is aligned with the hazard represented by the dam. The successful implementation and operation of a Dam Safety Management System relies on the sound facilitation and retention of knowledge and the competency of people involved. This is at all levels including governance, performance personnel, technical support and operational staff.

The following section separates knowledge management for dam safety into the following categories;

Governance	Organisational and group management.
Performance	Monitor the ongoing dam performance against defined performance criteria.
Operational	Operate the dams and associated structures on a day to day basis.
Technical	Provide specialist skills and knowledge.

1.5.1 Capabilities & Competence

The core roles and responsibilities for dam safety must be defined and communicated, and those undertaking those roles are required to have the appropriate capability and competency.

The skills and knowledge required to deliver the design, construction and operation of safe dams will be spread across many people, specialities and organisations. There is therefore a need for a high level of integrated and collective understanding across all people that contribute and jointly share responsibility for dam safety.

Further, knowledge and skills need to be continuously refreshed and transferred over time to ensure the sustainability and resilience of good dam safety practices.

The core competencies necessary to deliver good dam safety management is provided in Table **1.9**.

Table 1.9: Roles, Responsibilities and Competencies

Personnel	Role	Responsibilities	Competencies
Governance	Organisational and group management.	Overall dam safety and risk management and ensuring enough resource (people, time and finances) is made available to deliver good dam safety management.	Principles of risk and quality management and understanding the hazard posed by dams and the implication of failure.
Performance	Monitor the ongoing dam performance against defined performance criteria.	Undertake performance monitoring and related tasks and reporting performance and any anomalies to appropriate responsible managers.	Understanding how performance information and data relate to particular dam performance, deterioration and failure scenarios.
Operational	Operate the dams and associated structures on a day to day basis	Ensure operations stay with pre-defined safe limits and where this is not achievable escalate to pre-determined technical or management support.	Understanding the implications of operating outside normal limits. Able to identify anomalies and unusual operational issues.
Technical	Provide specialist skills and knowledge.	Provide specialist advice and recommendations on design, operational criteria and performance targets.	A wide range of specialist competencies which will depend on the needs to the dam, dam type and hazard rating.

The wide range of skills and competencies needed, particularly from technical specialists and support personnel is summarised in Table **1.10**.

Table 1.10: Technical Support

Specialisation	Responsibilities
Hydrology	Hydrological and meteorological risk assessment. Glacial lake outburst flood hazard assessment. Climate change risk assessment. Flood hazard assessment for design and periodic updates. Reservoir management during floods and spill releases.
Hydraulic	Hydraulic design of intakes, spillways, tunnels, discharge structures and downstream river hydraulics
Geology	Dam foundation, reservoir, and catchment landslides investigations and mapping. Structural geology. Glacial geomorphology.
Geotechnical	Foundation and dam interaction. Slope stability assessments. Design of slope stabilisation measures. Earth dam design and periodic performance reviews.
Seismology	Seismic risk assessments of entire catchment for design and periodic updates.
Structural	Design of concrete dam design and appurtenant structures. Provision of performance criteria and periodic review against these criteria.
Mechanical	Design of; gates and lifting system, discharge valves and screening systems. Periodic review of performance testing.
Electrical	Design of power systems for gates, valves and primary & backup systems.
Comms & Controls	Operational and emergency control systems and associated communication systems.
Environmental & Social	Environmental and social impact assessment

1.5.2 Training & Capacity Building

A training and capacity building programme and definition of responsibilities is required.

The best plans and procedures will not achieve their intended beneficial impact if the people required to use them do not have the commensurate knowledge. In the field of dam safety this is particularly complicated by the long-life span of the structures involved and the hazards and threats that impact those structures. There may be many years between events, such as major floods, that test processes and the people that are applying them.

Training and ongoing capacity building is a key component delivering the competencies that support performance in dam safety over the years. It is useful to consider training in terms of several broad classes as shown in Table 1.11.

Table 1.11: Types of Training

Type	Commentary
Routine	Regular, frequent and generally focused on aspects that need to be continually managed, monitored and reviewed. Involves a combination of training relevant to general dam safety and aspects that are specific to the given dam. Routine training will predominantly be undertaken internally and may consist of a combination of formal and informal training. Routine training across various topics should occur several times each year.
Targeted	Periodic and related to specific topics or issues. Includes training on; new processes, procedures, technology and in-depth training on specific aspects such as failure mode workshops and flood management training sessions. Conducted both internally and externally depending on the topic and involves a combination of internal personnel and external specialists. The frequency depends on the range of relevant topics, but typically at least once per year.
Special Event	Aimed at unusual and emergency events and includes running exercises and simulations to test both the understanding of personnel and the adequacy of systems and processes. Include training where unusual combinations of relatively minor issues occur and where component failures compromise performance. Typically run internally with input from external advisors and agencies responsible for emergency response (e.g. police, civil defence). Range from desktop simulations to full scale multiple organisation exercises that include consideration of other infrastructure such as flood protection works and power systems. The frequency depends on the dam's hazard (consequence) rating and range of emergency scenarios. Frequency of every 2-3 years is recommended with each training session using a different emergency scenario.
Post Event	Uses actual events to grow competencies through experience. Actual events are the best test of systems, processes and people. Whenever practical the opportunity should be taken for those involved in significant events to pass on and record their experience. Such events provide multiple training opportunities including; the lessons learned directly during the event, but also what upgrades were then adopted to systems, processes or physical structures to reduce the impact of future events. Can be run internally within an organisation as well as through industry led meetings, workshops and conferences. While the frequency of these training opportunities is a function of when such events occur, whenever practical the experience gained should be passed on as soon as possible after the event.

Where a dam owner operates multiple dams, it is worth considering involving personnel from different dams in combined training sessions. This helps build organisational wide growth in competencies through facilitating the transfer of ideas and experience.

As noted above, a high level of integrated and collective understanding is needed across all people that contribute and jointly share responsibility for dam safety. The following highlights some key areas where different levels within a dam owner's organisation hold responsibility around training and capacity building.

Table 1.12: Training Responsibilities

Personnel	**Training Responsibilities**
Governance	• Define key objectives for dam safety training across the organisation and monitor to ensure these objectives are met. • Provide enough time, capacity and opportunities for personnel to attend all relevant training sessions. • Participate in special event exercises and review the adequacy of capabilities and capacity and the effectiveness of the organisation's governance structure under such events. • Allow personnel to prepare, attend and present their experiences to others in the organisation and at industry forums.
Performance	• Provide historical performance information that can be used as examples for training. • Participate in routine and targeted training to ensure they are fully aware of the relevance between performance data and information and how it can identify issues with dam performance. • Participate in special event training and exercises responding to requests for information from the event team as they would in a real event. • Following actual events, review performance data and pass on any learnings to others and gaps in existing performance monitoring systems.
Operational	• Undertake routine and targeted training and proactively provide feedback on the relevance of the training and how it might be improved. • Participate in special event exercises and in doing so review where operating procedures do or don't work effectively. • Following actual events or incidents, document lessons learnt and seek ways to pass on their experience to others.
Technical Support	• Provide input into the development of routine training programmes especially around why each aspect of training is important for dam safety. • Contribute to the content and at times attend targeted training sessions to pass on knowledge but also to increase their understanding of operational aspects. • Participate in special event exercises providing specialist technical input and review of system and procedural performance. • Following actual events work collaboratively with operational and performance staff to produce and deliver experience and learnings to others.

1.5.3 Record Keeping & Documentation

All dams must have a reliable record and documentation system.

Preparing and maintaining comprehensive records and associated documents is a core component of good dam safety management. A robust system for record keeping should be established very early in the dam investigation and design stage. Good record keeping is also logical on a financial basis as the cost of re-establishing lost information is substantial.

There are several core reasons why maintaining good records is important as described in Table 1.13.

Table 1.13: Purpose of Record Keeping

Reason	Commentary
Periodic Reviews	It is good practice for dam performance against current design criteria to be periodically reviewed (refer Module 2, Section 2.4 and Module 3, Section 3.2). To be undertaken effectively, these reviews need access to comprehensive investigation, design and operational records.
Incidents & Emergencies	When dam safety incidents or emergency events occur, there is almost always a need to access core documentation relevant to that particular event.
Upgrades & Rehabilitation	Throughout the life cycle of the dam there is likely to be the need to undertake upgrades, enhancements of rehabilitation work (refer Module 2, Section 2.4). Having access to original investigation and design information makes the assessment and design of any upgrade or rehabilitation easier and more cost effective.

The nature and extent of records and documents through the development, construction and operation of a dam can be extensive. Through the operational life of the dam many documents will be revised and updated, such as design solutions during the development phase and operational procedures during operation life, while new information will be recorded. Wherever practical, previous versions should be retained but clearly identified as being superseded.

As well as recording the nature of any changes adopted between subsequent versions, the reason why the change was adopted needs to be recorded. It is important for people in the future to be able to understand why changes over the original design or operational intent have been adopted.

It is important that records of good performance are kept as well as any unusual or anomalous performance. The frequency of monitoring, surveillance and performance testing is stated in Module 3, Section 3.1. Unless the instrument is no longer reliable or necessary for dam safety monitoring, the instruments and systems that show stable and reliable performance must continue to be monitored and recorded because they provide a benchmark against which unusual results from other components can be compared.

In broad terms the nature and content of records and documentation is summarised in Table 1.14.

Table 1.14: Type and Content of Record

Records & Documents	Typical Content	Commentary
Investigation and Design (Ref. Sec 2.3 and 2.4)	• Core investigation data and conclusions (e.g. geological, hydrological). • Design loadings, criteria, assumptions and decisions. • Performance expectations. • Verification requires during construction and first reservoir filling.	The greatest volume of data, information and documentation will be produced through the various design stages and iterations. This provides a fundamental benchmark against which future performance, deficiencies and rehabilitation can be tested and verified.
Construction and First reservoir filling (Ref. Sec 2.5 and 2.6)	• Verification of and, variation from, design assumptions. • Design variations. • Detailed construction records and documentation including as-built drawings. • Detail of monitoring and surveillance instrumentation installations • Performance records during first reservoir filling and any actions taken to address anomalies. • Photographic Record.	This also forms a large portion of all records a dam may ever have. Of critical importance are the details around variations made to the design as construction progresses. This includes the reason why the variation was required and any implications on anticipated operational performance. Comprehensive and accurate as-built drawings are one of, if not the most important records a dam will ever have. The monitoring records of first reservoir filling are an important benchmark for future performance reviews and in the event that adverse performance trends are identified.
Operational (Ref. Sec 1.4)	• Operational data (e.g. lake level, inflows, discharges etc.) • Monitoring and surveillance data. • Performance deviations from expected limits. • Performance records during large events such as floods. • Performance test data (e.g. gate testing)	Most of these records are routine and repetitive. Overtime they provide a valuable picture of what normal performance looks like and hence abnormal performance can be identified. Performance testing (e.g. gates) gives an indication of reliability and hence informs decision making around risk management.
Maintenance (Ref. Sec 1.4)	• Component condition records pre and post maintenance. • Comparative maintenance needs between similar components (e.g. similar gates) • Unusual wear or damage. • Instrumentation repairs and maintenance. • Photographic record	This information will also accumulate and become more valuable as the history builds. This information provides a record of what has been required to keep each dam component operating. They indicate areas requiring disproportionately high maintenance needs and hence are potentially underperforming.
Reviews (Ref. Sec 3.2)	• Physical performance against design assumptions and current criteria. • Adequacy of systems and procedures. • Capacity and capability of personnel. • Performance during incidents and emergencies.	Periodic reviews (whether targeted at a specific issue or broadly considering the entire dam and its operations), provide an important assessment of historical performance to that point in time.

Records & Documents	Typical Content	Commentary
Incidents and Emergencies (Ref. Sec 3.4)	• Performance outside normal operating conditions. • Performance of procedures and plans • Details and purpose of repairs and upgrades. • Photographic record	A dam is not completely 'commissioned' until it has been subjected to all the anticipated design loads and scenarios. Incidents and emergencies provide verification of performance that is often unable to be undertaken during first reservoir filling and subsequent operations.
Upgrades and Rehabilitation (Ref. Sec 2.4)	• Dam aging and deterioration over time. • New or revised performance expectations • New operational procedures • Photographic record	Dams will require upgrades and rehabilitation work. These often provide an opportunity to inspect, assess and document dam conditions and performance in areas not normally accessible.

1.5.4 Data Quality & Management

All dams must have a reliable data management and quality system.

The recording and management of data is an integral aspect of performance monitoring for dam safety during the all phases of a dam's life. During investigation and design, data is used to develop design loading and solutions. Throughout construction, data is used to verify that the construction is achieving design requirements. Along with surveillance, it is essential for verifiable performance monitoring during first reservoir filling, commissioning of components and on into operational life stages.

Errors or poor data quality therefore impact on the ability to achieve and confirm performance. The nature of instrumentation and data capture in and around dams often means that standard data quality and verification checking is more complex. Sources of data including instruments are often buried within the structure or unable to be retrieved for testing and calibration under controlled conditions. Similarly, the data is typically difficult (if not impossible) and expensive to replicate. This means a broader approach is required to determining and managing data quality.

Methods of assuring data quality are described in Table 1.15.

Table 1.15: Data Quality

Reason	Commentary
Verification Instruments	These are secondary measurement systems against which the primary instruments performance can be verified. Ideally, they are simple, robust and frequently measured by manual methods. Examples include; • A water level stage boards against which lake level transducers can be checked. • Fixed marker plates against which gate position instruments can be checked
Cross instrument verification	Once enough data history is accumulated, it may be possible to check the performance of one instrument against a different one because they normally respond in a similar and repeatable way. Where a different response occurs, this may indicate a data quality issue with one or both instruments. Examples include; • A drain flow may show a repeatable pattern when compared to a water pressure transducer. • A dam tiltmeter shows a repeatable pattern compared to reservoir level.
Self-Verification	For some instruments it may be possible to establish verification points against which an instrument will show a repeatable record for the same value. Examples include; • Water pressure measurements that stabilise at repeatable levels corresponding to a given reservoir level. • Drain flows that always respond above a given lake level or following more than a certain amount of rain.
Instrument testing.	Some instruments can be tested in-situ by manually inducing a change and seeing if the instrument responds appropriately and then returns to the original reading following the test. Examples include; • Bailing out standpipe piezometers and monitoring the reestablishment of a stable level. • Lifting pressure transduces by a fixed amount and recording the measured response.
Multi trend-based verification	Modern data analytical and management packages have sophisticated algorithms and tools that can identify anomalies in instrument performance through comparison with other instruments as well as the instruments own history. While these may not directly indicate an instrument performance or data quality issue, any anomaly identified can then be investigated further by relevant technical specialists.

1.5.5 Knowledge Security & Transfer

All dams must have secure information management and retrieval system.

The safe keeping and protection of all records is vital to enable their retrieval and use when needed in the future and protect the significant financial and resource investment made in obtaining them. The cost of securely storing and providing backups of data, records and documents is very small when compared to the cost (if even feasible) of re-establishing them.

As with physical and digital data, the experience of personnel is equally vital to retain and pass on. This is particularly challenging when the first generation of operators and technical personnel, those that were there from first reservoir filling, start to retire from the dam owner organisation. It is impossible to directly replace a person who has years of direct experience with a dam, its history and operation. Rather it is about establishing an integrated net of people combining depth and breadth of experience. This is likely to include a combination of internal and external resource.

For all aspects of knowledge and knowledge security Table 1.16 outlines broad attributes need to be incorporated in the management system.

Table 1.16: Purpose of Record Keeping

Attribute	Commentary
Local and remote storage	A common source of knowledge loss, particularly with data, is between the recording site and the permanent storage location. Storing a copy of the data at the location of recording, even temporarily, can significantly reduce these losses.
Backups	This is a primary means of providing knowledge security. This includes backups of digital data, physical records and having multiple people with complementary or overlapping experience.
Different media	For some components it is advisable to adopt different storage media. For example, even with modern digital drawings having hard copies can significantly increase the resilience of knowledge management.
Independent Specialists	Utilising external independent specialists has two beneficial aspects. They hold knowledge of the dam in parallel with internal staff. They also bring outside experience that complements existing internal knowledge.
Industry Representation	Being involved in industry forums and technical groups provides a collective knowledge base that no single dam owning organisation could hope to replicate.

1.5.6 Staying Current

While a dam can be expected to exist for hundreds of years, platforms and systems used for knowledge management and security won’t. Similarly, new monitoring systems and instruments provide opportunities to further refine the understanding of how a dam is performing and more importantly will perform into the future.

Reviewing new technology and systems and how they may enhance, augment or replace existing systems is worth doing at an appropriate frequency. This often occurs at times of significant maintenance, upgrade or rehabilitation.

Table 1.17: Knowledge Management in to the Future

Issue	Commentary	Example
Obsolescence	A key challenge is knowing when a component or system is obsolete. When is the best time to retire an existing system even when it may still be meeting current need?	A data management system may still fulfil current need, but the database is no longer supported. At some time in the future the data will become difficult to transfer to a new system. Upgrading early would reduce this risk.
Redundancy	Reviewing the balance between quality instrumentation versus redundancy is another area that should be periodically considered. The conventional approach is to invest in high quality reputable instruments however with the availability of cheaper alternatives installing duplicate copies may be preferable.	Three pressure transducers could replace a single reservoir level recorder. This allows cross-verification of performance and provides redundancy if one fails.
New Technology	Provides opportunity to examine aspects of dam performance at an accuracy and frequency that may have been difficult, expensive, if not impossible, previously.	Advances in drone technology allow remote aspects of a scheme and catchment to be observed more frequently and safely than classical methods.

2.0 Module 2: Investigation, Design and Construction

This module provides a framework that can be used for the investigation, design, construction and first reservoir filling of new dams, the analysis of existing dams, and the design of rehabilitation works for existing dams.

The framework must include an integrated Geohazard Assessment (IGA) which should be carried out and updated during all phases of the development of dams, so that the upstream catchment is included in relevant investigations.

Investigation and design guidance in Sections 2.3 and 2.4 draws heavily on DHPS (2018) “Guidelines for Development of Hydropower Projects Part II Section A: DPR Preparation, Technical Aspects” [5].

Guidance on technical aspects of construction in Section 2.5 similarly draws heavily on DHPS (2018). “Guidelines for Development of Hydropower Projects Part III Section D: Construction Phase – Technical Aspects” [6].

First reservoir filling is not covered by the DHPS Hydropower Guidelines so Section 2.6 is an important addition to existing guidance material.

2.1 Introduction

The Designer’s objective is to design a dam and its associated structures in a manner that suitably reflects the characteristics of the site, the loading conditions applicable to the site, and the consequences of dam failure. The Designer must demonstrate that the design has considered all hazards, and the threats that arise from those 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 structure can be constructed safely and the completed structure can be safely operated and maintained, and
- the completed structure will meet durability requirements, and achieve the specified intended life for the structure.

The Designer must consider not only 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.

Robust and resilient features and systems are recommended 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. Standards-based design is the usual first step in dam design but these methods do not cover all conditions that the entire dam at the site could experience. Resilient features that provide defence against unexpected or unplanned situations will improve the reliability of the design. Figure 2.1 shows these concepts. Potential Failure Modes are a key step in identifying what needs to be addressed outside conventional standards-based design.

Dams typically have a long operational life. Interventions and upgrades following first reservoir filling 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, where possible, be readily replaceable without compromising the safety of the dam.

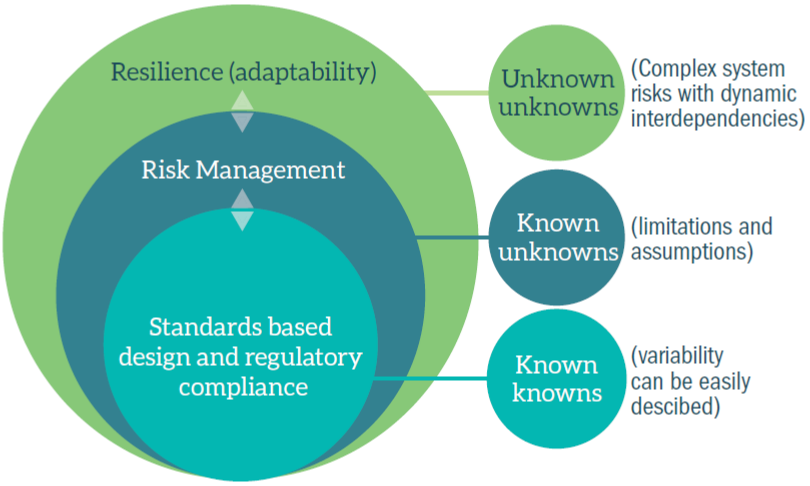


Figure 2.1: Risk and Resilience in Design to cover Gaps in Standards-based Practice (adapted from NZSOLD [6])

While the following information is directed primarily at the investigation, design and construction of new dams, the hazard descriptions and design methods are equally applicable to safety assessments of existing dams.

2.2 Hazards and Consequences

Natural hazards and associated consequences, that can affect dam safety must be identified and considered in the investigation, design and construction of dams and appurtenant structures and reservoir area, including upstream and immediate downstream catchment. It is important to understand how the entire system in the catchment responds to certain external stimuli and events.

Natural hazards include floods and storms, earthquakes, landslides and debris. Natural hazards, and the threats that they induce, must be understood and the dam designed (or existing dam assessed) for the performance criteria outlined in Section 2.4, considering the consequence category determined in Module 1 Section 1.3.1 and the results of an integrated Geohazard Assessment (IGA).

Other threats to dam safety may arise from errors and omissions in design, inappropriate operation and inadequacies in specifications, construction supervision, maintenance and surveillance. These threats are mitigated by ensuring that:

- appropriately qualified persons undertake tasks,
- review processes and supervision are robust, and
- operation, maintenance and surveillance are undertaken in accordance with approved procedures and manuals.

Security breaches and sabotage are also potential hazards. These hazards are subject to controls specified by the dam owner and are not covered in these guidelines.

Floods and Storms

Flood estimation is a key dam safety input. The required design and check flood capacities are key parameters for the design of the spillway and the selection of appropriate freeboard for the non-overflow dam sections. Flood estimation is also a necessary input into the design and selection of the river diversion scheme for construction.

In addition to floods due to meteorological events, the potential in Bhutan for Glacial Lake Outburst Floods (GLOF) must also be assessed and, where required, provided for in the design flood passage capacity.

During such events large amounts of coarse debris are transported and reworked which can have impacts on the reservoir area and dam structures. This can result in significant effects in the catchment which must be taken account of in the design. Further information is referred to under section ‘Debris’.

Earthquakes

Bhutan is located in one of the most seismically active parts of the world, directly above the Indian – Eurasian tectonic plate boundary. Seismic load assessments are a key input for the design of the dam, appurtenant structures and the hydro-mechanical equipment.

Major earthquakes play a large role in generating many thousands of landslides across large areas and multiple catchments. A proportion of such landslides may form valley-blocking landslides with consequential impoundment of water on the upstream side. Such natural dams commonly fail within the first few days to months and may impound substantial volumes of water that would then be released in the form of Landslide Dam Outburst Floods with the attendant large volumes of coarse material. The discharge from such events can have the capacity to destroy major hydropower facilities.

The understanding of seismic hazard in Bhutan is still developing particularly in regard to probabilistic risk assessment. The Seismology Division of the Department of Geology and Mines was established in 2011.

Recent seismic hazard studies of relevance in Bhutan include:

- World Bank, 2014. Seismic Risk Assessment in Thimphu Bhutan [7]
- University of Bristol, 2018. Building Resilience to Earthquakes in Bhutan: A Probabilistic Seismic Hazard Assessment to inform the National Building Code [8]

- Safety of Dams and Downstream Communities, Technical Notes 3 Seismic Risk, The World Bank Group., 2021

Landslides

Creation of a reservoir with an unstable (or potentially unstable) slope influenced by the reservoir may both affect its stability and increase the consequences of failure. With the reservoir full, or being filled, the risk increases from slope failure into a valley to that of failure into a body of water. In the event of rapid failure, impulse waves or flood waves from reservoir landslides may overtop and damage the dam which can have effects that extend beyond the confines of the reservoir. This can endanger public safety over a large area adjacent to the reservoir and downstream from it (ICOLD Bulletin 124 [9]).

It may also be possible for a landslide to block a reservoir and create a landslide dam. It is essential to understand the geology and geological structures within a catchment, not only at the site of a hydropower scheme. These can indicate the susceptibility within the catchment to form landslides and their probable size and dependence on the impacts of climate change (e.g., rain-induced landslides). The river downstream of the landslide will, most likely, dry up until a lake forms behind the landslide. The risk then becomes the effects of failure of the landslide, including damage to the dam downstream and threat to the community downstream of the dam. The lake formed behind the landslide may also flood land at elevations not previously flooded by the reservoir. (See also regarding earthquake-triggered landslides and landslide dams under the section on earthquakes above).

Landslides within some distance downstream of a dam may result in impacts that can affect the upstream hydropower facility, such as by submergence following impoundment of water behind a downstream landslide dam.

Debris

Large accumulations of debris can potentially block spillways and intake structures, jam gates and impede reservoir discharges. The potential for this is dependent on the amount of forest in the reservoir and the catchment. First filling of the reservoir often produces a lot of floating debris.

In the event of a Glacial Lake Outburst Flood (GLOF) or a Landslide Dam Outburst Flood (LDOF), in addition to very large volumes of coarse rock debris and mud, etc., within the water flood, if the flow traverses heavily forested areas, the flood will incorporate large tree trunks and associated vegetation. The momentum of a major flood, especially with a large amount of debris, would destroy a log boom. The presence of large numbers of tree trunks in the Luggye Tsho GLOF in Bhutan in 1994 caused the river to divert through Punakha resulting in the loss of 21 lives. In relation to coarse rock debris, this can include boulders many metres in diameters. The percussive effect of such boulders can be substantial. Water reservoirs can easily be filled by coarse debris in a matter of a few hours.

The potential for debris to accumulate at the dam needs to be assessed and where necessary taken into account in the selection of the spillway type, gate selection, orientations of log booms and a debris removal programme.

Multiple Hazard Scenarios

Scenarios with multiple hazards and possible complex cascading processes should be considered as detailed in the above descriptions and based on the outcome of the Integrated Geohazard Assessment (IGA).

2.3 Investigations

2.3.1 Topographic Survey and Mapping

Topographic maps are essential for the investigation and design of a dam. Maps at various scales will be required to cover the upstream and downstream catchments, reservoir, the site area and the downstream river channel. Ground control points will be needed for the control survey. Topographic information of the river valley in the upstream and downstream of the dam is also required for assessing the effects of a potential dam breach and the consequences of significant processes originating within the upstream catchment and their prospective impacts on the reservoir and dam infrastructure such as a GLOF or a LDOF, as well as what would happen in the event of a dam breach on the downstream riparian communities and environment.

Detailed guidance on topographic survey and mapping requirements for hydropower projects is given in DHPS Hydropower Guidelines Part II [5]. This information can be readily adapted for any dam project.

2.3.2 Hydrology and Flood Estimation

Hydrological information is the basis for development and operation of dam and reservoir projects. Hydrological and meteorological data is also utilised for flood estimation and the assessment of freeboard requirements. The flood estimates required for the design and assessment of the spill capacity of the dam are outlined in Section 1.3.2.

Large and Intermediate Classification dams will require the determination of the PMP and the PMF. Procedures for the development of the PMP and PMF suitable for use in Bhutan are given in DHPS Hydropower Guidelines Part III [6]. This information can be readily adapted for any dam project. Guidance is also given on the estimation of the GLOF where this is applicable.

Where multiple hydropower schemes are built as part of a cascade along a reach of the same river, their respective hydrological analyses of the upstream catchment should be broadly similar for the areas of the catchment that overlap. However, in the light of the other component analyses, it might be useful to undertake a more refined hydrological analysis of either the entire catchment, or selected sub-basins, to generate better hydrological models. Key to this also will be the results of the glacial hazard assessment in terms of GLOF magnitudes and behaviour. Maximum hydrological flows occur during the monsoon period, and 80 per cent of GLOFs happen during the same period [Richardson and Reynolds, 2000], The role of integrated geohazard assessments in disaster risk management, International Journal of Hydropower & Dams, 2003] so it is plausible to have a pluvial flood occurring at the same time as a GLOF. Heavy rain can often trigger processes that initiate GLOFs. It is also important to note the presence of engineered structures within the river systems present in the upstream catchment. These can, by their very design and presence, modulate river flows; they can also act as impediment barriers to flood and sediment flux events. Thus, the river systems may not be unconstrained open-channel flow regimes, and this can have implications for hydrological run-off modelling.

2.3.3 Geological and Geotechnical Investigations

Bhutan is located in the Himalayan Mountains along the boundary between the collision of the Indian and Eurasian tectonic plates. This means that the rock formations are faulted, folded and sheared and that it is high seismicity environment. Research is still ongoing into the structural geology and seismic hazard in Bhutan.

As part of an Integrated Geohazard Assessment the investigations should include a regional geological analysis, landslide susceptibility mapping, Neo- tectonic provinces and seismicity, and event mapping and subsequent process identification as described in Reynolds, The role of integrated geohazard assessments in disaster risk management, International Journal of Hydropower & Dams, 2023.

Soundly executed geological and geotechnical investigations are therefore particularly important in managing the geological and geotechnical risks associated with the development of dam and reservoir projects. The dam type must suit the geological conditions of the site and the materials available to build the dam. The initial planning of the investigation programme must consider the key geological issues associated with the rock masses present in the project area and the associated geotechnical questions. A particularly useful explanation of these issues and questions is given in ‘Geotechnical Engineering of Dams (Fell et al, 2005) [10].

Detailed guidance on the development and staging of geological and geotechnical investigations through to feasibility level design of hydropower projects is given in DHPS Hydropower Guidelines Part III Section 5 [6]. This information can be readily adapted for any dam project.

DHPS Hydropower Guidelines Part III [6] notes that the investigation plan may need to be modified due to unexpected geological conditions or if the project layout is modified. This reference also contains information on the investigation methods and the field and laboratory testing applicable to various ground conditions and project structures.

For dam safety purposes, the geological and geotechnical investigations of the dam and reservoir must determine and document:

- the nature and properties of the dam foundation and abutments;
- the characteristics of the groundwater systems present near the dam site;
- the strength and durability properties of the soil and rock materials used in the dam construction;
- the stability of slopes adjacent to the dam and within and above the reservoir rim;
- the characteristics of any natural barriers forming glacial lakes in the catchment area upstream of the dam; and
- the seismicity of the region and the presence of any active faults in the dam foundation or crossing the reservoir.

Investigations need to be relevant and relate to the conditions of the site as follows:

- Choose suitable techniques for the materials present.
- Use a range of techniques to validate the information coming from each technique. For example, validate foundation boundaries identified by geophysical tools with boreholes.

Unexpected foundation conditions may cause re-consideration of the dam design in order to ensure that dam safety requirements are still met.

Documenting Geotechnical Investigations

Documenting geotechnical information is vital to ensure developing knowledge of the project geology, hydro-geology, natural hazards and engineering materials are being retained for the record and passed to other parties participating in the project and operating the completed facility into the future. This will reduce the risk of errors and omissions as the project advances. Furthermore, documented geotechnical details become the baseline evidence during any contractual disputes between the constructor and the dam owner. Records can be compiled many ways but the following are recommended allocations of documentation:

1. **Geotechnical Data Reports (GDR)**, The GDR is the factual report prepared by geologists to contain all the raw data from investigation, such as borehole logs and laboratory results. If geotechnical hazards are known, they should also be included. GDRs are intended to provide enough information to reduce the risk for projects and transfer factual information to the Contractor.

2. **Geotechnical Baseline Reports (GBR)**: The GBR is prepared by geologists to provide a summary of anticipated ground and groundwater conditions for the purpose of understanding the risks directly applicable to the project. The GBR can be used for defining anticipated ground conditions which helps in allocation of risk in the proposal and bid preparation process for projects and during contract pricing. The GBR is prepared from geotechnical data reports and requires care in preparation particularly when the foundation is highly variable. Geotechnical baseline reports may reduce construction costs and minimize disputes over unforeseen ground conditions.

3. **A Geotechnical Interpretative Report (GIR):** The GIR is prepared by qualified engineers and geologists to translate the factual report information for geotechnical analysis. For example, carrying out rock mechanics analysis to estimate foundation strength properties. Expert judgement is likely necessary in developing conclusions in these reports.

These reports must clearly differentiate between factual data and interpretation. The GBR in particular must clearly state what geotechnical risk is borne by the Developer and what risk is borne by the Contractor. This has a direct impact on the contractual environment during construction. Challenging ground conditions would make the GBR far more important than at a site with a consistent good quality dam foundation. Strong capability within the Developer and their designer is more important when more complex site conditions are present.

2.3.4 Seismic Hazard

The assessment of seismic hazard in Bhutan is an area of current research and development. The increasing use of probabilistic methods for determining seismic hazard is assisting in the characterisation of the applicable earthquake generating sources and their seismicity and the choice of suitable ground motion prediction equations.

In the event that active faults are identified in the dam foundation it is preferable to re-position the structures away from the fault if at all possible. It is very difficult to construct concrete dams across active faults such that fault movement can be safely accommodated by the structure, hence concrete dams across active faults are not generally recommended. It is possible to construct embankment dams across active faults but they must be carefully engineered (under advice from international experts). If an active fault is discovered under an existing dam, then international experts should be engaged to advise on engineering mitigation to make the dam more resilient to fault movement.

If active faults are present in the reservoir area, the effect of fault movement and seiches (earthquake induced waves) will need to be assessed for their effect on the safety of the dam.

Investigations to support seismic hazard assessment include:

- assembling information on the regional geologic and tectonic setting,
- assembling information on the geologic and tectonic setting of the project area,
- mapping of the geology and faults in the project area,
- where necessary conducting detailed investigation of the age and characteristics of fault movement, and
- assembling information from available seismic catalogues on past earthquakes,

The utilisation of this information to perform deterministic and probabilistic seismic hazard analysis is an area of specialist expertise and the engagement of suitably experienced advisors to perform the seismic loads analyses required for structural design is recommended. Many of the investigation steps listed above also require experts in the required field.

Guidance on seismic hazard assessment methodology is available in references such as:

- ICOLD Bulletin 52. Earthquake Analysis for Dams. [11]
- ICOLD Bulletin 123. Seismic Design and Evaluation of Structures. [12]
- ICOLD Bulletin 148. Selecting Seismic Parameters for Dams – Guidelines. [13]
- Safety of Dams and Downstream Communities, Technical Notes 3 Seismic Risk, The World Bank Group., 2021

The seismic loads required for structural design are given in Section 1.3.3.

2.4 Design

This section provides an overview of design requirements for concrete dams and embankment dams. Detailed design steps are located in a number of design guidelines/manuals. The DHPS Hydropower Guidelines Part II Section A: DPR Preparation, Technical Aspects” [5] is a good starting point, noting that these were written for preparation of the Detailed Project Report (DPR), and do not cover all aspects of dam design. A variety of detailed design guidelines/manuals from international bodies can be referred to, including those listed in Section 2.4 below.

2.4.1 General Requirements

From a dam safety perspective, the design of the dam and its appurtenant structures must:

- conform to established dam engineering principles and use recognised and accepted dam design methods;
- meet the required performance standards for stability under the applied loads;
- meet the required performance standards for flood passage;
- where practical and economic and supported by failure modes assessment, provide secondary lines of defence within the design arrangements;
- accommodate inadequate performance of features such as drains and pumps;
- be built of durable materials that with planned maintenance will maintain their function for the planned design life;
- be able to be safely operated and maintained by the dam personnel;
- include an assessment of potential failure modes to both inform the designers; and
- utilise the failure modes assessment to equip the dam with instrumentation to provide warning of unfavourable performance.

Discharge facilities will need to be provided for:

- dam safety releases (appurtenant structures such as spillway, low level outlets),
- power station operation (turbines), and
- environmental flow release (a low level outlet capable of continuous discharge during first reservoir filling and power station outage to prevent fish stranding).

Foundations and Abutments

In the performance of dams around the world, foundation defects have been a major contributor to dam failures. Geological and geotechnical investigations are important risk mitigation steps if they provide accurate information on the nature and properties of the dam foundation and abutments.

Particular risks associated with foundations in sediments include:

- highly compressible materials,
- loose materials susceptible to liquefaction,
- weak materials,
- dispersive materials,
- coarse materials which can provide pathways for leakage and internal erosion and,
- broadly graded materials that are internally unstable under seepage flows.

Particular risks associated with rock foundations include the presence of:

- soluble rocks,
- pervasive open joints with erodible infill that can develop into seepage paths,
- persistent joints, shears and faults that can control the strength of the foundation and,
- landslides that can affect the dam abutments.

The stability of any dam is dependent on the provision of foundations and abutments that with appropriate engineering treatment:

- are stable and have sufficient stiffness,
- control seepage flows and piezometric pressures to acceptable limits,
- prevent erosion of materials into the foundation, and
- are themselves durable and not subject to degrading over time.

An essential feature of the design is the development of appropriate foundation treatments to ensure the control of seepage and the stability of the dam and abutments. Such treatments are often specific to the dam type and include:

- consolidation and curtain grouting,
- cut-off walls,
- drainage curtains,
- slush grouting of open joints,
- excavation and concrete treatment of shear and faults, and
- trimming of the foundation profile and the infilling of steps in the excavation.

ICOLD Bulletin 129 [14] provides descriptions of dam foundation treatments and their applicability.

A range of investigation techniques are likely necessary to develop the geological and geotechnical model of the dam site. Techniques to consider include:

- Surface mapping by geologists to identify joint, shears and faults that may impact dam design.
- Test pits and trenching to allow retrieval of large samples and map soil / rock profiles and jointing patterns.
- Borehole drilling to retrieve core samples. These should target potential geological features and may not necessarily be vertical.
- Downhole pressure tests in the boreholes to determine seepage transmission at various depths.
- Geophysical surveys to determine sub-surface profiles based on shear wave velocity.
- Geophysical tests to determine parameters for structural analysis (e.g. shear modulus).
- Monitoring of groundwater levels, seepage and deformation of slopes.
- Shear tests of samples of rock to determine shear resistance of foundation under dam loads.
- Atterberg and shear tests to determine engineering properties of soils.
- Lineament mapping to deduce active lineaments. Field in-situ tests in exploratory drift to determine the in-situ properties of rock mass.

Investigations for the DPR are described in 2018 DHPS “Guidelines for Development of Hydropower Projects PART II Section A” [5].

Fell et al (2005) [10] also provides guidance for dam investigations.

2.4.2 Concrete Dams

Types of Concrete Dam

There are five main types of concrete dam:

i. Concrete gravity dam; relying on the weight of the structure to withstand the applied loads.
ii. Arch dam; utilising abutments to take thrust from the arch form.
iii. Gravity-arch dam; a combination of the above two forms.
iv. Buttress dam; with stiff thick concrete buttresses supporting an upstream concrete slab facing.
v. Hardfill dam; referred to in some countries as “cement-sand-gravel” (CSG) dams. These dams are shaped more like an embankment dam and use a fill with low cement content protected by a high quality concrete surface on the upstream and downstream face.

There are two main types of construction used which relate to the equipment used for construction. These can be used for each type of dam listed above, although RCC is rarely used for arch dams.

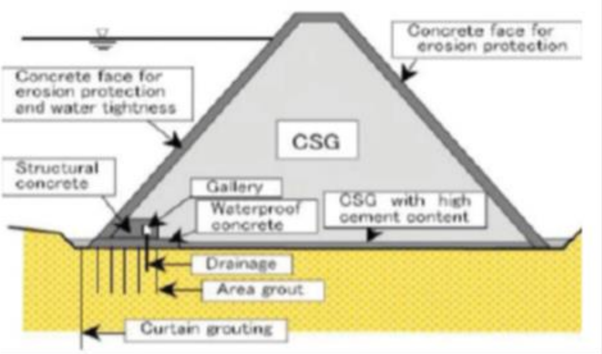
i. Mass concrete (Conventionally vibrated concrete (CVC)) where normally mixed concrete is placed in thick layers against formwork and compacted with regular concrete vibration tools.

ii. Roller compacted concrete (RCC) where a lean dry concrete mix is placed and compacted in thin layers using road construction equipment.

Gravity Dam

Arch Dam

Buttress Dam



Cement-sand-gravel example of Hardfill Dam

Figure 2.2: Examples of Concrete Dam Types

<u>General Considerations</u>

The selection of a concrete dam must take into account:

- Valley shape. For example, narrow steep valleys in good quality rock will be attractive for arch dams. The crest length/height ratio of the dam should not exceed 2.0 if an arch dam is being considered.

- The availability of suitable materials for the manufacture of concrete. In particular the availability of aggregates that will not degrade in manufacturing of concrete, or degrade over time through chemical breakdown (e.g. alkali silica reactivity (ASR)).

- The strength, permeability and compressibility properties of the dam foundation. Important considerations include:
  - High modulus (i.e. low deformability) foundation and abutments will be necessary for an arch dam. Low strength dam foundations will not be suitable for an arch dam.
  - Modulus of rock will still be important for a gravity dam to prevent excessive deformation. A gravity dam will require a very broad footprint on a low strength dam foundation.

  - Rock at the site that has been folded may have pervasive weak shears. If these are adversely oriented, they may form low strength sliding surfaces under the dam or wedges of rock in the abutment that could move under load. If these affect the dam stability, they will require removal or mitigating works such as shear keys or buttresses.
  - Soil foundations are unlikely to be suitable for a concrete dam, although dense alluvial foundations can be suitable.
  - Foundations with permeable zones (open joints or clay infilled joints in rock) require special attention for the seepage control measures (e.g. grout curtains or cut offs). The clay infill joints may become future leakage paths sometime after reservoir filling and so consideration of methods to block the potential seepage paths is needed.
  - The time required for foundation treatment affects the time required for construction.

- Climate – it is difficult to construct concrete dams in very wet or freezing conditions. Construction may have to cease in adverse weather.

Basic Technical Requirements

The basic technical requirements for a concrete dam are:

- The dam, foundation and abutments must be stable under all static and dynamic loading conditions.
- Significant confidence is required in the stability of abutments and low deformability of the foundation.
- Seepage through the foundation and abutments must be controlled and monitored to ensure safe operation. Seepage control measures include foundation cut-offs (most commonly a grout curtain), foundation contact treatment, drainage, and relief wells to keep uplift within acceptable limits.
- The spillway and outlet capacity must be sufficient to control reservoir discharge in extreme events.
- Construction practices need to consider in detail the necessary steps to reduce the risk of cracking in the concrete (e.g. mix design, lift height, heat of hydration temperature control, contraction joint locations etc.).

It may be acceptable for the dam to overtop in extreme events but this should be avoided if possible. If overtopping does occur the stability of the dam needs to be checked for excess reservoir level and the downstream toe area needs to be protected from scour. Dam equipment should be protected from damage for the full range of reservoir discharge, including when the reservoir level drops and dam safety critical equipment is still operable.

Defensive Design

The provision of defensive measures in the dam design improves the ability of the dam to withstand extreme seismic loads or accommodate flaws in the dam's construction. Potential failure modes should be addressed and mitigated by the defensive design measures. Defensive measures include:

- Removing or treating foundation materials that are low strength or potentially erodible.
- Shaping the foundation to avoid abrupt changes in profile, overhangs or steps.
- Shaping the dam to avoid significant changes in cross-section geometry or alignment.
- Avoiding siting critical equipment in prominent positions on the dam crest (to reduce earthquake damage).
- Including shear keys between concrete elements to ensure structural behaviour is uniform.
- Providing freeboard to reduce risk of overtopping.
- Considering if low level outlets can be used effectively to lower the reservoir level after an event (this is highly recommended if it is possible).
- Protecting the toe area from overtopping flow damage (if this is likely).
- Providing substantial drainage to control seepage pressures under all load conditions.
- If the concrete structure has an interface with an earth structure, sloping the concrete face in contact with the earth dam to provide a contact surface even if the earth dam settles.
- Provide a system to manage floating debris.
- Design areas for high abrasion due to suspended sediment and moving rocks.

The dam layout (location of spillway, powerhouse, low level outlets etc) needs to recognise the hazards and threats that could impact the site. Debris passage for example could be improved depending on the location of spillway gates and type of gate (e.g. flap gate). Outlets at lower levels are unlikely to be suitable for passage of debris, but these outlets will likely have to pass sediment past the dam, so their location and design needs to ensure the outlet can perform its function and not be damaged by the passage of sediment and debris.

Loading Conditions for Design

Loading conditions for the design of concrete dams are presented in a number of guidelines and widely accepted manuals.

The loading conditions to be considered are:

- Normal loading conditions – those which the dam is expected to withstand during normal operation e.g. uplift from steady state seepage and stability with normal maximum water level.
- Unusual loading conditions – those which occur on an infrequent basis and for which minor damage is acceptable e.g. the spillway design flood, OBE or DBE.
- Extreme loading conditions – those associated with very low probability events and for which damage is acceptable but the reservoir and controlled release must be retained e.g. earthquakes at or near the SEE including post-earthquake stability and floods greater than the spillway design flood.

The load combinations to be considered for each of these loading conditions are shown in Table 2.1 below (from DHPS Hydropower Guidelines PART II Section A” [5]).

Table 2.1: Loading Conditions for Design of Concrete Dams

Loads	Load Conditions for Gravity Dams (including abutments and foundation)								
	Usual Load Case	Unusual Load Case						Static	Dynamic
	Reservoir filled	End of Construction	Drains Inoperative	Design Flood	Ice	Avalanche/ Mudflow	Operation Basis Earthquake	Check Flood	Safety Evaluation Earthquake
Self-weight	X	X	X	X	X	X	X	X	X
Water pressure, reservoir at normal operation level	X		X		X	X	X		X
Water pressure, min. tailwater level	X		X		X	X	X		X
Normal uplift, drains operative	X				X	X	X		X
Exceptional uplift, drains inoperative			X						
Water pressure, reservoir at design flood level				X					
Water pressure, tailwater level acc. to design level				X					
Uplift condition acc. to design flood water levels				X					
Water pressure, reservoir at check flood level								X	
Water pressure, tailwater level acc. to check flood								X	
Uplift condition acc. to check flood water levels								X	
Sediment design level (upstream)	X		X	X	X	X	X	X	X
Earth pressure (downstream)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)
Earthquake							X		X
Ice pressure					X				
Pressure from avalanche or mud flow						X			
Temperature changes	X	X	X	X	X	X	X	X	X

(X) means "if applicable / when indicated"

Stability Criteria and Minimum Stress

Global stability of concrete dams is assessed in terms of minimum factors of safety.

These minimum factors of safety require strength parameters to be chosen conservatively. If there are high levels of uncertainty in the parameters then higher factors of safety may be required. This is discussed in the referenced concrete dam design documents.

Stress within the concrete is also checked against maximum criteria. Generally tensile stresses are to be avoided (if possible) to prevent cracking. However under extreme loads tensile stresses may be difficult to avoid, but FERC guidelines [15] note that under intense dynamic loading a small amount of tensile stress can occur momentarily without cracking of the concrete.

The minimum requirements to be considered for each of these loading conditions are shown in Table 2.2, Table 2.3, and Table **2.4** below (from DHPS Hydropower Guidelines PART II Section A" [5]).

Table 2.2: Minimum Stability Criteria for Design of Concrete Dams

Load Case	Overall and Interior Stability		
	Sliding		Uplift γsf
	Cohesion γmc	Friction Angle $\gamma m\phi$	
Usual	3.0	1.5	1.15
Unusual	2.0	1.3	1.05
Extreme (static)	1.1	1.1	1.00

Table 2.3: Minimum Overturning Stability Criteria for Design of Concrete Dams

	Usual Load Case	Unusual Load Case	Extreme Load Case
Resultant Location	Middle 1/3	Middle 1/2	Within Base

Table 2.4: Minimum Stress Criteria for Design of Concrete Dams

Concrete Stress	Static			Dynamic	
	Usual Load Case	**Unusual Load Case**	**Extreme Load Case**	**Unusual Load Case**	**Extreme Load Case**
Compressive	$0.3 \cdot f'_c$	$0.5 \cdot f'_c$	$0.9 \cdot f'_c$	$1.3 \cdot 0.5 \cdot f'_c$	$1.3 \cdot 0.9 \cdot f'_c$
Tensile	0	$0.6 \cdot f'_t$	$1.0 \cdot f'_t$	$1.5 \cdot 0.6 \cdot f'_t$	$1.5 \cdot 1.0 \cdot f'_t$

As indicated above, a minimum Factor of Safety is not given for the extreme earthquake case. This is the practice outlined in FERC [15] and other international recommendations, which require that if sliding assessments indicate displacement occurs during the earthquake, then the Designer must assess the post-earthquake stability following the displacement. If the post-earthquake sliding factor falls below 1.1 there is a high likelihood of failure. Static stability after a post-earthquake after–shock has the same post-earthquake stability requirements.

Concrete Dam Design

The specific design steps for concrete structures to satisfy the above technical requirements and load and performance conditions are outside the scope of this guideline. Advice is available in the references and guidelines listed at the end this Section 2.4.2.

The extent of design calculation should reflect the size of the structure, its hazard classification and any hazardous conditions. Simplified methods are to be used initially, progressing to detailed analyses only if results are unclear or risks are high. Simplified analysis results are then to be used to validate more complex analysis.

The following steps are to be considered in concrete dam design:

Foundation Stability

i. Utilise the geological investigation to identify any adversely oriented shears, bedding planes or foliation planes.
ii. Determine from field and laboratory tests the shear strength of intact rock mass and any low strength surfaces.
iii. If considering an arch dam, determine the rock modulus from field tests. Apply arch thrusts to abutment rock to determine if deformations would be satisfactory.
iv. Develop wedge models based on geological findings using sliding shear strengths determined above and apply dam loads. Assess whether sliding stability criteria are met.
v. For new design make assumptions for uplift based on the drainage design. If no deliberate drainage beneath the dam block, assume a linear uplift profile under the dam block from reservoir level to tailwater level. If adequate drainage is installed, assume uplift of 1/3 the difference between reservoir level and tailwater level at the line of the drainage curtain.
vi. For existing dams consider both the theoretical uplift profile and the actual uplift measurements.

vii. Determine if global stability of dam block on foundation meets sliding and overturning stability criteria.

Abutment Design

i. Identify unfavourable geological defects that could form a wedge failure in the rock.
ii. Determine from field and laboratory tests the shear strength along geological defects in the rock mass. Determine the modulus of the rock using test equipment (e.g. jacking tests).
iii. Calculate stability of abutment blocks using actual wedge geometries and properties of the joint surfaces.
iv. Check that the abutment is not part of a landslide.
v. If the abutment is to receive thrust from the dam (e.g. an arch or a gravity-arch dam) then determine the deformation due to that load.
vi. Confirm that the abutments are not existing landslides.

Dam Block Design

i. Determine if two-dimensional sliding stability of dam block on horizontal construction joints meets sliding and overturning stability criteria.
ii. Calculate stresses in dam concrete and confirm they are less than criteria
iii. For arch dam determine stresses of 3-dimensional shape and confirm they are less than criteria.

Seismic Design

International guidance for seismic design acknowledges that at high seismic loads dam deformation may occur. Therefore, minimum Factors of Safety criteria are not considered during the earthquake, but displacement is estimated and post-earthquake static stability calculated and compared to minimum criteria.

Pseudo-static analyses may be sufficient for low hazard, low height, structures (under 10m high). Pseudo-static analyses are based on the peak ground acceleration of the earthquake.

For more complex analysis the Designer is to step through from pseudo-static to linear elastic analyses using response spectra. These analyses require computer software. Again, commence with two dimensional analyses (i.e. analyse the maximum 2-D cross sections). Output from two-dimensional analysis should be used to validate three-dimensional analysis results.

If dam block displacement occurs (i.e. sliding Factor of Safety is less than 1.0), a non-linear solution is indicated. Non-linear time history analysis should only be necessary if previous analyses are showing dam block displacement during the earthquake. Three dimensional analyses require time history acceleration records for upstream/downstream, cross valley and vertical components. Because each solution is unique, between three and ten different time histories should be run to provide a range of results.

Equipment on the dam (particularly the dam crest) need to be analysed for accelerations amplified from the base of the dam. Elements subject to cross valley loads (such as spillway piers), can be analysed for the peak ground acceleration.

Determine post-earthquake static stability after determining the state of the dam due to the earthquake. If dam block displacement has occurred, consider if residual strength properties should be used for the sliding plane beneath the dam block. Increased seepage pressures may develop under the dam resulting in increased uplift.

Apply an after-shock to the structure after these post-main shock conditions have developed. The after-shock is to be at least one order of Magnitude less than the main shock.

Concrete Dam Design Selected References

- DHPS Guidelines for Development of Hydropower Projects – Part I to Part III [16] [5] [6]
- FERC Engineering Guidelines for the Evaluation of Hydropower Projects, Revised Chapter 3 – Gravity Dams [15]
- ICOLD Bulletin 117. The Gravity Dam: A Dam for the Future. [17]
- ICOLD Bulletin 136. The Specification and Quality Control of Concrete Dams. [18]
- ICOLD Bulletin 157. Small Dams: Design, Surveillance and Rehabilitation. [19]
- USACE (2005). Stability Analysis of Concrete Structure [20]
- USACE Strength Design for Reinforced Concrete Hydraulic Structures [21]
- USACE Arch Dam Design [22]
- USACE Gravity Dam Design [23]
- USBR Design of Gravity Dams [24]
- USBR Design of Arch Dams [25]
- USBR Design of Small Dams [26]
- Fell et al (2005). Geotechnical Engineering of Dams [10]
- Weaver, K.D. and Bruce, D.A. (2007). Dam Foundation Grouting [27]

2.4.3 Embankment Dams

Types of Embankment Dam

There are many different types of embankment dam including:

- Earthfill Dams (with or without drainage zones)
- Earth Core Rockfill Dams (ECRD)
- Concrete Face Rockfill Dams (CFRD)
- Asphalt Face Rockfill Dams (AFRD)
- Asphalt Core Dams
- Geomembrane Face (GFRD) or Core Dams

General Considerations

The selection of an embankment dam must take into account:

- The availability of suitable materials, particularly those required for filter and drainage zones and, where applicable, core material.
- Climate – it is difficult to construct embankment dams in wet or freezing conditions. High rainfall and humid conditions favour CFRD, upstream sloping core rockfill dams or geomembrane faced rockfill dams. Climatic conditions may therefore affect the time required for construction.
- The strength, permeability and compressibility properties of the dam foundation have a major influence on the dam design including:
    - Low strength dam foundations require flat embankment slopes.
    - Sandy soils may be susceptible to liquefaction under earthquake shaking and require removal, densification or changes to the dam geometry.
    - Permeable soil foundations and foundations with permeable zones require special attention to seepage control measures.
    - Rock foundations that have been folded may have pervasive weak shears. If these are adversely oriented, they may affect the dam stability and require flat embankment slopes.
    - Foundations with deep compressible soils in all or part of the foundation require consideration of settlements and differential settlement. Settlement must be allowed for in the freeboard assessment and differential settlement may cause cracking requiring particular attention to filter and drainage design.
    - The time required for foundation treatment affects the time required for construction.
- Valley shape may also influence the selection of dam type e.g. narrow steep valleys with restricted access may favour CFRD with their simple zoning.

Basic Technical Requirements

The basic technical requirements for an embankment dam are:

- The dam, foundation and abutments must be stable under all static and dynamic loading conditions including rapid drawdown if applicable.
- Seepage through the dam, foundation and abutments must be controlled and monitored to ensure safe operation. Seepage control measures include impervious

upstream blankets, foundation cutoffs, core contact foundation treatment, suitable width impervious and filter zones, drainage zones and blankets, and relief wells.

- The provision of adequate freeboard to prevent overtopping by waves.
- The dam slopes shall be protected against wave erosion and erosion by surface runoff due to rain.
- The spillway and outlet capacity must be sufficient to prevent overtopping of the embankment during normal operation and floods.
- Discharge from the spillway and other outlets must not erode or undermine the dam body or spillway.

Defensive Design

The provision of defensive measures in the dam design improves the ability of the dam to withstand extreme seismic loads or accommodate flaws in the dam construction. Defensive measures include:

- Remove or treat foundation materials that may present problems.
- Shape the foundation to avoid abrupt changes in profile, overhangs or steps.
- Provide ample freeboard and a wide crest.
- Use wide core zones of plastic materials resistant to erosion.
- Provide wide filter and transition zones to accommodate deformation and ensure continued material compatibility between zones.
- Provide substantial drainage zones to control seepage under all load conditions.
- Where possible avoid penetrations of the dam core by culverts and conduits.
- Provide robust details including appropriate filter protection at all interfaces e.g. dam/foundation interface, dam/concrete structure interfaces, core penetrations.

Loading Conditions for Design

Loading conditions for the design of embankment dams are presented in a number of guidelines and widely accepted manuals.

The loading conditions to be considered are:

- Normal loading conditions – those which the dam is expected to withstand during normal operation e.g. steady state seepage and embankment stability with normal maximum water level.
- Unusual loading conditions – those which occur on an infrequent basis and for which minor damage is acceptable e.g. severe wave action, rapid drawdown of the reservoir and the OBE.
- Extreme loading conditions – those associated with very low probability events and for which damage is acceptable but the reservoir and controlled release must be retained e.g. earthquakes at or near the SEE including post-earthquake stability, floods greater than the spillway design flood.

The load combinations to be considered for each of these loading conditions are shown in Table **2.5** (reproduced from 2018 DHPS Hydropower Guidelines Part II Section A [5]):

Table 2.5: Load conditions for embankment dams

Loads	Load conditions for embankment dams (including abutments and foundation)								
	Usual Load Case		**Unusual Load Case**					**Extreme Load Case**	
								Static	**Dynamic**
	Reservoir empty (drained embankment)	**Reservoir at full supply level**	**End of Construction**	**Design Flood**	**Rapid Drawdown**	**Avalanche or Mudflow w/ impact**	**Operation Basis Earthquake**	**Check Flood**	**Safety Evaluation Earthquake**
Self-weight	X	X	X	X	X	x	x	x	x
Water pressure, reservoir at normal operation level		X				(X)	x		x
Pore pressures, reservoir at normal operation elevation		X			X	(X)	x		x
Water pressure acc. to design flood				X				X	
Pore pressure acc. to design flood				X				X	
Pore pressure before consolidation		(X)	X						
Earthquake							X		X
Pressure from avalanche or mudflow						X			

(X) means "if applicable / when indicated"

Stability and Deformation Performance Criteria

The stability of embankment dams is assessed in terms of minimum factors of safety.

These minimum factors of safety require strength parameters to be chosen conservatively. If there are high levels of uncertainty in the parameters, then higher factors of safety may be required. Fell et al (2005) provides guidance for these situations. If rapid drawdown occurs relatively frequently then the 1.3 factor of safety should be used.

The minimum factors of safety for static load cases are shown in Table **2.6**. This table is adapted from NZSOLD [4] and reflects those used by the Canadian Dam Association. The values are similar to those in USBR and USACE guidelines.

Table 2.6: Slope stability factors of safety for static load cases

Load Case	Slope	Minimum Factor of Safety[1,2,4]
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]
Check flood	Upstream and downstream	1.2 to 1.3

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.

The minimum factors of safety for seismic load cases are shown in Table **2.7**. This table is adapted from NZSOLD [4] and reflects those used by the Canadian Dam Association.

Table 2.7: Slope Stability Factors of Safety for Seismic Load Cases

Load Case	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

The methods and analytical procedures to assess material parameters and perform these analyses are described in Fell et al [27], NZSOLD [4] and FEMA 2005 .

Embankment Dam Design

The selection of a dam type and the design of embankment dams to satisfy the above technical requirements and load and performance conditions are outside the scope of this guideline. Advice is available in the following references and guidelines:

- FEMA Technical Manual: Conduits through Embankment Dams [28]
- FEMA Filters for Embankment Dams: Best Practices for Design and Construction [29]
- ICOLD Bulletin 91. Embankment Dams Upstream Slope Protection – Review and Recommendations [30]
- ICOLD Bulletin 92. Rock Materials for Rockfill Dams – Review and Recommendations [31]
- ICOLD Bulletin 95. Embankment Dams – Granular Filters and Drains [32]
- USACE Slope Stability [33]

- USACE General Design and Construction Considerations for Earth and Rockfill Dams [34]
- USBR Earth Manual [35]
- USBR Design Standards No. 13, Embankment Dams [36]
- DHPS Guidelines for Development of Hydropower Projects – Part I to Part III [16] [5] [6]
- Fell et al (2005). Geotechnical Engineering of Dams [10]
- Weaver, K.D. and Bruce, D.A. (2007). Dam Foundation Grouting [27]

2.4.4 Appurtenant Structures and Dam Safety Critical Equipment

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. 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 feasibility of a low level outlet to provide a means for reservoir lowering is to be considered in the DPR phase. While these features are to be installed if feasible, in some dams it may not be possible to have a feasible low level outlet.

Figure 2.3: Appurtenant Structures include spillway gates and gate lifting equipment

Design Loads

Design loads for an appurtenant structure relate to the function it performs, the asset it protects and the potential consequences if the structure fails.

Under normal conditions a closed gate would be expected to withstand static loads and then be capable of opening to perform its discharge function.

Low level gates, particularly those in tunnels need to be designed to withstand hydrodynamic forces from earthquake ground motions.

If a gate is required to operate post-earthquake, then the gate, its operating equipment and the structure supporting the gate must be designed for the same level of ground acceleration as the dam.

Design Considerations

The following points must be considered in design and review of appurtenant structures and dam safety critical equipment:

- Mechanical equipment for dam safety must be reliable for all operating conditions. Backup systems are important to operate the gate should the main operating equipment fail to operate. A second independent power source is required for operating the gate should the usual power supply fail.

- Flow induced vibrations can be an unexpected problem for equipment. ICOLD Bulletin 102 [37] includes a detailed discussion on flow induced vibrations and guidelines to limit flow induced vibrations.

- Rate of gate opening must be faster than reservoir rate of rise.

- Gate lifting systems need to be designed to operate without being affected by debris in the reservoir. Trees and debris can jam the gate lifting gear.

- Consider unexpected loading conditions such as equipment malfunction (e.g. hoist rope failure, seized trunnion or roller bearing, jammed gate), gate overpour, floating debris and sunken log interference.

- All gate designs must consider material durability and the prevention of corrosion in the specification of critical components (e.g. bearings, bushes, pins, etc.). Design of low level outlets should consider sediment passing the gate and consequential wear and tear on components.

- Appurtenant equipment sited on the dam crest will be subject to amplified earthquake ground accelerations. Where possible minimise the amplification effect on structures (e.g. avoid the use of prominent superstructures in high seismic zones). Design spillway piers to ensure they do not deform during earthquakes and jam spillway gates, preventing them from operating.

- All gates must be designed and detailed to limit deformations. Excessive gate deformation during extreme loading conditions could result in gate jamming or severe loss of sealing. At low level gates, excessive leakage at high pressure could limit access for repairs.

- Dewatering pumps and discharge facilities for the control of uplift pressures are appurtenant equipment that needs to operate during normal loading conditions, and during and following extreme loading conditions. The pumps should be protected if overtopping flows could prevent them performing their function.

- All structural arrangements must facilitate ready access for the operation, inspection, maintenance, repair or replacement of gates, valves and their components. Safe access under emergency conditions and during exceptional circumstances must be considered (e.g. storm, failure of electricity supply, severe winter conditions, etc.).

- All control systems and associated equipment (e.g. control cabinets, cabling, and batteries) must be located where the rupture of water carrying conduits cannot threaten their integrity.

- Any facilities housing control systems and associated equipment must not collapse and prevent equipment operation post-earthquake.

Appurtenant Equipment Operation and Testing

The dam operator must carry out frequent tests of the appurtenant equipment as recommended in Section 1.4.2. This includes frequent testing of the back-up gate operating systems.

2.4.5 Reservoir Slope Stability

The key objective of reservoir slope stability assessment is to ensure that the reservoir slopes are sufficiently safe to enable the reservoir to be filled and operated without adverse impacts. Most historic reservoir landslide issues have been caused by pre-existing features identified in the later stages of projects with consequential effects on project costs, first filling date and operation. Reservoir slope stability may also be adversely affected in the event of a significant flood event, howsoever caused, originating from upstream. Although many reservoir studies are confined to maximum rim level + 50 m, given the nature of the topography and geology in Bhutan, this should include the entire valley flanks to crest (interfluve) level when considering slope stability.

As the reservoir is the key resource for most projects, slope stability hazards must be evaluated to the same degree as earthquake and flood hazards. Reservoir slope stability monitoring must be included in the dam safety programme for long term management.

When the reservoir is filled the stability of the reservoir slopes is affected. In addition to the direct effect of inundation, effects may include changes in slope material properties and the establishment of more adverse groundwater conditions than previously existed.

An important reference on reservoir slope stability issues is ICOLD Bulletin 124 “Reservoir Landslides: Investigation and Management” [9]. This reference addresses reservoir slope stability issues and their investigation and management within the context of both new project developments and existing reservoirs.

Other useful references for slope stability risk assessment are a series of reports from the University of New South Wales Australia:

- UNICIV Report No. R-390 August 2000. Report on the Analysis of ‘Rapid’ Natural Rock Slope Failures. [38]

- UNICIV Report No. R-400 June 2001. Rapid Failure of Soil Slopes. [39]

- UNICIV Report No. R-403 February 2002. Report on the Analysis of the Deformation Behaviour of Excavated Rock Slopes. [40]

- UNICIV Report No. R-406 February 2002. Report on the Post-Collapse Behaviour of Debris from Rock Slope Failures. [41]

2.4.6 Peer Review of Dam Developments

It is normal practice in the design and construction of dams to have peer review. Peer review processes are adapted to each project and may be required by:

- regulatory authorities,
- the financing institutions,
- the dam owner, and
- the contractor.

The Designer must have internal peer review as a part of their quality assurance process.

Peer review may be carried out by experienced individuals on parts of the design, by consulting companies or by a Panel of Experts (engineers experienced in the different disciplines and engaged to act together as expert advisors and reviewers).

A particular focus of peer review on dam projects is the management of the natural hazard and geologic and geotechnical risks within the project layout and the choice of dam and appurtenant structure type.

2.4.7 Instrumentation

All dams must have an adequate level of instrumentation to monitor and evaluate the safe performance of the dam during the construction, reservoir filling periods and throughout the operational life of the dam. Instrumentation enables the detection of change in dam performance which might indicate deterioration or potential failure of the dam structure and facilities.

The planning, design and layout of instrumentation is initially the decision of the Designer, to confirm that the performance of the dam is in accordance with expectation and to serve for the monitoring of the dam during its service life.

For example, instrumentation for thermal rise in a concrete dam is monitored only during construction and first reservoir filling. Other instrumentation, such as piezometers measuring pore water pressure is monitored during construction, first reservoir filling and throughout the life of the dam.

The design of the permanent dam instrumentation should be informed by a potential failure modes analysis of the dam. The first PFMA is to be undertaken during the DPR preparation. Instruments are to be selected and positioned to monitor both the general performance of the dam and to monitor indicators of potential failure.

During the life of a dam, additional instrumentation may need to be installed to gain a satisfactory level of confidence in assessing dam safety. Additional instruments would normally result from an engineer identifying changing conditions, a review of behaviour, or recommendation arising from a dam safety inspection.

Table 2.8 lists examples of potential failure modes for concrete and embankment dams together with key potential failure mode indicators that may signify the onset of failure. The instrumentation required to monitor the indicators is also listed in the table.

Table 2.8 – Potential Failure Modes, Indicators and Instrumentation Requirements

Potential Failure Modes	Description	Failure Mode Indicators		Instrumentation to Monitor Potential Failure Mode**
		Concrete Gravity Dam	Embankment Dam	
Abutment Failure	Instability or defect in abutment material. Initial seepage may	▪ Pore water pressure: changes in pressure readings ▪ Seepage: flow from groyne / toe		▪ Piezometers ▪ Seepage Weirs

Potential Failure Modes	**Description**	**Failure Mode Indicators**		**Instrumentation to Monitor Potential Failure Mode****
		Concrete Gravity Dam	**Embankment Dam**	
	cause erosion of the abutment leading to collapse. Collapse may occur very rapidly.	▪ Deformation: Rock / slope movement ▪ External Indicators: Earthquake, heavy rainfall/flooding		▪ Deformation survey
Sliding of Dam – in Foundation	Sliding of the dam at the foundation interface.	▪ Deformation: movement ▪ Pore water pressure: changes in pressure readings ▪ External Indicators: Earthquake, heavy rainfall/flooding	N/A	▪ Piezometers ▪ Deformation survey ▪ Reservoir water level gauge
Sliding of Dam – in Dam Body	Sliding on a poorly constructed horizontal interface in the dam body.	▪ Pore water pressure: changes in pressure readings ▪ Seepage: in dam body ▪ Deformation: movement ▪ External Indicators: Earthquake, heavy rainfall/flooding	N/A	
Scour of Dam Toe	Erosion of the area immediately downstream of the dam by spillway flows. The erosion develops to such an extent that the dam is undermined and support is lost leading to failure.	▪ Deformation: erosion at toe of dam ▪ External Indicators:, heavy rainfall/flooding	N/A	▪ Spillway water level gauge
Overtopping of Embankment	Extreme flood flow causes the reservoir to rise and overtop the dam crest.	N/A	▪ Deformation: Erosion of embankment or toe ▪ External Indicators: Heavy rainfall/flooding, rising reservoir water level, gate failure	▪ Reservoir water level gauge
Embankment Failure	Instability of embankment evident by sliding or slumping. Failure could be due to loss of support in weak foundation sediments.	N/A	▪ Pore water pressure: changes in pressure readings ▪ Seepage: flow from groin / toe ▪ Deformation: in embankment; cracks in embankment	▪ Piezometers ▪ Weirs ▪ Deformation survey

Potential Failure Modes	**Description**	**Failure Mode Indicators**		**Instrumentation to Monitor Potential Failure Mode****
		Concrete Gravity Dam	**Embankment Dam**	
			▪ External Indicators: Earthquake, heavy rainfall/flooding	
Piping through embankment or foundation or along conduit through the dam	Seepage through dam carries fine material from core potentially leading to excessive leakage or failure	▪ Pore water pressure: changes in pressure readings ▪ Seepage: at toe or groin; turbid water	▪ Pore water pressure: changes in pressure readings ▪ Seepage: at downstream shoulder, groin or toe or around a pipe penetrating through the dam; turbid water	▪ Piezometers ▪ Weirs
Penstock / Power Pipe Slope Failure	Slope instability is most likely to be caused by either: (1) high rainfall saturating slopes, (2) seepage from pipeline saturating the slope below, or (3) severe earthquake shaking.	▪ Pore water pressure: changes in pressure readings ▪ Seepage: from penstock power pipe ▪ Deformation: Cracks in access track; settlement/deformation measured or observed ▪ External Indicators: Earthquake, heavy rainfall/flooding, loss of water supply to the power station		▪ Piezometers ▪ weirs ▪ Deformation survey

**** NOTE: Visual observations reported by the dam inspector, in conjunction with instrument readings are an important component of ALL potential failure modes.**

Installation of the instruments should always be performed in accordance with the manufacturer's installation manual. Generally, installation is a specialist activity that must be carried out by, or under the direction of an experienced technician. Appropriate testing is required to be carried out after installation to check that sensible data is being obtained.

As-built records of the installation, including calibration data must be kept securely in long term storage.

A maintenance program must be prepared as part of the instrumentation plan. It is to include the anticipated frequency of maintenance inspections and, if necessary, the frequency of calibration checking.

Advice is available in the following references and guidelines:

- Dunnicliff J, 2013. Systematic Approach to Planning Monitoring Programmes using Geotechnical Instrumentation. [42]
- Dunnicliff J, 1988. Geotechnical Instrumentation for Monitoring Field Performance. [43]
- ICOLD Bulletin 158. Dam Surveillance Guide [44]

- DHPS Guidelines for Development of Hydropower Projects Part II [5]

2.5 Construction

For construction the project is handed over to the SPV or Project Authority responsible for construction and first reservoir filling. Design will continue during construction as excavation uncovers unexpected features and design requires adaption to suit. The SPV/Project Authority must engage a Designer to continue this role through to completion of first reservoir filling and handover to the dam operator. It is likely that the DPR consultant will continue as Designer through the next phase. Dam safety considerations apply during construction and the SPV/Project Authority and Contractor are responsible for managing dam safety risks through this phase.

2.5.1 Dam Safety Risks during Construction

Dam safety risks must be proactively managed during the delivery of the project. This is the time when a dam site, and all those working on and close to it, are most vulnerable to catastrophic events from upstream (e.g., GLOF, LDOF, etc.). Consequently, a project’s Risk Register and Disaster Response Plan (and any related Emergency Response Action and Communication Plans) must consider these inherent vulnerabilities.

The quality of construction and the adaptation of the design for unexpected conditions encountered during construction are important for dam safety. If the construction materials or the quality of construction do not meet the design requirements the intended standard of dam safety will not be achieved.

Other construction-related dam safety risks that the SPV/Project Authority must avoid are defects created during construction and unauthorised changes to the design.

Construction-related dam safety risks are primarily managed by:

- choosing an appropriate form of contract for the dam construction;
- selecting a Contractor who has experience of successfully completing comparable dam projects;
- ensuring that the appointed Contractor is fully aware of identified hazards and have their own Risk Assessments, etc.
- ensuring that an appropriate level of resource is provided for supervision of construction, involvement of the designer and peer reviewers and implementation of quality assurance,
- identifying the dam safety related aspects of construction that require inspection by the designer and, where necessary, peer reviewers during construction; and
- having procedures that allow design changes
- Routine monitoring of the upstream catchment in relation to identified geohazards prior to, during, and after the-construction phase.

2.5.2 Key Personnel

Key personnel on the Developer team are likely to be members of the SPV/Project Authority. The Developer's key personnel must include persons who have experience in the construction of this type of dam.

2.5.3 Contractor and Form of Contract

The SPV/Project Authority engages the Contractor to construct the dam. Harmonised bidding documents for constructing dams and hydropower are being developed for Government of Bhutan. The bidding documents are based on a FIDIC contract form.

Senior members of the Contractor's team must include persons who have experience in construction of this type of dam, including dams with similar hazard ratings.

2.5.4 Supervision

The SPV/Project Authority and Designer must supervise the construction phase of the project with staff experienced in construction of this type of dam.

2.5.5 Quality Assurance and Quality Control

A Quality Management Plan must be prepared for the delivery of the project.

The respective roles and responsibilities of the SPV/Project Authority, Designer and Contractor for the management of quality will vary according to the type of contract employed for the execution of the project and is outside the scope of this Guideline.

The purpose of managing quality throughout design, construction and first reservoir filling is to ensure that the dam is designed and built to the specified requirements. Quality management is the combination of all quality assurance and quality control activities required to achieve the specified quality. ISO standards 9000 and 9001 are the international standards that specify the requirements for a quality management system.

The purpose of Quality Assurance and Quality Control is shown on Figure 2.4 and can be described as follows:

- Quality assurance is directed at those management processes and procedures required to achieve the specified quality requirements.
- Quality control is part of the monitoring and control process concerned with checking (by means of inspection, measuring and testing) that the quality requirements are being met.

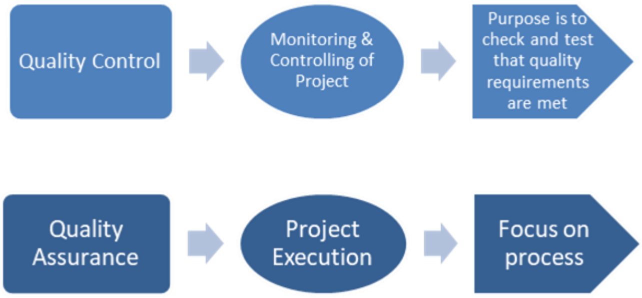


Figure 2.4: Quality Control and Assurance (adapted from NZSOLD [6])

The Quality Management Plan describes the policies and procedures for achieving quality requirements in the delivery of the project, defines who is responsible for what and documents compliance. The plan needs to address:

i. Organisational structure for all key roles in the project.
ii. Designer and peer reviewer involvement during the construction and first reservoir filling.
iii. Management and co-ordination between the designer and the contractor including the communication of the design intent.
iv. SPV/Project Authority’s role in approval of key milestones during project development.
v. Site personnel understanding their roles and responsibilities including those related to achieving the quality of the works they are involved with.
vi. The procedures for design changes. Design changes must be subject to checking and approval before construction of the changed components occurs.
vii. The procedures for confirming the quality of off-site manufacturing and transportation to the site.

The technical specifications and drawings prepared by the Designer largely determine the detailed scope of the quality control inspection, certification and testing. This will include the common hold-points for foundation inspections, pre-concrete pour inspections, required material properties and test requirements, instrument specifications and equipment installation and testing.

The Contractor’s Quality Plan for construction must include:

i. The quality control system.
ii. All project components.
iii. The quality control personnel and their roles and responsibilities.
iv. Inspection and verification procedures and records.
v. Sampling and testing procedures and records.
vi. Inspection hold-points.

vii. Procedures for assessing and recording compliance and managing non-compliances.
viii. Templates for logging and recording all quality control activities.

Advice is available in the following references and guidelines:

- GDHP Guidelines for Development of Hydropower Project Part III [6]
- ICOLD Bulletin 126 Roller Compacted Concrete Dams [45]
- ICOLD Bulletin 136 Specification and Quality Control of Concrete [46]
- ISO 9000/9001
- USACE Quality Management [47]

2.5.6 Construction Records

Key construction records must be prepared and retained throughout the delivery of the project.

Construction records are essential for the operation of the dam, future safety evaluations and in the event that rehabilitation works are required. Accurate and comprehensive construction records can reduce the necessity for investigations required for dam safety investigations or rehabilitation works. It is important that the records are catalogued and securely stored.

The construction records required for long term dam safety purposes include:

- Records of all investigations including:
    - drill hole logs and photos,
    - trench, pit and shaft logs, and
    - field and laboratory test reports, and investigation reports.
- Foundation records comprise the surveying, mapping and photographing of the foundation and the preparation of a foundation report. The report must include the results of laboratory and field testing associated with determining the engineering properties of the foundation.
- The quality control inspections and testing records and reports.
- Any records of construction monitoring relevant to dam safety such as weather records, location and nature of seepages, construction pore pressures, settlement, slope deformations and concrete temperatures.
- Photographs taken to record construction suitably identified with dates, locations and descriptions. Photographs of critical dam safety features such as foundations defects

and treatment, material placement in embankment dam core, filter and drainage zones, concrete construction and contraction joints, and embedded items such as gate guides are particularly important.

- As-built drawings. These are an essential record of what was actually constructed.

Once construction is complete a construction report shall be prepared by the Contractor, reviewed by the Designer and approved by the SPV/Project Authority before the contract is discharged. The report is to include:

- the construction method and equipment;
- conditions encountered,
- changes made to the design,
- problems arising during construction and their resolution,
- key photographs and drawings, and
- summaries of the field and laboratory testing.

All these records are required to be lodged with the SPV/Project Authority after the completion of construction. The SPV/Project Authority shall transfer these to the dam operator at the time of transfer after first reservoir filling. The dam operator shall retain these records in a secure location(s).

2.6 First Reservoir Filling

A defined Reservoir Filling and Commissioning Plan is required before first filling of the reservoir will be authorised to commence.

The initial filling of a reservoir is the first test of the dam design and construction. There are many examples of problems being experienced during this initial filling and the first few years of operation. This section promotes sensible planning and close management of the first reservoir filling phase in order to prevent loss of control or a dam incident in this critical phase.

2.6.1 Dam Safety during First Reservoir Filling

The Reservoir Filling and Commissioning Plan must define anticipated performance criteria.

First filling is regarded as complete when the reservoir has reached the desired maximum operating level and the dam and reservoir have been observed for a sufficient period that long term monitoring and operational procedures can be implemented. In the event that repairs or modifications are required, the first filling period may need to be extended to ensure the satisfactory performance of these changes.

The records of the response of the dam and reservoir slopes during and following the first filling of the reservoir are important benchmark records that must be available for the lifetime of the dam.

First filling should occur after the construction of the dam and the structures necessary for the control of the reservoir (e.g. spillway, bottom outlet and the installation of instrumentation) is complete. If hazardous conditions develop it may be necessary to halt the filling of the reservoir (or even lower it) while remedial measures are undertaken, hence control of the reservoir level throughout filling is essential. The reservoir filling may need to be carried out in stages to allow the response of the dam or reservoir slopes to be assessed.

Maintenance of some river flow downstream of the dam for environmental reasons (e.g. prevent fish stranding) is most likely to be necessary during first reservoir filling. A low level outlet capable of continuous discharge of the environmental flow will probably need to be included in the dam design.

The primary management of the dam safety risks during first reservoir filling is by:

- having specific reservoir filling procedures for the management of the reservoir level and the monitoring of the dam and reservoir slopes response;
- having effective participation by the SPV/Project Authority, the Contractor, the Designer and the eventual Operator; and
- being equipped and prepared to act in the event that unsatisfactory performance is detected.

An excellent example of the planning and management of a staged lake filling process is given in Gillon et al, 1997. “Filling the Landslide affected Clyde Reservoir, New Zealand” [48].

Advice is available in the following references and guidelines:

- NZSOLD New Zealand Dam Safety Guidelines [4]
- USACE Safety Of Dams – Policy and Procedures [49]
- ICOLD Bulletin 59 Dam Safety Guidelines [50]

2.6.2 Roles and Responsibilities During First Reservoir Filling

The Reservoir Filling and Commissioning Plan must specify roles and responsibilities.

The SPV/Project Authority, the Contractor, the Designer and the eventual Operator must all be closely involved during the planning and management of first reservoir filling.

Regulatory agencies may also be involved not just for dam safety purposes, but for any re-settlement and environmental issues.

Downstream communities affected by the change in river flows during reservoir filling and requiring to be informed about operational and emergency related river flow changes shall also be informed beforehand.

In terms of the dam safety management aspects of first reservoir filling of the dam and commissioning of the spillway and flow control equipment, the expected roles and responsibilities are typically as follows:

i. The SPV/Project Authority, through their project manager, receives notification from the Contractor and advice from the Designer on the readiness for lake filling. The SPV/Project Authority shall notify and consult with the eventual Dam Operator. During the period of first reservoir filling, the performance of the structures will be reported by the Designer and the SPV/Project Authority will authorise any necessary remedial actions.

ii. The Designer advises on reservoir filling procedures and confirms readiness to commence filling. During reservoir filling, the Designer monitors the performance of the structures and equipment against the design expectations. Engineers of the future operator are to be briefed and consulted on dam behaviour during reservoir filling. In the event of adverse performance, the Designer advises promptly on corrective measures.

iii. The Contractor notifies the SPV/Project Authority and Designer when the site is ready for reservoir filling. Once the SPV/Project Authority authorises commencement, the Contractor implements first reservoir filling and must be equipped and prepared to carry out any required corrective measures.

iv. The future Owner’s operational personnel is required to participate in the first reservoir filling as part of their training to take over the operation after the completion of first reservoir filling and handover by the Contractor.

v. For a complex dam, the Panel of Experts (PoE) may also participate in the decision to commence reservoir filling and in the assessment of the performance of the structures and equipment.

2.6.3 First Reservoir Filling Procedures

The Reservoir Filling and Commissioning Plan must be specific to the dam and associated reservoir.

First reservoir filling procedures are specific to each dam and reflect the classification of the dam, potential failure modes and the dam’s complexity. They are also frequently influenced by environmental considerations and the needs of other users downstream. The Designer shall prepare the first reservoir filling and equipment commissioning plan and procedures in consultation with the SPV/Project Authority, the Contractor and eventual Operator.

Before the Reservoir Filling and Commissioning Plan is prepared, a Potential Failure Modes Assessment shall be carried out. The PFMA is to be used to identify key reservoir filling management parameters, such as rate of reservoir rise, hold points, inspection and instrument reading frequency.

First reservoir filling procedures shall include the following:

i. The responsibilities of the SPV/Project Authority, the Contractor and the Designer and the roles and responsibilities of their key personnel.

ii. The physical works that must be completed before lake filling can commence.
iii. The plan for reservoir filling, including expected reservoir inflows, the desired rate of reservoir filling, procedures for releases including floods, reservoir hold points and the criteria for the continuation of reservoir filling. The plan also normally includes weather and catchment inflow monitoring.
iv. An inspection and instrument monitoring plan designed to monitor performance and detect adverse performance including those behaviours and signs associated with PFMs. Baseline measurements of all monitoring instrumentation and initial visual observations for scheduled inspections must be available before the commencement of lake filling. The plan should include the expected range of instrument responses associated with the reservoir filling for all instruments.
v. The inspection plan must include the required inspections of the dam, the appurtenant structures and the reservoir slopes and their frequency, recording and reporting of performance.
vi. The instrument monitoring plan must include the instruments to be monitored, the frequency of measurement, the recording, the assessment against expected ranges and the reporting of performance.
vii. Procedures for testing dam safety-related equipment e.g. spillway gates.
viii. Procedures for testing spillway performance.
ix. Procedures for inspecting and monitoring the reservoir slopes.
x. Emergency Preparedness planning and liaison with relevant stakeholders.

As part of the quality control system, readiness check lists shall be prepared for all structures, equipment and systems necessary for the commencement of lake filling and the management of the reservoir.

2.6.4 Handover to Operators

The Reservoir Filling and Commissioning Plan must include a process for handing over to operations staff.

From a dam safety perspective first reservoir filling is complete after the Designer is satisfied that the dam and all dam safety critical equipment is performing satisfactorily in accordance with the design expectations.

On the completion of first reservoir filling there will be a handover to the future dam Operator who then becomes responsible for operation of the facility. Prior to handover, operations personnel must be familiar with all operating, maintenance, surveillance and emergency plans and procedures. To assist in this process, key operations staff should have been involved in the first reservoir filling phase.

It is important to recognise that there are likely to be dam components that cannot be fully tested and commissioned to anywhere near their maximum design loads. Spillways for example cannot be tested under high flood flows until a natural event provides that opportunity. It is vital therefore that the dam and appurtenant structures are not considered as having been fully commissioned until they are subjected to loads beyond normal operations. This might not occur for many years after first filling, long after the Contractor has left and the SPV/Project

Authority has been disbanded. Hence the Operator takes over the responsibility for long term performance and has to be satisfied that the facilities will perform adequately before the construction project is disbanded. Where practical the Designer should be involved in reviewing the performance of the dam under the first few abnormal loading situations.

Handover will include all project documentation necessary for the operation, maintenance and surveillance of the facility and its long term management.

A review of the Potential Failure Modes shall be undertaken on completion of reservoir filling. This serves two important purposes:

i. confirmation that the potential failure modes have been identified and mitigated if necessary, and
ii. transfer of dam design knowledge and first filling lessons to the new operators.

A First Reservoir Filling Report shall be prepared to record the initial performance of the structures, an assessment of performance against expectations and details of any changes made or remedial actions taken.

3.0 Module 3: Dam Safety Performance

Where the consequence of a dam failure would adversely impact on people, property or the environment, dam safety performance and associated management must be encapsulated into an overall Dam Safety Management System (DSMS). The DSMS needs to have the following attributes:

- *Ensuring a broad perspective which encapsulates the upstream catchment and takes account of the Integrated Geohazard Assessment.*
- *Be consistent with the purpose, objective and principles of good dam safety management. (Refer Module 1, Section 1.2).*
- *Be commensurate with the type and hazard rating for the dam and its identified failure modes. (Refer Module 1, Section 1.3).*
- *Confirm requirements for; governance, communication, competencies, training and information management. (Refer Module 1, Section 1.5).*
- Detail monitoring and surveillance requirements, frequency and performance criteria
- *Define the requirements for inspection and testing of dam safety critical components such as spillway gates, valves and control systems. (Refer Module 1, Section 1.4)*
- Provide the requirement, type and frequency of dam safety reviews and audits.
- Contain or reference emergency action plans.
- Contain procedures for the identification, management and resolution of dam safety deficiencies and issues.

The attributes shown in italic are directly relevant to dam safety throughout all life stages and as such have been covered in Module 1. This Module (#3) addresses those attributes that are only directly relevant to the operational stage or stages of a dam’s life.

3.1 Monitoring and Surveillance

Monitoring and surveillance is a requirement for all dams throughout their operational lifetime and must be defined in a Monitoring and Surveillance Manual.

Monitoring and surveillance is a core aspect of assessing dam safety performance, particularly during normal operation. Monitoring during construction and first reservoir filling is covered in Module 2 Section 2.5 and 2.6. ICOLD Bulletin 158 [44] provides a comprehensive discussion of monitoring and surveillance processes.

In addition to monitoring and surveillance of the dam and appurtenant structures it is important that the upstream catchment is included in the routine and regular monitoring and surveillance. The key aspects of the upstream catchment identified and recommended for inclusion in appropriate monitoring regimes during the IGA should be part of the monitoring and surveillance regime.

The type and frequency of monitoring and surveillance will depend on the situation under which the dam is currently operating. Three broad states (as listed in Table 3.1) describe the main situations that could exist:

Table 3.1: Monitoring and Surveillance States

State	Condition
Routine	• Under normal operating conditions • No significant anomalies or issues exist.
Enhanced	• During, and for a period after, unusual loading, e.g. flood or earthquake. • Where a potential dam safety deficiency exists.
Intensive	• A dam safety deficiency has been confirmed. • A developing threat has been identified.

While most of Section 3.1 focuses on the extensive topic of instrumentation monitoring, surveillance (inspections and observations) is introduced first to ensure its importance to dam safety performance is not overlooked.

There is no substitute to the observations of dam performance made by experienced operators and technical personnel. Irrespective of how sophisticated an instrumentation network may be, it is still limited by the specific locations and anticipated nature of monitoring need.

The observational aspects of surveillance have many advantages, difficult to replicate through instrumentation alone. The core ones are described below:

Table 3.2: Benefit of Surveillance

Advantage	Commentary
Wider Coverage	Can cover much broader areas and aspects between and beyond instrumentation locations.
New Changes	New changes or issues can be identified quickly. Example; damp areas which were previously dry.
Rapid Inclusion	Any new observation sites can be immediately incorporated into the Monitoring and Surveillance network.
Use Experience	Draws on the depth and breadth of experience.
Develop Experience	Helps develop and increase the depth and breadth of experience.
Complements Monitoring	Where unusual instrument readings occur, visual surveillance can often quickly identify potential reasons. Example: Instrument malfunction or damage.

While surveillance is predominantly visual, a range of pre-determined descriptors are recommended to provide comparison over time and a level of consistency between observers. The use of pre-determined descriptors also allows the observations to be more readily included within a computerised monitoring and surveillance system. It also guides technical specialists as to what the observed changes might mean in terms of dam performance. Examples are included in Table 3.3 below.

Table 3.3: Useful Surveillance Descriptors

Observation	Type	Possible Descriptors
Seepage	Rate	Dry, Drip, Trickle, Flow
	Zone	Dry, Damp, Moist, Wet, Saturated, Flowing
	Colour	Clear, Slightly Discoloured, Opaque, Turbid
Climatic	Rain	Dry, Light, Moderate, Heavy, Snowing
	Temperature	Cold, Cool, Warm, Hot
Deformation	Cracks	New, stable, recent change.
	Slopes	Stable, recent erosion, clear movement.
Dam Condition	Face	Stable, erosion, vegetation growth, movement.
	Toe	Stable, erosion,

3.1.1 Instrumentation, Types and Purpose

The Monitoring and Surveillance Manual shall document the type, location and purpose of each monitoring point.

Monitoring instruments relevant to dam safety incorporate both operational and dam performance installations. Wherever practical some of the monitoring network should be installed well ahead of the start of actual dam construction to establish a natural baseline against which changes induced by the dam and reservoir can be compared.

When selecting instrument types for a dam, consideration should be given to;

- How and when will they be installed?
- Will they compromise dam integrity in any way (i.e. introduce leakage paths)?
- Will they introduce unrealistic construction challenges?
- Can they be safety accessed to be read?
- Can they be serviced and maintained?
- Can they be readily tested and verified?
- How responsive will they be to changing conditions?

They can be broadly categorised into the areas listed in Table 3.4;

Table 3.4: Monitoring Locations and Typical Instrument Types

Key Indicator	Typical Location of Instrumentation	Typical Instrumentation Type	Suitable Monitoring Frequency
Performance Monitoring			
Pore Pressure	Foundation (E/R) Dam body (E/R) Foundation interface Foundation abutment Abutment Reservoir slopes	Observation Wells & Open standpipes Gauged single tube hydraulic piezometers Twin tube hydraulic piezometers Vibrating wire piezometers	Low Low-Med Low-Mod High
Seepage	Abutment toe Toe Internal drains Gallery (Conc) Landslide drainage	Weirs or flumes Conduit Flow Turbidity meter Temperature (E/R)	Low – High High Low - High Low - High
Deformation	Dam crest Abutments Reservoir Slopes	Deformation & Alignment survey Crack/Joint meters, Extensometers Plumb Lines / Tiltmeters (Conc) Inclinometers	Low Low-High Low-High Low
Operational			
Water Level	Lake Level Tailrace	Ultrasonic or Vibrating Wire transducer Gauge boards	High Low
Hydrology	Climatic	Rainfall Gauge, Temperature, Pressure	Low – High
Flow	River flow stations Gate discharge	Continuous of periodic gauging stations Gate vs discharge ratings	Low – High
Position	Gate & valve positions	Radial or linear position transducers Locator plates	High Low
Specific Purpose			
Seismic	Dam Crest & Toe Natural Ground	Solid state. Continuous recording.	Mod-High High
Thermal	Mass Concrete	Buried Thermistor	Mod-High
Stress	Large Concrete Dams Gates & Lifting structures.	Embedded concrete cylinder. Stress/stain meters	High High
Key	Conc = Concrete Dams E/R = Earth/Rockfill dams		

Pore Water Pressure

The measurement of pore water pressure is important to determine the overall pattern of seepage in the dam embankment and foundation and also provide an indication of the phreatic surface.

A piezometer is an instrument that measures pore water pressure. There are several types of piezometer each with its advantages and disadvantages. A broad summary of piezometer types and their advantages and disadvantages is shown in Table 3.5:

Table 3.5: Pore Water Pressure Instrument Types

Type	Comment	Advantages	Disadvantages
Observation Well	Simplest form of pore pressure measuring device.	Simple Robust Can be tested	Not a point measurement Slow to respond
Open Standpipe	Open standpipe but measures a defined zone.	Simple Can be manually read or have transducer fitted.	Less effective in low permeability material. Often slow to response
Gauged Standpipe	Sealed standpipe for artesian conditions	Simple Can be manually read (gauge) or transducer.	Less effective in low permeability material. Needs good seal.
Twin Tube Hydraulic	porous filter element connected via two tubes, to a pressure gauge	Manual or continuous recording. Fast response	Require regular maintenance. Challenging to install Gauge level must be above measurement level.
Vibrating wire	Metallic diaphragm separating the pore water from the measuring system	Stable over time Permanent or temporary installations.	Difficult to test/verify. Some installation challenges
Pneumatic	Use gas to monitor pressure on a diaphragm between the gas and the pore water being measured	Gauge level can be below measurement level.	Moisture can impact on reliability.

In addition to those discussed in Table 3.5 above, there is a range of other piezometer types that are typically designed for relatively specific situations and as such are not typically adopted for wider monitoring networks.

Seepage and Drain Flows

Seepage is used to monitor both the effectiveness of; the dam at holding back the reservoir, and the drainage systems, at capturing and controlling seepage. It is important to understand that seepage monitoring is about looking for changes from the norm. In this context a reduction in seepage can be as concerning as an increase, as it may indicate failure of a drainage system with seepage now migrating via a different and possibly more dangerous path.

Seepage flow can be measured by weir, flumes, conduit gauges and timed flow into a container. Subjective measuring using descriptive terms can also be used (Refer Module 3, Section 3.2, Table 3.3). Other seepage characteristics, such as turbidity, temperature and chemical characteristics are measured by specialist instruments as described in Table 3.6:

Table 3.6: Seepage Instrument Types

Type	Comment	Advantages	Disadvantages
Weirs	Uses a calibrated depth vs flow relationship.	Different weir options depending on flow range. Allows visual, manual and continuous recording.	Can require significant space for larger flows. Impacted by debris. Can require frequent maintenance.
Container Volume	Flow determined from a time taken to fill a volume.	Very simple Allows visual appraisal of turbidity at the same time.	Only practical at low flows. Manual only.
Flume	Formed channel that has a specific depth vs flow relationship.	Relatively simple Not typically impacted by debris. Manual and continuous.	Can be physically large. Not usually applicable for lower flows.
Conduit Flow	Where seepage or drain flow is conveyed via a full pipe.	Moderate to high flows. Accurate and continuous	Not practical for low flow. Must be full pipe flow. Complex to calibrate.
Visual	For small or diffuse seepages using descriptors. e.g. “Dry. Drip, Trickle, Flow” or “Dry, Damp, Wet, Flowing”	New seepages easily added to network.	Weather impacts. Inconsistency between observers.
Temperature	Temperature changes over time or depth can indicate seepage patterns & pathways.	Relatively simple. Can use existing standpipe piezometers. Can cover significant range/depth.	Does not give a direct flow measurement. Cannot separate natural, and rainfall from dam seepages
Turbidity	Change in the level of sediment in flow can indicate issues.	Can indicate an adverse change. Visual (manual) and automatic options	Does not directly indicate where or what the issue may be.
Water Chemistry	The nature of seepage water chemistry can determine its source.	Can be sourced from most seepage, drains and wells.	Requires laboratory. Often not definitive about source.

Movement and Deformation

As shown in Table 3.7, deformation and movement can be monitored by a range of mechanism often targeting particular types of movement or displacement. Movement of dams can be identified at a macro level through traditional land survey techniques or at a micro level by high resolution instruments.

Dams will respond with permanent deformation to applied loads (such as settlement of embankment dams during construction and the horizontal load from the reservoir on concrete dams). Dams will also respond to changing loading patterns with temporary deformation (e.g. seasonal response to temperature change or changing reservoir operating level). The monitoring and Instrumentation system should be able to differentiate between these temporary and permanent states, and most importantly be able to identify gross deformation indicative of a developing potential failure mode.

Deformation surveys are part of the monitoring of many dams. They primarily consist of standard land surveying methods to monitor the magnitude and rate of horizontal and vertical deformation of survey marks on the dam, abutments and at the dam toe.

Deformation surveys are often employed during dam construction. Frequently these survey marks are suitable for subsequent performance monitoring of the dam during operation, with other more precise methods (such as plumblines in concrete dams) employed if greater accuracy is required. Where possible the survey network should be established before any site works in order to achieve a baseline. Survey networks need to be set out to minimise survey closure error. Survey control (reference) points must not be located on unstable ground.

Dams, especially concrete dams, respond to seasonal temperature change. It is common to see concrete dam crests moving upstream in warmer seasons as concrete warms and downstream as temperatures cool. Deformation measurements need to recognise this deformation variation so that it is possible to identify movement outside normal trends.

Even where little of no movement is being detected deformation surveys and associated movement measurements provide an important baseline against which future events can be checked. For example; a deformation survey might be repeated after a significant earthquake to check for any change that might indicate hidden damage.

A common issue with most, if not all, deformation monitoring systems is they need protection from being knocked and damaged. Even relatively small bumps can cause significant disruption to the accuracy of readings which is difficult to correct.

Table 3.7: Deformation Instrument Types

Type	Comment	Advantages	Disadvantages
Deformation Surveys	Use standard survey methods to establish horizontal and vertical displacements.	Can cover large areas and most points on and around a dam. Able to be checked and verified. Manual and semi-automatic options. Can cross-check other displacement instruments	Can only measure accessible points – typically surface. Requires stable reference points. Require specialist skills. Not accurate enough for small localised movements
Scanner surveys	Identifies deformation by comparing point cloud surveys of faces.	Accurate. Measures whole face rather than specific fixed markers.	Very large data volume and powerful computing power needed.
Alignment Survey	Measures movement by the offset from a baseline alignment.	Relatively simple. Does not need specialist survey equipment or skills. Can be incorporated into wider deformation survey network.	Line of sight requirements limit use. Only one horizontal direction and possible vertical.
Joint or Crack Meter	Measures movement across a discrete joint or crack.	Can be very simple or more precise. Can measure 1, 2 or 3D movement. Can measure relatively small movements.	Only accessible locations. Typically, manual only. Can be affected by temperature.

Type	Comment	Advantages	Disadvantages
		Small to moderate distances.	
Extensometers	Optical and physical options for measuring linear displacements.	Wide range of options Very accurate and continuous recording. Typically, easy to install.	Need testing and verification. Typically, small distances
Plumb line	Measures rotational displacements such as dam tilting.	Very simple. Typically, manual. 2D measurement.	Typically, limited range. Physically very long (high) Can be affected by environmental conditions.
Tiltmeters	Measures rotational displacements such as dam tilting.	Very accurate. 1 or 2 D options. Typically, continuously monitored options	Typically, limited range. Can be affected by environmental conditions.

Operational Monitoring

Operational monitoring includes measurements that are primarily required for operational purposes but complement dam safety monitoring. These are summarised in Table 3.8. Where operational monitoring is relevant to one or more dam safety measurement type, it is advisable to record that particular operational monitoring at the same or high frequency to that of the dam safety monitoring point.

Table 3.8: Operational Monitoring

Type	Location	Relevance to Dam Safety Monitoring
Water Levels	Lake Level Tailrace	Pore pressure Seepage flows Deformation & Displacement
Rainfall	Catchment Dam Site	Pore pressure Seepage flows Slope stability and movement
Temperature	Dam Site	Deformation & Displacement Dam stresses (Conc) Seepage flows
Pressure	Dam Site	Pore pressure
River flow	Upstream Downstream	Not directly relevant
Gate position and discharge	Dam Site	Pore pressure Seepage flows Localised Displacement Stress / strain of gates and lifting gear.

Other Monitoring

Table 3.9 shows a range of other monitoring relevant to both operational and dam safety. The use of these will be very dependent on the dam size, type and location, and the nature of hazards within the catchment upstream.

Table 3.9: Other Monitoring

Type	Location	Relevance to Dam Safety Monitoring
Seismic Recorders or Intensity Triggers	Dam Site Upstream	Deformation & Displacement Reservoir stability
Snow/Heavy rain gauges	Catchment Dam Site	Potential flood loading. Reservoir rim stability
Flash Flood (GLOF) gauges or flow depth exceedance triggers	Catchment	Unexpected sudden low flow could indicate upstream river blockage/landslide dam. Potential flood loading. Emergency preparedness plans needs to be prepared in advance and trigger alerts used to put the plans into action.
Video Surveillance	Dam Site Downstream	Visual indication of significant change.
Geohazards which can generate flash floods, including stability and erosion stability and erosion	Entire upstream catchment, Reservoir and downstream as defined in the Integrated Geohazard Assessment (IGA).	Potential flash floods
Other monitoring of hazards identified in IGA	Catchment – as identified in IGA	Enhancing hazard resilience.

3.1.2 Data, Recording, Frequency and Alerts

All monitoring and surveillance must be undertaken at an appropriate frequency with resulting information securely recorded and retained.

The data produced from the monitoring network shall be recorded in a secure storage system. The frequency of this recording will be primarily based on the level of hazard posed by the dam but will also be influenced by the type of instrument selected.

For key instruments, alert levels are to be assigned to each instrument to warn if readings are exceeding predefined levels or specific thresholds such as expected inflow rates are being exceeded. This does not remove the need for reviewing the data when no alerts occur, rather it acts as an initial warning system on which pre-defined actions may occur.

Recording

The way data is recorded can range from completely manual paper-based systems to predominantly automatic systems. Most dams will have a range of instrument types and could have a mix of manual and automatic recording.

Manually recorded data can be captured on a pre-formed template or via a portable electronic recording device. Electronic devices have the advantage of reducing the chance of erroneous readings being recorded.

Automatic data will either be periodically downloaded from the instrument or fed directly into the operational SCADA (Supervisory Control and Data Acquisition) network. As discussed in Module 1 Section 1.5.4 all data recorded should be managed in such a way that ensures its security.

It is vitally important that the database where monitoring data is stored has sufficient capacity and operating speed to manage the data volume being collected. Data volume from automatically collected data acquisition systems can be very large. The database must be able to process, store and retrieve data as such speed that it can be readily available to dam safety engineers during a dam safety incident (when no delay due to technology weaknesses will be tolerated).

Frequency

The frequency of monitoring and surveillance is primarily driven by the combination of dam hazard rating, associated potential failure modes, and state of monitoring and surveillance alertness. Where significant portions of the monitoring and surveillance network is automatic and continuous, standard frequencies for manual and surveillance aspects can be reduced however, given the importance of surveillance, a reasonable frequency is still recommended.

The frequencies provided in Table 3.10 are considered a minimum requirement.

Table 3.10: Minimum Requirement for Monitoring Frequency

State[1]	Type	Hazard Rating		
		Low	Medium	High
Routine	Visual Inspection	Annual	Quarterly	Monthly
	Pore Water	At time of inspection	Quarterly	Monthly
	Seepage			
	Deformation	10-yearly	5-yearly	
	Operational	At time of inspection	Daily	Continuous
Enhanced	Visual Inspection	Periodic depending on issue		
	Pore Water	At time of inspection	Monthly	Weekly
	Seepage			
	Deformation	10-yearly	Periodic depending on issue	
	Operational	At time of inspection	Daily	Continuous
Intensive	Visual Inspection	Periodic depending on issue		
	Pore Water	At time of inspection	Daily	Daily to continuous
	Seepage			
	Deformation	10-yearly	Periodic depending on issue	
	Operational	At time of inspection	Continuous	
Note	[1] Refer Table 3.1			

Alerts

Performance thresholds or “alerts” must be defined for key monitoring locations.

Alerts provide a set of pre-defined limits against which monitoring data is checked as a first indication of anomalies. They can range from simple limits or levels to more complex trends and inter-instrument comparisons. Where instrument readings are predominately manual and use paper templates anything more than simple limits is of questionable value. Where electronic recording is used more complex alerts can be incorporated in to the recording database.

There shall be a notification system and recording of alerts to demonstrate that action is being taken until the alert condition is resolved.

For some instrument types the limits may only be defined on one side of what is deemed normal (e.g. high water levels). Other instruments may have both upper and lower alerts to highlight unusual changes in either direction (e.g. unusually low seepage indicating a blocked drain or high seepage rate indicating a developing leak).

Thresholds can also be used to identify readings that are outside the measuring range of the instrument and hence clearly false.

It is not necessary for all instruments to have every alert level set. This will depend on matters such as; how representative the instrument is, if it directly relates to a design load or potential failure mode, and historical reliability of the instrument.

Table 3.11: Types of Monitoring Alerts

Alert	Type	Set At	Commentary
Simple Limits	Warning	Set before a design limit is reached.	Warns that design limit may be reached
	Design	Set at a level that directly relates to a design limit.	If this level is exceeded, then loading potentially exceeds design.
	Alarm	Set at a level where dam integrity could be compromised.	May be same as design limit.
	Historical	Set at a level that is not normally exceeded by that instrument	Could use statistical basis e.g. 90% level of historical readings.
	Data Error	Readings exceeding this limit must be in error	Reading is implausible, e.g. exceeds the range of the instrument
Trends and rates	Warning	The rate of change in a data record exceeds anticipated limits.	Rapid changes in recorded data, even when other limits have not been exceeded, can point to concerning changes.
	Design	Rate of change exceeds pre-determined design expectations.	Some rates of change may have been anticipated during the design phase particularly associated with fist filling.
	Change	A notable change in trend has occurred	Where a historical trend stops or is reversed.
Inter data	Compare	A change in one instrument is not reflected in another that usually exhibits similar behaviour	Typically limited to two or three instruments at a time or where sophisticated data analysis tools are used.

Depending on the type of alert, pre-determined actions such as those described in Table 3.12 may take place.

Table 3.12: Potential Actions Arising from Alerts

Type	Potential Action
Warning	Repeat the reading of that instrument. Repeat the reading of other relevant instruments. Repeat or expand visual inspection
Design Limit, Alarms	Repeat one of more readings Increase frequency of monitoring until issue is resolved. Increase frequency of visual inspections.
Changes in Tend & Rates	Repeat & or increase monitoring frequency Undertake targeted review of data and instrument. Where practical test and if required re-calibrate instrument

3.1.3 Assessment and Reporting

All surveillance observations, monitoring and operational data must be reviewed and assessed against performance criteria and with reference to each other.

While pre-defined alarms may be able to be assigned to monitoring data and information, this primarily only provides a first indicator of an anomaly or issue.

The data analysis, dam safety assessment, and any subsequent reporting, actions and recommendations must be undertaken as soon as practical following the data collection and any related inspections. To achieve a balance between timely reporting, action and assessment rigour means a deliberate sequential approach to data capture, review assessment and reporting is typically adopted.

The collection of data and the pre-defined alert settings applied to this data is the first stage of this sequence approach. The following represents a typical assessment and reporting process;

Table 3.13: Requirements for Monitoring and Surveillance Assessment and Reporting

Stage	Process	Potential Actions
Field data collection and observations	Collect and check data and observations against pre-defined limits and “alerts”	• Repeat and take additional readings where anomalies are noted.
Routine information review and assessment	Review and report on data and inspection information against limits and recent history. Typical to use simple graphical comparisons and trends to identify unusual or unexpected results.	• Request further data readings. • Request technical review. • Escalate potential issues to senior personnel. • Raise potential dam safety deficiencies
Periodic review	Undertaken every few monitoring rounds or more frequently where dam	• Request instrument maintenance or replacement.

Stage	Process	Potential Actions
	safety deficiencies are under investigation. Incorporates any additional information, analysis or external advice. Raise any potential instrument performance issues.	• Request additional monitoring locations or instruments. • Request specialist technical analysis and recommendations. • Escalate as required. • Raise potential dam safety deficiencies.
Full record reviews	Undertaken periodically, often associated with wider performance reviews. Examines the full data record and the implication of changes over time. Check applicability of current alarm levels.	• Request instrument maintenance or replacement. • Request additional monitoring locations or instruments. • Request any changes to alarm levels identified. • Raise potential dam safety deficiencies
Specialist Review	Review specific data and observations against dam design and performance criteria.	• Raise potential or confirm dam safety deficiencies. • Recommend actions.

3.2 Inspections and Reviews

All dams are required to be periodically inspected and subjected to review.

Inspections and reviews provide the core function of determining if the dam is meeting its performance expectations. In this context undertaking inspection and reviews aligns with many if not all of the core principles defined in Module 1 but in particular;

> ***Principle 9**: Due diligence should be employed at all stages of a dam's life cycle.*

If an initial Integrated Geohazard Assessment (IGA) has been undertaken, then it is recommended that it is maintained and updated regularly in accordance with the recommendations that would be made within the initial IGA.

As with monitoring and surveillance, inspection and reviews are recommended to be undertaken as a cascade of increasing depth and thoroughness (refer Figure 3.1). This provides a balance between expediency and accuracy.

As a general rule those responsible for undertaking each level of review should be independent from those responsible for the previous level. It is however important that they utilise the knowledge and experience of the people involved in previous level review.

Figure 3.1: Example of Relative Frequency of Inspection and Cascade of Reviews

Inspection & Review	Relative frequency and cascade.
Routine	x x x x x x x x x x x x x x x x x x x x x x x x x
Intermediate	x x x x x x x x x x
Comprehensive	x x
Special	x x x

3.2.1 Routine, “Site Based” Inspections

Routine inspections and reviews must be undertaken on all dams.

Routine inspections and reviews are largely a component of normal monitoring and surveillance processes and as such would broadly encompass the routine and periodic processes summarised in Table 3.1.

They are most likely undertaken by internal staff with support from technical advisors particularly where there are current issues and deficiencies under investigation.

The main purpose is to provide a review of dam safety performance against largely pre-defined limits and criteria. Where these are exceeded, or anomalies identified, action is required. Actions that must be considered include;

- Undertaking repeat or supplementary data collection to check and verify information and confirm if the anomaly is potentially real.
- Initiate additional technical analysis and reporting that will provide guidance on further actions that may be required.
- Escalate to senior personnel responsible for dam safety. For major potential deficiencies, reporting needs to be through to governance level.
- If a major potential dam safety issue was identified, consider if any interim mitigation measures are necessary until the situation can be resolved, for example lowering the reservoir.

These reviews and corresponding analysis and reporting form a resource available for the more in-depth intermediate and comprehensive reviews.

3.2.2 Intermediate (e.g. Annual) Dam Safety Reviews

Intermediate inspections and reviews must be undertaken on all dams.

The primary purpose of an Intermediate Dam Safety Reviews (IDSR) is to review existing dam safety deficiencies (potential and conformed) and non-conformance and identify any new ones. They are largely based on a thorough visual inspection by technical advisors with support from operational personnel.

For dams that pose a significant hazard to people, property or the environment IDSR’s would typically be undertaken on an annual basis but could be required more frequently where significant dam safety performance issues exist.

For dams with higher hazard ratings they will typically involve independent external advisors. For lower hazard dams’ internal personnel could fulfil the roles required. While the extent and depth of these reviews will depend on the hazard posed by the dam, in general they will include review and reporting of;

- observations made during the site inspection;

- the information contained in recent; routine data, inspection and reviews;
- any performance testing results from dam safety critical plant such as spillway gates;
- the dam's performance during any significant natural event that may have occurred since the last IDSR;
- the status and progress made in addressing any existing and unresolved potential or confirmed dam safety deficiencies;
- summaries of any significant specialist assessment undertaken since the last IDSR such as flood hazard assessments;
- any new potential of confirmed dam safety deficiencies; and
- recommendations for any adjustments to the monitoring and surveillance network and frequency.

As described in section 3.2, the initial IGA should be updated as recommended. For some processes, it would be annual (e.g., pre- and post- monsoon) and for others, at specified intervals, and especially following identification of any emerging situation, e.g., development of an ice dam across a river valley.

It is not typically the purpose of IDSR's to make recommendations on how to address specific issues or deficiencies as this is more appropriately dealt with within a dedicated deficiency management framework (refer Module 3, Section 3.3.3). The IDSR may however make recommendations around increasing or expanding monitoring and surveillance to help provide greater information to guide work on addressing deficiencies.

3.2.3 Comprehensive (e.g. Five Yearly) Safety Reviews

Comprehensive Dam Safety Reviews (CDSR) are required to be conducted for all dams with an Intermediate or Large Classification at a frequency of no less than every 5-years after first reservoir filling. CDSR's are also recommended for dams with a Small Classification, but a lesser frequency may be appropriate.

The comprehensive safety review should also include an update of the elements of the Integrated Geohazard Assessment (IGA) which are due for review according to the recommendations of the initial and subsequent IGAs.

The primary purpose of a CDSR is to undertake a full review of the dam against; design, operation and safety performance.

CDSR's for Intermediate and Large Classification dams are to be undertaken by independent external specialists and it is desirable to use different specialists for each subsequent CDSR. Because of the depth of assessment undertaken during a CDSR for Intermediate and Large Classification dams, it is likely that more than one technical specialist will be involved including;

- Dam engineer specialist, usually leads the review team.

- Geologist or geotechnical engineer to review foundation and dam interaction and reservoir stability.
- Mechanical Engineer, particularly for dams which have gated spillways or discharge valves.
- Electrical Engineer, to review power systems associated with gates and similar components.

In addition, the review team may need to access the expertise of;

- Seismologists; to review seismic hazards.
- Hydrologists; to review flood hazards.
- Structural Engineer; to review specific dam components.
- Control System Engineer; to review the communication and control systems.

A CDSR will largely cover the same aspects listed for an IDSR with the inclusion of reviewing and reporting on;

- original investigation, design and first reservoir filling information;
- how changes in design practises and associated criteria since construction, might impact on the dam as an existing structure;
- any changes in loading scenarios that may impact on dam safety and performance;
- the appropriateness of the hazard rating and failure modes for the dam;
- the suitability of associated dam safety processes, procedures and documentation and evidence that these are followed;
- adequacy of emergency preparedness planning;
- evidence of training and exercises relevant to dam safety;
- the suitability and results from testing and verification programmes;
- the level of redundancy and resilience in core dam safety functions;
- the adequacy of governance, management and resourcing;
- the appropriateness of knowledge management and security systems;
- any upgrades, enhancements or changes in operation that may have impacted on dam safety performance; and
- previous IDSR, and CDSRs and the actions that arose from these reviews

As for IDSR’s, it is not typically for CDSR’s to make direct recommendations on how to address specific issues or deficiencies, because this is more appropriately dealt with within a dedicated deficiency management framework (refer Module 3, Section 3.3.3).

The Dam Safety Reports may however make recommendations around additional assessment or analysis to confirm or otherwise dam performance against modern design criteria and loadings. Recommendations may also be provided on increasing or expanding monitoring and surveillance to help provide greater information to guide work on addressing deficiencies.

3.2.4 Special Dam Safety Reviews

A Special Dam Safety Review (SDSR) is; required for all Intermediate or Large Classification dams where a significant performance issue is identified, or stress event has occurred. The SDSR approach could also be used for a Small Classification dam

A SDSR is not undertaken as a routine review. Rather it is in response to a specific issue, either directly related to the dam or potentially remote to the dam. Undertaking a SDSR may be considered appropriate following a significant;

- natural event (flood, seismic),
- unexplained performance issue,
- recent emergency, or
- sudden change in hazard setting or risk (e.g. upstream landslide dam, vulnerable infrastructure downstream).

They may also be undertaken to assess the significance of a potential or confirmed dam safety deficiency (Refer Module 3 Section 3.3).

Because the reason for a SDSR can be quite varied the scope will similarly be unique to the dam and problem at hand. It is likely however that it will involve one or more of the aspects covered by IDSR’s and CDSR’s but may go into greater depth in particular areas.

A SDSR is likely to make specific recommendations relevant to the issue under review and may for example include;

- interim operating limits to reduce risk,
- options for further investigation that will permanently address the issue,
- requirements for further investigation and analysis, and
- the inter-relationship between other identified deficiencies.

3.3 Managing Dam Safety Issues

3.3.1 Identifying Dam Safety Issues

The primary purpose of a dam safety programme is to ensure the safe performance of the dam. An important element of a dam safety programmes is the identification and management of dam safety issues. All dams must have a process for the identification and management of dam safety issues.

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 NZSOLD [4]) The categories for dam safety issues are shown in Figure 3.2.

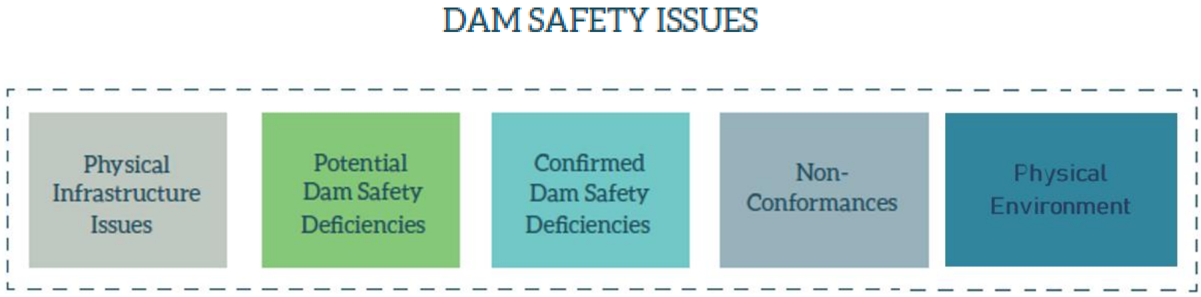


Figure 3.2: Dam Safety Issues (adapted from NZSOLD **[4]**)

Dam safety issues are typically identified as a result of:

- surveillance,
- inspections,
- equipment testing,
- operational problems
- dam safety reviews,
- Potential Failure Mode workshops, and
- emergency plan testing.

Physical infrastructure issues are where equipment access, instrumentation, communications or maintenance is insufficient to verify satisfactory dam performance. They therefore may not indicate an actual dam safety issue, rather the ability to verify dam safety is compromised. Examples are:

- unsafe access for inspections or to instruments,
- monitoring instruments that are unreliable,
- drains and relief wells that need maintenance,
- concrete repairs required, and
- spillway gate lifting equipment requiring maintenance.

Dam safety deficiencies include **potential dam safety deficiencies**, where particular performance requirements may not be met or 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.

Deficiencies can result from a number of causes including:

- elements of the original design or construction that do not meet modern dam safety criteria,
- improvement in understanding from consideration of failure modes,
- new information on flood and seismic related hazards and associated threats, and
- deterioration or damage.

Examples are;

- As a result of revised catchment hydrology, the dam does not have the required flood capacity.
- A stability concern has arisen at an abutment.
- A major leak through the dam foundation is developing and could become uncontrollable.
- Erosion in the spillway plunge pool threatens the spillway stability.
- A sinkhole has developed on the dam crest above the core of an embankment dam.
- Embankment dam materials do not satisfy compatibility criteria.

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

Examples are:

- Dam surveillance processes are inadequate.
- Dam surveillance inspectors are not trained.
- Emergency plans are inadequate.
- Instrument monitoring results are not interpreted.
- Surveillance and monitoring records are not kept.
- Dam safety issues are not recorded and tracked.

Physical Environment Issues

Physical Environment Issues include consideration of the upstream catchment as part of an Integrated Geo-Hazard Assessment including:

1. A desk study
2. A Gap analysis
3. Event mapping
4. Process identification
5. Neo-tectonic provinces and seismicity
6. Local and regional geological analysis
7. Landslide susceptibility mapping

8. Glacial hazard assessment
9. Hydrological analyses
10. Sediment management
11. Other analyses identified in gap analysis

Methodologies for each component are to be found in relevant literature including the paper "/8/ The role of integrated geohazard assessments in disaster risk management, J.M. Reynolds, Reynolds Geo-Solutions Ltd, UK, 44Hydropower & Dams - Issue One, 2023

3.3.2 Recording and Prioritisation

Dam safety issues shall be systematically recorded and tracked. This is typically done in a spreadsheet or database with access restricted to those responsible for managing dam safety issues.

The recording system should record:

- the issue and its category,
- reference when and how the issue was identified,
- the priority attached to the issue (periodically updated as necessary),
- actions taken to investigate or resolve the issue, and
- the closing out of the resolved issue by an authorised person.

Overall tracking and reporting on the status of a dam's dam safety issues is to be included in the regular management reporting within the dam safety programme.

Prioritisation is usually different for the different categories of dam safety issue.

Physical infrastructure issues are typically prioritised within the maintenance system associated with the dam and require the allocation of budget and human and material resources.

Non-conformances are typically related to management issues associated with operations. They may require alterations to procedures and processes or the provision of training. Non-conformances are usually resolved by the provision of human resources to make the required changes. Prioritisation is typically by dam safety managers.

Dam safety deficiencies are often characterised by having high consequences if the risk occurs, but the likelihood of its occurrence is often very low. This makes it very different from other higher likelihood risks. Dam safety deficiencies are often associated with large asset losses, there may be worker and public safety implications and they may require large capital expenditure to resolve.

The management and prioritisation of dam safety deficiencies is discussed in the following sections.

3.3.3 Assessment and Management of Dam Safety Deficiencies

Dam safety issues must be assessed and managed commensurate to the severity and likelihood of consequences should the deficiency potentially lead to dam failure.

In addition to focus on the dam structure and the reservoir impounded, attention must be paid to the upstream catchment conditions assessed in the Integrated Geo-hazard Assessment described in section 3.3.1.

Dam safety deficiencies can range widely in their severity and likelihood. This results in a correspondingly wide range of possible management responses.

Dam safety deficiencies commonly result from the investigation of potential dam safety deficiencies. These investigations may themselves require substantial studies and expenditure.

The change from a potential dam safety deficiency to a confirmed dam safety deficiency, together with the severity and likelihood of the deficiency, are key elements in defining the appropriate management and disclosure responses.

Dam safety deficiencies are managed within a risk management framework. The application of this framework to dam safety deficiencies is shown as a 7 step process in Figure 3.3.

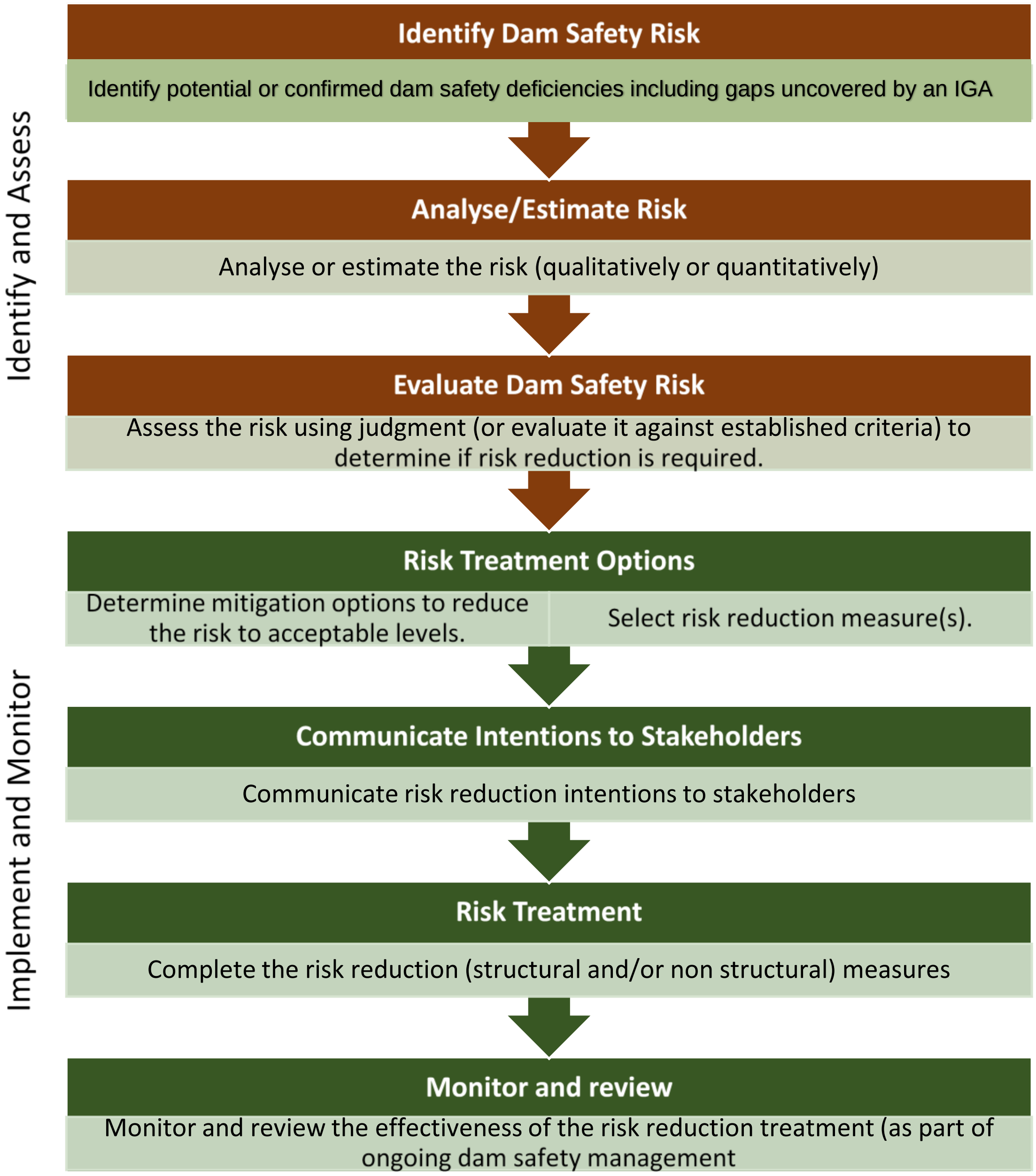


Figure 3.3: Dam Safety Risk Management Process

Step 1: Identify Dam Safety Risk

The identification of the risk has been made in the establishment of a confirmed dam safety deficiency. This may have resulted from the investigation of a potential dam safety deficiency. The identification of a confirmed dam safety deficiency will likely have to be communicated with stakeholders – for example regulatory authorities, Government officials, insurance companies, and local government authorities.

Step 2: Analyse/Estimate Risk

The risk – the consequences or impact of the deficiency being realised and its likelihood is assessed so that there is a clear understanding of the risk together with any uncertainties. The impact of the deficiency being realised are to be described and documented. Similarly, the factors that make its realisation more or less likely are to be documented.

The consequences or impact must consider potential downstream consequences in terms of the population at risk, the possibility of fatalities, economic damages to infrastructure and environmental damage as well as losses due to damage to the dam.

The likelihood may be described qualitatively using judgement-based descriptions or numerically using semi-quantitative or quantitative methods.

Qualitative assessments are made using judgement and might consider the extent of the departure from accepted dam safety standards. For example, if a structure was required to resist the 1:2,500 AEP earthquake and was assessed as resisting only the 1:500 AEP earthquake this gives a measure of the departure from the standard. Semi-quantitative methods are likely to require expert judgements to assess the likelihood of failure.

Quantitative assessment and evaluation of the dam safety risk is a complex process and requires specialist advice and is not considered in this Guideline. A description of the process is given in the US ‘Federal Guidelines for Dam Safety Risk Management’ (FEMA P-1025/January 2015) [51]

Step 3: Evaluate Dam Safety Risk

Assess the risk and its tolerability. The tolerability of a risk needs to reflect societal acceptance that they can agree to live with the remaining risk. This is specific to each country, its values and societal norms and must be considered in that context. It is unreasonable to impose another country’s societal risk tolerance on Bhutan. Many countries find this difficult to define so do not impose a limit of tolerability, but rather aim to reduce the risk to become “as low as reasonably practicable” (often referred to as ALARP).

In a qualitative assessment the impact and likelihood might be displayed on a risk matrix as shown in Figure 3.4.

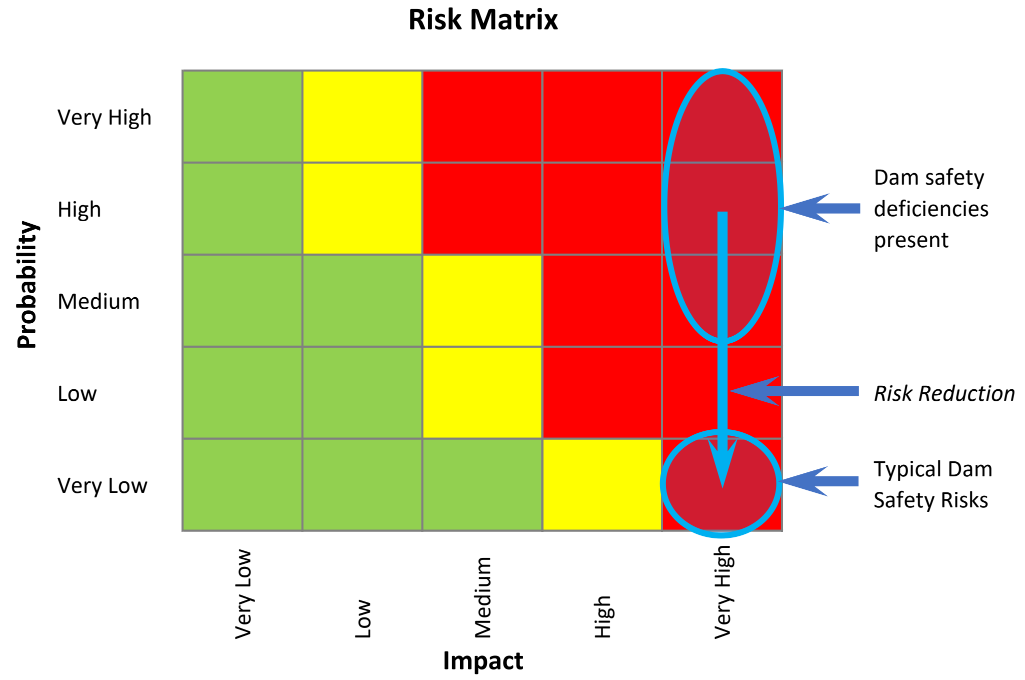


Figure 3.4: Example Risk Matrix to Display Quantitative Risk Results

In a semi-quantitative assessment, the matrix might be modified to show a numerical likelihood scale and the impact in terms of, for example, economic damages or the population at risk.

Step 4: Risk Treatment Options

The development of risk treatment options considers the range of applicable options together with the risk reduction associated with each option. This allows a risk reduction option to be selected. A combination of risk reduction measures could be selected which together provide the chosen risk reduction.

Step 5: Communicate Intentions to Stakeholders

The various stakeholders will need to be advised of the outcome of the risk assessment and the chosen treatment option.

Step 6: Risk Treatment

Engineering treatment of the risk will likely require the preparation of a design and the engagement of a contractor. The treatment works may require the lowering of the reservoir or the use of special methods to carry out the work with a full reservoir.

Step 7: Monitor and Review

Following the completion of the risk treatment, the work needs to be monitored and reviewed within the dam safety programme.

The management of this risk reduction process needs to be designed to ensure an effective process. A team should be established to carry out the process. Where the matters are complex, specialist advisors should be retained. Independent peer review or international expertise may also be warranted. The resourcing of the team should reflect the level of the risk.

Where the risk is very high, then interim risk reduction measures such as reducing the reservoir level shall be considered.

3.3.4 Interim Risk Management

As discussed above, management of a dam safety deficiency involves several important steps. The steps can take time particularly when there are multiple options available that require consideration and assessment in terms of seeking the best overall solution in terms of risk management.

If it not possible to immediately remediate the situation, it may be necessary to implement interim risk reduction measures to provide time for the appropriate permanent solution to be developed. Some options for interim risk reduction are given in Table 3.14.

Table 3.14: Interim Risk Reduction Options

Interim Risk Reduction	Commentary
Integrated Geohazard Assessment (IGA)	Enables holistic disaster risk management action plans increasing the resilience of the dam to weather-related disasters.
Increased surveillance and monitoring.	Highly likely to be one of the options adopted.
Change operational procedures	Most commonly this might mean lowering the reservoir level but could also mean reducing diverted inflows etc.
Additional Warning Systems	Install additional warning systems for operators and downstream communities where people or infrastructure is at risk.
Enhanced emergency planning	Operate emergency preparedness at a heightened state which might include permanent staffing and having emergency organisations on standby.
Stockpile material and equipment	Have material (e.g. rock, sand) available near the site. Also have heavy earthmoving equipment on standby.
Temporary support	Construct temporary buttressing or similar support structures.

In some situations, these interim measures may form part of the permanent solution or following the assessment of all options, be deemed the best long-term solution. As any solution will almost always trigger supplementary changes, either physical or operational, a full review of the dam and associated operational procedures should be undertaken with input from appropriate technical advisors and relevant regulatory authorities and external stakeholders.

3.3.5 Risks when Installing Instruments

It is often necessary to install additional instrumentation as part of the assessment of dam safety related issues and deficiencies. Care needs to be exercised when siting and installing such instrumentation as the installation operation can in itself increase the risk to the dam particularly when it is already in a compromised state.

In particular, the installation of instruments that penetrate in or through the structure (e.g. piezometers, inclinometers) can introduce additional seepage paths or increased water pressures that can compromise dam stability. The installation works themselves can cause damage to the structure, for example drilling that introduces fluid pressures that cause hydraulic fracturing of an embankment dam core or foundation.

The location, planning and installation of any instrumentation, especially associated with assessing dam safety issues and deficiencies, should be closely overseen by qualified technical advisors.

3.4 Emergency Preparedness Planning

Emergency Preparedness Planning shall be undertaken for all dams.

The purpose of Emergency Preparedness Planning is to; reduce the potential for a dam to fail and, where failure is unavoidable, reduce the potential consequence of failure. In this context emergency preparedness is directly aligned with two of the core principles defined in Module 1.

> ***Principle 7****: All reasonable efforts should be made to prevent inappropriate or accidental releases from the dam or associated structures.*
>
> ***Principle 8****: An effective emergency preparedness, response and mitigation plan should be in place for each dam.*

Historically, emergency preparedness has focused on reducing the consequence of the hazard (typically the reservoir contents) being uncontrollably released. This was in part driven from a perception that most threats were natural and hence beyond the dam owners' control.

Improved current practices focus on the management of risk in the Disaster Risk Management Cycle where an integrated Geohazard Assessment is utilised to give a holistic picture of the probabilities of the occurrence of events which are included in a disaster risk management plan. The overall process is a cycle which should be updated during the lifespan of the dam and is shown in Figure 3.5. as described by Reynolds, 2022, 2023a,b)."

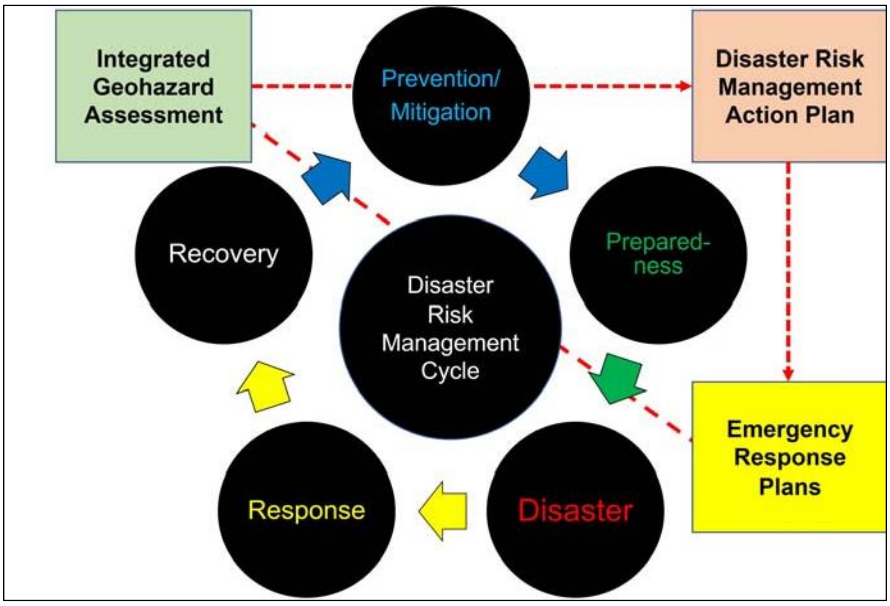


Figure 3.5: The Disaster Risk Management Cycle (as described by Reynolds, 2022, 2023a,b)

The culmination of emergency preparedness planning is the preparation of an Emergency Action Plan (EAP). This documents the actions to be taken in advance of, during and post an emergency event.

The Emergency Action Plan shall serve the following purposes:

- Be the primary document for use by the dam operator to:
    - record the plan for responding to an emergency,
    - describe the actions to take place in an emergency, and
    - contain the supporting data needed to take actions during the emergency.
- Conform to the Disaster Management Contingency Plans required by the Disaster Management Office.
- Provide alignment between the dam operator and the Disaster Management Contingency Plans of Local Government.

3.4.1 Hazard and Threat Assessments

The purpose of undertaking a hazard and threat assessment is to define which threats are most relevant and how these may cause uncontrolled release of the hazard (reservoir) either partially or fully.

In undertaking a hazard and threat assessment it is normal to start with the hazard, being the contents of the reservoir. The hazard and, given an uncontrolled release of that hazard, consequence of a dam failure will already have been determined as part of determining the dam's hazard classification (Refer Module 1 Section 1.3).

Threats are things that could potentially induce release of that hazard and therefore cause consequences. Potential threats to a dam arise from natural events, accidental damage, component malfunction or failure and deliberate actions.

Table 3.15: Examples of Potential Threats to a Dam

Threat	Process	Commentary
Natural	Floods Earthquakes Landslides Flash Floods (GLOF / dam failure upstream)	Potential to lead to complete dam failure.
Deterioration	Internal erosion. Concrete degradation	Potential to lead to complete dam failure.
Accidental	Incorrect operation (gates etc.) Damage during maintenance	More likely to induce partial release of reservoir
Malfunction or failure	Gate collapse Unplanned gate opening	More likely to induce partial release of reservoir
Deliberate	Sabotage	Partial or full release.

3.4.2 Pre-event and Preventative Actions

With the threats identified, focus is then on any control measures or barriers that can be put in place to reduce or eliminate that threat. Many of these measures will be part of standard dam design and may have been considered as part of failure mode assessments.

Control measures and barriers can however fail or be overwhelmed and so consideration is then given to what escalation or fall-back options are available. This means, where practical, providing a level of resilience and redundancy in control measures. There could be more extreme escalation measures necessary, some of which will in themselves induce consequences but to a lesser level than would occur under a full dam failure scenario.

Preventative action may involve one or more of the following listed in Table 3.16.

Table 3.16: Examples of Preventative Action

Action[3]	Example	Commentary
Reduce Hazard	Lake drawdown	This is the control measure that is usually most available to a dam owner. How rapid drawdown is undertaken will depend on the level and how imminent the threat is. In some situations, more drastic measures may be adopted including beaching conveyance systems to increase the rate or extend of drawdown.
Remove threat.	Remove the potential for accidental releases	It may be possible to eliminate the threat by removing the chance it can arise. Removing the ability for operators to directly operate gates may remove the risk of accidental operation but care must be exercised as this might increase other risks though reduced flexibility.
Reduce threat	Provide additional controlled discharge capacity.	Providing additional and preferably alternative discharge capacity provides resilience against component failure as well as many natural threats.
Control threat	Controlled breach of upstream lake.	Undertaking a controlled initiation of a threat can mean that it occurs at a time when the ability to control is maximised and consequences minimised.
Reduce Consequence	Public warning and evacuation of downstream population.	This is a standard action within emergency planning. Undertaking it as a control (pre-event) rather than reactive (post-event) measure provides time that would otherwise not be available.
Reduce Consequence	Training and exercises	People trained and understanding what they need to do help utilise the time available to greatest impact on reducing consequences.

3.4.3 Post-event and Reactive Action

Post event does not mean that an emergency is over, rather is means that the event, being the release of the hazard (reservoir contents) has or is occurring. Preventing the event is therefore no longer an option. Focus now turns to reducing or mitigating as much as possible the level of consequence.

Some of the preventative actions, such as evacuating people from downstream, will continue. This however is now progressed with the realization that there is a defined and reducing amount of time remaining before the hazard reaches them.

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[3] *Note: This should only be an option of last resort as this could lead to a run-away failure out of anyone's control. There are many ways in which the water level of and volume within an upstream lake might be controlled, such as siphoning, open channels controlled by sluice gates, and tunnels, to name but three methods (Reynolds, 1992, 1998; Reynolds et al., 1998; Rana et al., 2000; Richardson and Reynolds, 2000; RGSL, 2003). Extreme care must be taken prior to any remedial activity and should only be done following comprehensive site studies including geophysical surveys, as appropriate.*

Table 3.17: Examples of Post-event Actions

Action	Example	Commentary
Reduce Consequence	Continue evacuation of downstream population.	This is a standard action within emergency planning. Undertaking it as a control (pre-event) rather than reactive (post-event) measure provides time that would otherwise not be available.
Mitigate Consequence	Rapid mobilisation of recovery processes.	In most situations this will be coordinated by emergency or civil defensive agencies.
Reduce residual hazard	Empty or secure remaining dam reservoir	In many events there may remain storage in the reservoir. This needs to be secured against further release of future events such as floods or earthquake aftershocks

3.4.4 Procedures and Documentation

An Emergency Action Plan shall be prepared and maintained for all dams, that documents emergency preparedness planning.

The outcome from the emergency preparedness planning including; assessment of hazards and consequences, control measures, failure scenarios and response actions is recorded in a single document, or series of documents. This document or series of documents is frequently referred to as an Emergency Action Plan (EAP) but can be known by a range of similar titles (e.g. Emergency Preparedness Plan, Disaster Management Plan).

The purpose of the EAP is to document prescribed responsibilities, information and processes to follow in the event of an emergency. This is important as it provides certainty to those involved during an event. The EAP and associated inputs needs to have been prepared and reviewed ahead of the pressure and stress that will exist during an emergency event and, as such, should provide confidence to users that defined actions and potential consequences have been carefully considered.

The choice of using a single or series of documents depends on the nature of the organisation that owns the dam, the number of dams owned and the individual dam. For example, where an owner operates several dams in cascade, they may choose to have a high-level document that covers all dams, responsibilities and organisational actions. Individual documents are still required for each dam that provide information on site specific threats, responsibilities and actions relevant to that structure, but this approach ensures the cascade impacts are accounted for.

Classification of Emergencies

It is beneficial for emergencies to be classified against predefined criteria. This helps define how they might be managed and what external entities, if any, might be involved and the urgency around that involvement. A typical classification system is shown in Table 3.18.

As a further example in Table 3.18, if an upstream glacial lake has been adequately assessed, the degree of hazard will have been identified, i.e., that the lake poses a serious hazard. The hazard assessment would have identified possible trigger mechanisms (e.g., landslide, lack of freeboard) at the time of the assessment. Using a series of satellite images acquired over a long enough time period (e.g., 10-20 years), it is possible to determine how the degree of hazard changes with time. In some cases, the degree of hazard may diminish or conversely might increase over time. If suitable monitoring has been instigated, then the feasibility of a breach occurring and by what mechanism should have been defined. A scenario of a GLOF from such a lake can be simulated numerically and the flood characteristics determined. It is from these simulations that it is possible to determine whether a GLOF from a specific lake may or may not impact a reservoir and dam and to what degree. However, it is important to recognise that a GLOF or LDOF may not only provide a substantial volume of water but also mobilise significant volumes of sediment including very large (>5 m diameter) boulders, all of which would impact on a downstream hydropower scheme.

Table 3.18: Classification of Emergency Events

Event Classification	Discussion
Internal event	Will only affect dam operator and hence can be managed internally with appropriate external technical support. Example; A jammed or significantly damaged spillway gate. While no flood is anticipated and alternative spill capacity exists, this would be managed internally
Potential Emergency	Has the potential to have consequences beyond the dam owners' assets and hence require external agency involvement. Example; a glacial lake upstream could breach in the near future, but breach is not imminent.
Imminent Emergency	A threat that could lead to dam breach or significant uncontrolled release of reservoir contents has occurred, is occurring, or is about to occur. External agencies will be involved. Example; the glacial lake that has been monitored has failed and a flash flood is expected. Emergency reservoir dewatering has been initiated.
Current Emergency	A dam breach, or significant uncontrolled release has or is occurring. External agencies are involved and operating under prescribed flood wave and inundation plans and maps. Example; the glacial lake outflow flood overwhelmed the dam causing the dam to partially collapse adding significant additional volume to the GLOF.

Content of Emergency Action Plan

The full content of an EAP will depend on the; type of dam, nature of threats, potential modes of failure and assessed consequences of failure or uncontrolled release of the reservoir. There is value however in adopting a consistent format across an organisation or even across Bhutan. This is because EAP's can be requested by the Disaster Management Office, so it is beneficial therefore if everyone is familiar with a relatively consistent format.

Table 3.19: Example Structure of Emergency Action Plan

Section	Content
Preface	***Define*** the purpose of the EAP and the organisations philosophy on emergency preparedness
Roles and responsibilities	***Define*** the roles and responsibilities of personnel that are expected to be involved in an emergency event need to be clearly documented. This should include escalation details if specific personnel are not available and for when the emergency classification increases. ***Indicate*** where and when responsibility may transfer from one entity to another e.g. from the dam owner to an external agency.
Contact List	***Provide*** the contact details of all individuals and agencies potentially involved in an emergency, including technical specialists and contractors.
Emergency classification and escalation	***Define***, as discussed in Section 3.4.4 the criteria by which emergencies are classified and escalated should be defined.
Emergency preparedness and actions.	***Describe*** the treats that could induce an emergency. ***Define*** the control measures for each threat and associated actions that should be taken if the threat is likely to or has occurred. ***Describe*** the dam failure scenarios and the threats that can induce these ***Define*** details of response actions to be undertaken should dam failure or uncontrolled release of the reservoir be about to or has occurred. ***Describe*** any specific downstream vulnerabilities and thresholds and the flood wave and depth criteria at these locations. Example; schools, hospitals, critical roading, other dams. ***Provide*** procedures required to undertake action (typically as appendices). Many actions involve significant processes in order to undertaken. Example; Emergency lake drawdown procedure.
Support Systems	***Describe*** core support systems and resources, including primary and any back-ups, such as • Communications (internal and external) • Power systems, (onsite, remote, mobile) • Sources of emergency material, supplies & equipment • Emergency access providers (helicopters, excavators) • Personnel support (for families of personnel involved)
Post emergency	***Define*** any post event processes, inspections and procedures.
Process improvement	***Describe*** how emergency preparedness will be reviewed and improved including; • Frequency and nature of training and exercises. • Reviews and update processes and frequency
Technical Details	***Provide*** core technical details relevant to the dam, threats and consequences including; • Drawings • Catchment map of potential threats • Downstream inundation maps and flow travel time details. • Specific procedures, templates and checklists, • Record of major Maintenance and overhauling activities.

Review and Update

Emergency preparedness and resulting EAP's shall be periodically reviewed.

The frequency at which reviews and updates are required can be informed through appropriate monitoring regimes. These would be indicated through undertaking an Integrated Geohazard Assessment, which would include recommendations for what monitoring would be required and at what intervals. Emergency Action Plans (EAPs) should be updated in the light of these recommendations.

There are a range of reasons that periodic review and updates are required. The most common are listed in Table 3.20;

Table 3.20: Reviews of EAP

Reason	Discussion	Typical Update Frequency
Personnel Changes	It is common for the roles and responsibilities of people to change. It is important for EAP's to record current roles, responsibilities and contact details. EAP's are often formatted to have a sub-section containing roles, responsibilities and contact details to make updating simple.	Annual
Periodic Review	EAP's should be periodically reviewed by independent specialists. This is commonly incorporated as part of a CDSR (Ref Section 3.2.3). These reviews will often make recommendation for improving EAP's	5-yearly
Dam Life Stages	Emergency planning and hence EAP's should be in place throughout a dam's life, including construction, first reservoir filling, operation and rehabilitation. The nature of threats, potential control measures and response actions will similarly change in response to these life stages	In advance of any significant change in life stage
Post Event	Following a significant event or emergency the dam or downstream communities and environment is likely to be more vulnerable to further events. A change, typically interim, to emergency preparedness and documentation is often required in such situations	Post any significant event.

3.4.5 Training and Exercises

Training and exercises in emergency preparedness shall be undertaken.

As outlined in Module 1 Section 1.5.2, exercises and simulations should be run to test both the understanding of personnel and the adequacy of systems and processes. As well as major events, training should also cover unusual combinations of relatively minor issues and where component failures compromise performance.

Critical reviews shall be undertaken of each exercise and iterative improvements made to the EAPs as a consequence of the reviews. An exercise that goes badly wrong can be more informative than one that just about works. If an EAP is revised, exercises based upon this updated protocol should also be revised and then retested, as appropriate.

An exercise is typically run internally with input from external advisors and agencies responsible for emergency response (e.g. Emergency Management Office, police, civil defence). The format of an exercise can range from desktop simulations to full scale multiple organisation exercises that include consideration of other infrastructure such as flood protection works and power systems.

The frequency of testing the EAP depends on the dam’s hazard rating and range of emergency scenarios. Every two to three years is reasonable with each training session using a different emergency scenario.

References

[1] RGOB, “The Electricity Act of Bhutan,” Royal Government of Bhutan, 2001.

[2] FERC, “Engineering Guidelines for the Evaluation of Hydropower Projects, Dam Safety Performance Monitoring Program, Chapter 14,” Federal Energy Regulatory Commission, 2017.

[3] ANCOLD, “Guidelines on Risk Assessment,” Australia National Committee on Large Dams, 2003.

[4] NZSOLD, “New Zealand Dam Safety Guidelines,” New Zealand Society on Large Dams, 2015.

[5] DHPS, “Guidelines for Development of Hydropower Projects Part II,” Department of Hydropower and Power Systems, Ministry of Economic Affairs, Bhutan, 2018.

[6] DHPS, “Guidelines for Development of Hydropower Projects Part III,” Department of Hydropower and Power Systems, Ministry of Economic Affairs, Bhutan, 2018.

[7] World Bank, “Seismic Risk Assessment in Bhutan,” World Bank and Royal Government of Bhutan, 2014.

[8] K. Goda, D. Drukpa, M. Werner, B. Adams, F. Cooper, D. Haines, R. Sarkar and A. Velasco, “Building Resilience to Earthquakes in Bhutan: A Probabilistic Seismic Hazard Assessment to Inform the National Building Code,” University of Bristol, 2018.

[9] ICOLD, “Bulletin 124. Reservoir Landslides: Investigations and Management - Guidelines and Case Histories,” International Commission on Large Dams, 2002.

[10] R. Fell, P. MacGregor, D. Stapledon and G. Bell, “Geotechnical Engineering of Dams,” A.A. Blakema, 2005.

[11] ICOLD, “Bulletin 52. Earthquake Analysis for Dams,” International Commission on Large Dams, 1986.

[12] ICOLD, “Bulletin 123. Seismic Design and Evaluation of Structures Appurtenant to Dams,” International Commission on Large Dams, 2002.

[13] ICOLD, “Bulletin 148. Selecting Seismic Parameters for Large Dams - Guidelines,” International Commission on Large Dams, 2016.

[14] ICOLD, “Bulletin 129. Dam Foundations - Geologic Considerations, Investigation Methods, Treatment, Monitoring,” International Commission on Large Dams, 2005.

[15] FERC, “Engineering Guidelines for the Evaluation of Hydropower Projects, Revised Chapter 3 - Gravity Dams,” United States Federal Energy Regulatory Commission, 2016.

[16] DHPS, “Guidelines for Development of Hydropower Projects Part I,” Department of Hydropower and Power Systems, Ministry of Economic Affairs, Bhutan, 2018.

[17] ICOLD, “Bulletin 117. The Gravity Dam: A Dam for the Future,” International Commission on Large Dams, 2000.

[18] ICOLD, “Bulletin 136. The Specification and Quality Control of Concrete for Dams,” International Commission on Large Dams, 2009.

[19] ICOLD, “Bulletin 157. Small Dams: Design, Surveillance and Rehabilitation,” International Commission on Large Dams, 2016.

[20] USACE, “EM 1110-2-2100 Stability Analysis of Concrete Structures,” US Army Corps of Engineers, 2005.

[21] USACE, “EM 1110-2-2104 Strength Design for Reinforced-Concrete Hydraulic Structures,” United States Army Corps of Engineers, 2003.

[22] USACE, “EM 1110-2-2201 Arch Dam Design,” United States Army Corps of Engineers, 1994.

[23] USACE, “EM 1110-2-2200 Gravity Dam Design,” United States Army Corps of Engineers, 1995.

[24] USBR, “Design of Gravity Dams,” United States Bureau of Reclamation, 1976.

[25] USBR, “Design of Arch Dams,” United States Bureau of Reclamation, 1977.

[26] USBR, “Design of Small Dams,” United States Bureau of Reclamation, 1987.

[27] K. Weaver and D. Bruce, “Dam Foundation Grouting,” American Society of Civil Engineering, 2007.

[28] FEMA, “Technical Manual: Conduits through Embankment Dams,” United States Federal Emergency Management Agency, 2005.

[29] FEMA, “Filters for Embankment Dams: Best Practices for Design and Construction,” United States Federal Emergency Management Agency, 2011.

[30] ICOLD, “Bulletin 91. Embankment Dams. Upstream Slope Protection - Review and Recommendations,” International Commission on Large Dams, 1993.

[31] ICOLD, “Bulletin 92. Rock Materials for Rockfill Dams - Review and Recommendations,” International Commission on Large Dams, 1993.

[32] ICOLD, “Bulletin 95. Embankment Dams - Granular Filters and Drains,” International Commission on Large Dams, 1994.

[33] USACE, “EM 1110-2-1902 Slope Stability,” United States Army Corps of Engineers, 2003.

[34] USACE, “EM 1110-2-2300 General Design and Construction Considerations for Earth and Rock-Fill Dams,” United States Army Corps of Engineers, 2004.

[35] USBR, “Earth Manual, Third Edition,” United States Bureau of Reclamation, 1990.

[36] USBR, “Design Standards No. 13, Embankment Dams,” United States Bureau of Reclamation, 2011.

[37] ICOLD, “Bulletin 102. Vibrations of Hydraulic Equipment for Dams - Review and Recommendations,” International Commission on Large Dams, 1996.

[38] UNICIV, “Report No. R-390, Report on the Analysis of ‘Rapid’ Natural Rock Slope Failures.,” August 2000.

[39] UNICIV, “Report No. R-400 June 2001. Rapid Failure of Soil Slopes.,” 2001.

[40] UNICIV, “Report No. R-403 February 2002. Report on the Analysis of the Deformation Behaviour of Excavated Rock Slopes.,” 2002.

[41] UNICIV, “Report No. R-406 February 2002. Report on the Post-Collapse Behaviour of Debris from Rock Slope Failures.,” 2002.

[42] J. Dunnicliff, “Systematic Approach to Planning Monitoring Programmes using Geotechnical Instrumentation.,” 2013.

[43] J. Dunnicliff, “Geotechnical Instrumentation for Monitoring Field Performance,” 1988.

[44] ICOLD, “Bulletin 158. Dam Surveillance Guide,” International Commission on Large Dams, 2019.

[45] ICOLD, “Bulletin 126. Roller-Compacted Concrete Dams - State of the Art and Case Histories,” International Commission on Large Dams, 2003.

[46] ICOLD, “Bulletin 136. The Specification and Quality Control of Concrete for Dams,” International Commission on Large Dams.

[47] USACE, “ER 1110-1-12. Quality Management,” United States Army Corps of Engineers, 2006.

[48] M. Gillon and et al., “Filling the landslide affected Clyde Reservoir, New Zealand,” in *Proceedings 19th Congress on Large Dams*, Florence, 1997.

[49] USACE, “ER 1110-2-1156 Safety of Dams - Policy and Procedures,” United States Army Corps of Engineers, 2014.

[50] ICOLD, “Bulletin 59. Dam Safety Guidelines,” International Commission on Large Dams, 1987.

[51] FEMA, US ‘Federal Guidelines for Dam Safety Risk Management’ (FEMA P-1025/January 2015), FEMA, 2015.

[52] DRIP, “Guidelines for Safety Inspection of Dams,” Government of India, Central Water Commission, Central Dam Safety Organization, 2018.

[53] BEA, “Regulation for Minimum Safety Requirements for Operation and Maintenance of Hydroelectric Plants,” Bhutan Electricity Authority, 2018.

[54] DGPC, “Dam Safety Guidelines,” Druk Green Power Corporation Ltd., 2015.

[55] DGPC, “Terms of Reference, Dam Safety Committee,” Druk Green Power Corporation Ltd., 2010.

[56] DDM, “Bhutan Disaster Risk Management Status Review,” Department of Disaster Management (DDM), Ministry of Home and Cultural Affairs, Royal Government of Bhutan, 2015.

Annex A: Dam Development Flowchart and Responsibilities.

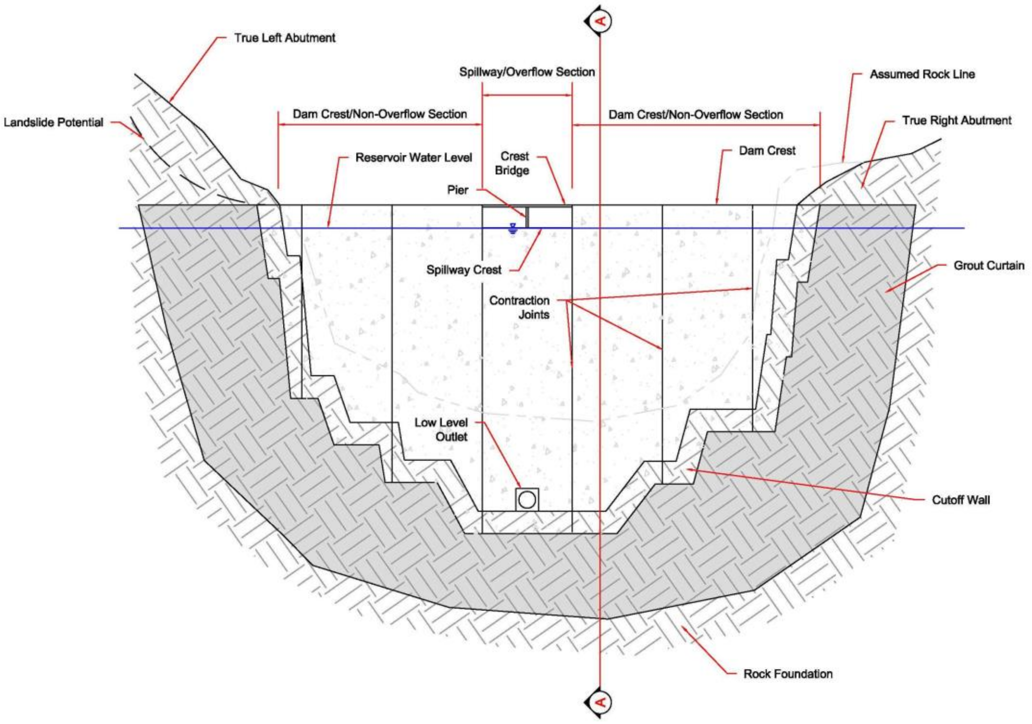
Dam Safety relevant aspects only

	Design Phases	**Responsible**	**Accountable**	**Consulted**	**Informed**
Concept	Preliminary Dam Design Concept.	Des	DHPS		
	Preliminary Failure Modes Assessment.	Exp	Des	DHPS	
	Preliminary Dam Break / Hazard Assessment.	Exp	Des	DHPS	
	Preliminary Dam Classification.	Des	DHPS		BEA
Feasibility	Selection of Initial Design Criteria	Des	DHPS	Peer	
	Specify and undertake Investigation	Geo	Des	Peer	DHPS
	Define hazard, threats and load cases	Exp	Des	Peer	DHPS
	Analyse investigation data/information	Exp	Des	Peer	DHPS
	Develop feasibility design	Exp	Des	Peer	DHPS
	Develop preliminary construction schedule	Des	DHPS	Exp	Peer
	Review & as required update PFM, Dam Class	Des	DHPS	Peer	BEA
Final Design	Define Design Criteria	Des	SPV	Peer	DHPS
	Specify and undertake further investigations	Geo	Des	Peer	SPV
	Reassess hazard, threats and load cases	Exp	Des	Peer	SPV
	Conduct full PFM, Dam Break & Classification	Exp	Des	Peer	SPV/BEA
	Analyse design against load cases & criteria	Exp	Des	Peer	SPV
	Finalise design including appurtenant structures	Exp	Des	Peer	SPV
	Prepare construction strategy	Des	SPV	Exp	Peer
	Define performance criteria and monitoring plan.	Des	Dev	Peer/ Ops	SPV
	Prepare all relevant documentations	Exp	Des	SPV	Peer/ Ops
Key	Designer	Des			
	Dept of Hydropower and Power Systems	DHPS			
	Developer (Special Purpose Vehicle)	SPV/Project Authority			
	Experts	Exp			
	Geologist/Geotechnical Engineer	Geo			
	Peer Reviewer(s) (including panel of Experts)	Peer			
	Regulator (Bhutan Electricity Authority)	BEA			
	Operator	Ops			
Notes	a) Presumes a standard design then build sequence. Responsibilities may change for ECI and Turnkey projects. b) For smaller dams “Peer Reviewer(s)” may be undertaken by internal personnel. c) Large projects are likely to have a prefeasibility stage which will largely mirror the feasibility stage but with less definition and specificity				

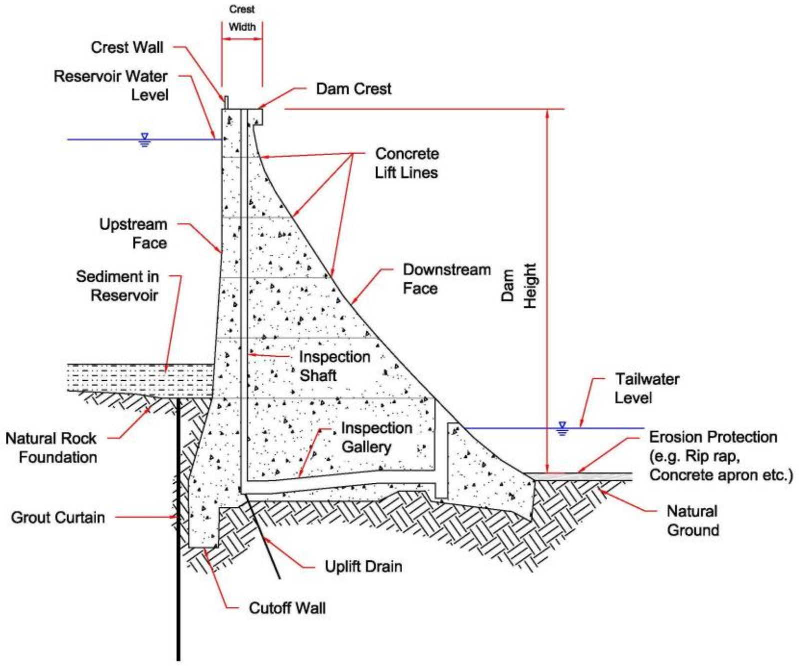
Annex B: Inspection Checklist for Concrete Dams

Dam Characteristics	
Dam name:	
Location:	
Coordinates:	
Coordinate System:	
Type of dam	Gravity Arch Buttress Composite* *(Use Embankment Dam Inspection Form for embankment inspection)* Other:____
Purpose for dam:	Hydropower Irrigation Flood control Water supply Other:____
Name of reservoir:	
Basic Dam Data	
Year Constructed	
Reservoir area (km^2):	
Reservoir capacity (Million m^3)	
Catchment area:	
Lowest point on dam crest (crest RL)	
Height of Dam (m)	
Crest Length (m)	
Crest Width (m)	
Vertical distance from reservoir water level to dam crest	
Downstream slope angle	
Upstream slope angle	
Emergency drawdown facility?	None Culvert Pipe Concrete Steel Weir Fuse plug Other:____
Foundation cut off?	None Grout curtain Cutoff Wall Trench Other:____
Appurtenant Works	
General description of appurtenant works	Spillway Outlet works Power Plant Penstocks Gates Trash Rack Diversion Works Switchyard Other:____________________________
Any other appurtenant works?	
Background Data	
Historic issues	
Upgrades since construction	
Operation Rules & Limitations	
eg. Can lake be filled, is there limitation on spillway, any regulatory requirements affecting operations	
General comments, etc	

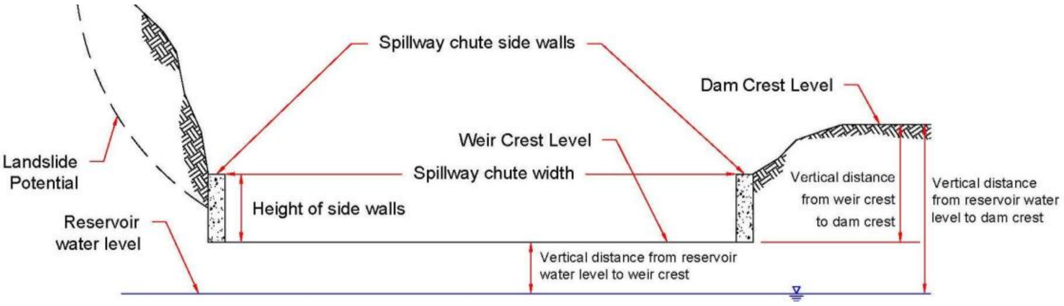
Typical Sections and Terms to assist Inspection Team



DAM ELEVATION VIEW



DAM CROSS SECTION (A-A)



REMOTE FROM DAM SPILLWAY CROSS-SECTION

Site Inspection				
Date and time of Inspection				
Lead Inspector/Team				
Weather	Fine Clear Overcast Raining Rain in last 24 hours			
Setting				
Catchment topography	Steep Mountainous Foothills Lowland Plains Densely Vegetated Bare Other:______________________________			
Access to dam	Easy access to dam Difficult access No access Sealed road Dirt road/ track Foot track only Evidence of slips			
Cross valley profile at dam	Narrow valley Broad valley Steep side slopes Gentle side slopes High side slopes			
Geological unit / lithology				
Dam Crest			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
General description	Sealed Road Unsealed Road Crest Wall Walking track Other:______________________________			
Settlement/ depressions	None Settlement Depressions Other:______________________	Minor Medium Significant		
Alignment deformation, cracking, offset	None Misaligned features Joint offsets Cracks Damaged features Other:	Minor Medium Significant		
Drainage or erosion issues	None Surface erosion Ponding Other:________________	Minor Medium Significant		
Damage from animals or people	None Rutting Tracking Other:______________________	Minor Medium Significant		
Concrete condition	Good Fair Poor None Cracks Spalling Reinforcing visible Rust Poor joint condition Other:___________	Minor Medium Significant		
Dam Crest Wall			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
General description	Concrete crest wall Other :_________________			
Height and thickness of crest wall				
Alignment deformation	None Misaligned features Offsets Settlement Kerbs Fences Walls	Minor Medium Significant		
Wall stability issue	None Instability Poor support Tilting Other:______________________	Minor Medium Significant		
Concrete condition	Good Fair Poor None Cracks Spalling Reinforcing visible Rust marks Vegetation	Minor Medium Significant		
Dam Upstream Face			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Concrete condition	Good Fair Poor None Cracks Spalling Reinforcing visible Rust marks Vegetation	Minor Medium Significant		
Settlement/ depressions/ offset	None Settlement Depressions Joint offset Other:______________________	Minor Medium Significant		
Erosion or Seepage Issues	None Surface erosion Leakage through joints Efflorescence/Calcification Other:________	Minor Medium Significant		
Damage from animals or people	None Rutting Tracking Other:______________________	Minor Medium Significant		

Dam Downstream Face and Toe			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Concrete condition	Good Fair Poor			
	None Cracks Spalling Reinforcing visible Rust marks	Minor Medium Significant		
Downstream Toe features	None Filter Drain Buttress Saturated Erosion Flooded Agriculture Other:____			
Settlement/ depressions/ offset	None Settlement Depressions Joint offset Other:____________________________________	Minor Medium Significant		
Seepage Issues	None Wet patches Leakage through joints Efflorescence/Calcification Other:_____________________________________	Minor Medium Significant		
Erosion concern	None Surface erosion Scouring in downstream toe	Minor Medium Significant		
Inappropriate vegetation	None Small trees Large Trees Dense vegetation Small bushes	Minor Medium Significant		
Damage from animals or people	None Rutting Tracking Other:_____________________________________	Minor Medium Significant		
True Right Abutment			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
General description	Concrete-lined Rock Alluvial Other:____________________			
Slope instability/ rockfall	None Slope failure Settlement Cracking Slumping Loose rock Rock fall	Minor Medium Significant		
Abnormal seepage	None Wet patches Flowing Other:_____________________________________	Minor Medium Significant		
	Clear Turbid			
Drainage or erosion issues	None Surface erosion Rilling Channels Gullys Ponding Other:____________________________	Minor Medium Significant		
Inappropriate vegetation	None Small trees Large Trees Dense vegetation Small bushes	Minor Medium Significant		
Damage from animals or people	None Rutting Pugging Tracking Termites Other:_____________________________________	Minor Medium Significant		
True Left Abutment			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
General description	Concrete-lined Rock Alluvial Other:____________________			
Slope instability/ rockfall	None Slope failure Settlement Cracking Slumping Loose rock Rock fall	Minor Medium Significant		
Abnormal seepage	None Wet patches Flowing Other:_____________________________________	Minor Medium Significant		
	Clear Turbid			
Drainage or erosion issues	None Surface erosion Rilling Channels Gullys Ponding Other:____________________________	Minor Medium Significant		
Inappropriate vegetation	None Small trees Large Trees Dense vegetation Small bushes	Minor Medium Significant		
Damage from animals or people	None Rutting Pugging Tracking Termites Other:_____________________________________	Minor Medium Significant		

Spillway Structure General Description			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Spillway type and location	Chute Stepped Bellmouth Siphon Weir Labyrinth Drop Inlet Fuse Plug Auxilary Spillway On dam body Remote from dam In natural ground			
Spillway chute width				
Height of side walls				
Spillway Crest Level (RL)	Spillway Flowing? Yes / No			
Vertical distance from reservoir water level to weir crest				
Vertical distance from weir crest to dam crest				
Approximate chute slope				
Spillway control	Uncontrolled Radial Gates Vertical Gates Manual Automatic Other:____________________			
Spillway Forebay/Approach			**Recommendation**	**Action Taken**
Slope instability	Slope failure Settlement Cracking Slumping Other:____________________	Minor Medium Significant		
Concrete condition	Good Fair Poor None Cracks Spalling Reinforcing visible Rust marks	Minor Medium Significant		
Abnormal flow pattern	None Vortices Flow behind concrete structure Other:____________________	Minor Medium Significant		
Flow obstruction/ blockage	None Vegetation Man made structure Agriculture			
Potential for blockage	None Floating debris Overhanging trees Other:____________			
Spillway Control/ Gate Structure (if applicable)			**Recommendation**	**Action Taken**
Abnormal alignment of block joints	Displacement Offset joints Other:____________________			
Concrete condition	Good Fair Poor None Cracks Spalling Reinforcing visible Rust marks	Minor Medium Significant		
Spillway gate issues	None Rust Damage Inoperable Other:____________________	Minor Medium Significant		
Winches/ hydraulic issues	None Rust Damage Inoperable Other:____________________	Minor Medium Significant		
Spillway Chute and Energy Dissipation			**Recommendation**	**Action Taken**
Chute lining	Concrete Rock Rip Rap Grass Earth Other:____________			
Block joint alignment abnormal	Normal Steps at joints Gaps at joints Cracks	Minor Medium Significant		
Chute lining condition	Good Fair Poor None Cracks Spalling Reinforcing visible Voids Rust marks Erosion Leakage	Minor Medium Significant		
Abnormal seepage	None Wet patches Flowing Other:____________________ Clear Turbid	Minor Medium Significant		
Abnormal drain condition	None Blocked Clear Flow Turbid Flow Other:____________________	Minor Medium Significant		
Seepage into spillway	None Clear Flow Turbid Flow	Minor Medium Significant		
Slope instability and erosion	None Side slope failure Settlement Cracking Slumping Floor erosion Depression behind walls Other:____________	Minor Medium Significant		
Abnormal condition when discharges are occurring	None Unusual Flow Pattern Erosion Unusual Seepage	Minor Medium Significant		
Downstream energy dissipator (eg. stilling basin) type and condition	Flip bucket Sharks Teeth Concrete Wall Rock lined Natural ground Other:____________________	Good Fair Poor		
Downstream erosion	None Undercutting of spillway structure Erosion of downstream channel Other:____________________	Minor Medium Significant		

Inlet/ Culvert/ Pipe/ Outlet			**Recommendation**	**Action Taken**
Photographs of inlet and outlet	Yes No Photo reference(s):			
Inlet type and location	Tower Walkway Access Weir Wing Walls Concrete Steel Other:____			
Inlet Control Type and Location	Knife Valve Gate Valve Radial Gate Manual Automatic Upstream Downstream			
Inlet Condition	Good Fair Poor			
	None Cracks Spalling Reinforcing visible Voids Inoperable Rusted Not inspected Other:_________________________________ _	Minor Medium Significant		
Abnormal conditions at inlet	None Vortices Floating Debris Blockages Slope Instability Other:__________________	Minor Medium Significant		
Culvert Type	Pipe Box culvert Concrete Steel Other:_________________________			
Culvert Size				
Seepage around culvert	None Damp Wet Soggy Flowing Clear Turbid	Minor Medium Significant		
Culvert features (if known)	Filter Seepage collars Other:___________________________________			
Culvert Condition	Good Fair Poor Blocked Not Inspected			
Outlet type and location	Concrete wing wall Concrete Pipe Tunnel Irrigation channel Steel Pipe Rock channel Concrete Channel River Bed Canal			
Outlet condition	Good Fair Poor Blocked Overgrown Drowned Not Inspected			
Abnormal/ turbid outflow	None From natural ground From behind concrete wall Clear Turbid	Minor Medium Significant		
Penstocks and Penstock Slope (hydro-power dams only)			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Abnormal condition of penstocks	None Damage Leaks Dents Rust Missing bolts	Minor Medium Significant		
Abnormal condition of penstock pedestals	None Damage Rust Collapse Cracking Not inspected	Minor Medium Significant		
Slope instability/ cracking	None Slope failure Settlement Cracking Slumping Other:________________________	Minor Medium Significant		
Seepage from slope	None Damp Wet Soggy Flowing Clear Turbid	Minor Medium Significant		
Penstock leakage	None Dripping Flowing	Minor Medium Significant		
Inappropriate vegetation	None Small trees Large Trees Dense vegetation Small bushes	Minor Medium Significant		
Damage from animals or people	None Rutting Pugging Tracking Other:_________________________________	Minor Medium Significant		
Drainage Gallery (if applicable)			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Concrete condition	Good Fair Poor			
	None Cracks Spalling Rust marks Joints offset Reinforcing visible Deformation Other:_________________________________	Minor Medium Significant		
Abnormal seepage	In to gallery Out of gallery Other:__________	Minor Medium Significant		
Abnormal condition of gallery drains	Blocked Collapsed Other:__________________	Minor Medium Significant		
Lighting and Ventilation	None No lighting Lighting non-functional No ventilation Ventilation non-functional	Minor Medium Significant		
Instrumentation	None Instrumentation non-functional Other:________________________			

Landslides and Instability			**Recommendation**	**Action Taken**
Instability photograph	Yes No Photo reference(s):			
Landslide into Reservoir	Landslide material in reservoir Recent failure Landslide ground features Other:____	Minor Medium Significant		
Landslide in Dam vicinity	None Historic landslide evidence Scarps/cracks on slopes Landslide ground features Recent failure	Minor Medium Significant		
Dam foundations	None Low strength material in exposures Adverse geological material in exposures Other:____	Minor Medium Significant		
Reservoir			**Recommendation**	**Action Taken**
General reservoir photograph	Yes No Photo reference(s):			
Abnormal condition	Other:____	Minor Medium Significant		
Erosion or beaching around reservoir rim	None Surface erosion Rilling Channels Gullys Cliffing Beaching Other:____	Minor Medium Significant		
Erosion or beaching around reservoir rim	None Surface erosion Rilling Channels Gullys Cliffing Beaching Abnormal flow patterns Other:____	Minor Medium Significant		
Floating debris in reservoir	None Trees Boom obstructed Other:____________________________________			
Sediment level in reservoir	High Medium Low			
Miscellaneous			**Recommendation**	**Action Taken**
Access to dam	Easy access to dam Difficult access Sealed road/ track Dirt road/ track Foot track only Evidence of slips			
Accessibility around dam	Foot access only Machine access Other:____________________________________			
Nature of downstream river bed	Rocky Gravelly Sands Silts Other:____			
General Comments			**Recommendation**	**Action Taken**
Provide overall comment on impressions/ maintenance/ operating regime/ experience of operators/ dam condition/ risk factors/ concerns etc.				
Note any instrumentation or surveillance undertaken				

Major/Main Issues - *Provide overall comment on main issues identified.*	
Issue	Comments

General Layout Sketch

GPS Coordinates

Sketch Signed ____________________

Ref ID	Easting	Northing	Elevation	Note

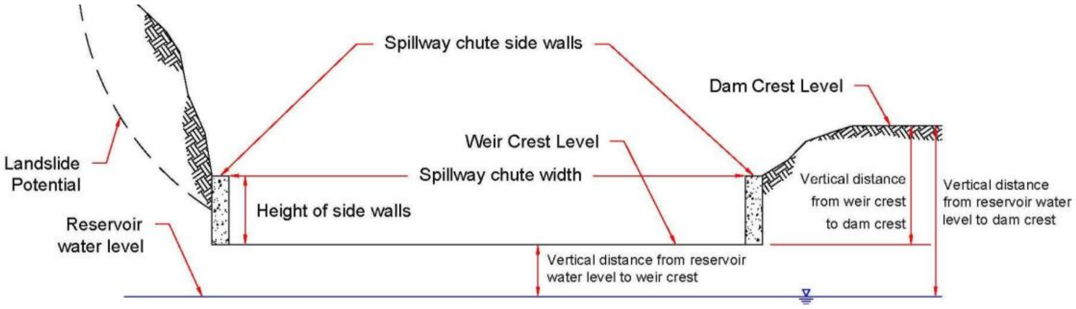
Annex C: Inspection Checklist for Embankment Dams

Dam Characteristics	
Dam name:	
Location:	
Coordinates:	
Coordinate System:	
Type of dam	Embankment
Purpose for dam:	Irrigation Flood control Hydropower Water supply Other:____
Name of reservoir:	
Basic Dam Data	
Year Constructed	
Reservoir area (km^2):	
Reservoir capacity (Million m^3)	
Catchment area:	
Lowest point on dam crest (crest RL)	
Height of Dam (m)	
Crest Length (m)	
Crest Width (m)	
Vertical distance from reservoir water level to dam crest	
Downstream slope angle	
Upstream slope angle	
Emergency drawdown facility?	None Culvert Pipe Concrete Steel Weir Fuse plug Other:____
Foundation cut off?	None Grout curtain Cutoff Wall Trench Other:____
Appurtenant Works	
General description of appurtenant works	Spillway Outlet works Power Plant Penstocks Gates Trash Rack Diversion Works Switchyard Other:__________________________
Any other appurtenant works?	
Background Data	
Historic issues	
Upgrades since construction	
Operation Rules & Limitations	
eg. Can lake be filled, is there limitation on spillway, any regulatory requirements affecting operations	
General comments, etc	

Typical Sections and Terms to assist Inspection Team

DAM ELEVATION VIEW

DAM CROSS SECTION (A-A)



REMOTE FROM DAM SPILLWAY CROSS-SECTION

Site Inspection				
Date and time of Inspection				
Lead Inspector/Team				
Weather	Fine Clear Overcast Raining Rain in last 24 hours			
Setting				
Catchment topography	Steep Mountainous Foothills Lowland Plains Densely Vegetated Bare Other:______________________________			
Access to dam	Easy access to dam Difficult access No access Sealed road Dirt road/ track Foot track only Evidence of slips			
Cross valley profile at dam	Narrow valley Broad valley Steep side slopes Gentle side slopes High side slopes			
Geological unit / lithology				
Dam Crest			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
General description	Sealed Road Unsealed Road Crest Wall Walking track Other:______________________________			
Settlement/ depressions	None Settlement Depressions Other:____________________	Minor Medium Significant		
Alignment deformation, cracking, slides/slips	None Misaligned features Local Slides Cracks Damaged features Other:	Minor Medium Significant		
Drainage or erosion issues	None Surface erosion Ponding Other:_______________	Minor Medium Significant		
Damage from animals or people, vegetation	None Rutting Tracking Vegetation Other:____________________	Minor Medium Significant		
Condition of auxilliary items (parapet wall, lighting, railings, etc)	Good Fair Poor			
	None Cracks Spalling Reinforcing visible Rust Other:__________	Minor Medium Significant		
Dam Upstream Slope			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Stability Status	Good Fair Poor	Minor Medium Significant		
Settlement/ depressions, Bulging	None Settlement Depressions Bulging Size & Location:______________	Minor Medium Significant		
Cracking	None Crack Description: Length, Opening, Depth and Direction________________	Minor Medium Significant		
Vegetation - Trees, Shrubs, Etc.	None Minor Moderate Significant Description:______________	Minor Medium Significant		
Slope Protection - Rip-rap, Etc.	Intact Damaged Eroded Other:____________________	Minor Medium Significant		
Condition of facing	Intact Damaged Eroded Other:____________________	Minor Medium Significant		
Damage from animals or people	None Rutting Tracking Holes Other:____________________	Minor Medium Significant		

Dam Downstream Slope and Toe			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Stability Status	Good Fair Poor	Minor Medium Significant		
Settlement/ depressions, Bulging	None Settlement Depressions Bulging Size & Location:___________________________	Minor Medium Significant		
Cracking	None Crack Description: Length, Opening, Depth and Direction_______________________________	Minor Medium Significant		
Seepage, Leakage, Piping	None Minor Moderate Significant Description:___________________________	Minor Medium Significant		
Intentional vegetation - grass, bushes, etc.	Intact Damaged Missing Other:_______________________________________	Minor Medium Significant		
Unintended Vegetation - Trees, Shrubs, Etc.	None Minor Moderate Significant Description:___________________________	Minor Medium Significant		
Slope Protection - Rip-rap, Etc.	Intact Damaged Eroded Other:_______________________________________	Minor Medium Significant		
Condition of facing	Intact Damaged Eroded Other:_______________________________________	Minor Medium Significant		
Erosion channels, debris, slides, or other damage	None Minor Moderate Significant Description:___________________________	Minor Medium Significant		
Damage from animals or people	None Rutting Tracking Holes Other:_______________________________________	Minor Medium Significant		
True Right Abutment			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
General description	Concrete-lined Rock Alluvial Other:____________________			
Slope instability/ rockfall	None Slope failure Settlement Cracking Slumping Loose rock Rock fall	Minor Medium Significant		
Abnormal seepage	None Wet patches Flowing Other:_______________________________________ Clear Turbid	Minor Medium Significant		
Abutment/ Embankment Junction - Wet areas, depression, bulges, etc.	Dry Wet Depression Bulges Cracks Slides Other:________________________	Minor Medium Significant		
Drainage or erosion issues	None Surface erosion Rilling Channels Gullys Ponding Other:______________________________	Minor Medium Significant		
Inappropriate vegetation	None Small trees Large Trees Dense vegetation Small bushes	Minor Medium Significant		
Damage from animals or people	None Rutting Pugging Tracking Insects Other:_______________________________________	Minor Medium Significant		
True Left Abutment			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
General description	Concrete-lined Rock Alluvial Other:____________________			
Slope instability/ rockfall	None Slope failure Settlement Cracking Slumping Loose rock Rock fall	Minor Medium Significant		
Abnormal seepage	None Wet patches Flowing Other:_______________________________________ Clear Turbid	Minor Medium Significant		
Abutment/ Embankment Junction - Wet areas, depression, bulges, etc.	Dry Wet Depression Bulges Cracks Slides Other:________________________	Minor Medium Significant		
Drainage or erosion issues	None Surface erosion Rilling Channels Gullys Ponding Other:______________________________	Minor Medium Significant		
Inappropriate vegetation	None Small trees Large Trees Dense vegetation Small bushes	Minor Medium Significant		
Damage from animals or people	None Rutting Pugging Tracking Insects Other:_______________________________________	Minor Medium Significant		

Spillway Structure General Description			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Spillway type and location	Chute Stepped Bellmouth Siphon Weir Labyrinth Drop Inlet Fuse Plug Auxilary Spillway			
	On dam body Remote from dam In natural ground			
Spillway chute width				
Height of side walls				
Spillway Crest Level (RL)	Spillway Flowing? Yes / No			
Vertical distance from reservoir water level to weir crest				
Vertical distance from weir crest to dam crest				
Approximate chute slope				
Spillway control	Uncontrolled Radial Gates Vertical Gates Manual Automatic Other:____________________			
Spillway Forebay/Approach			**Recommendation**	**Action Taken**
Slope instability	Slope failure Settlement Cracking Slumping Other:____________________	Minor Medium Significant		
Concrete condition	Good Fair Poor			
	None Cracks Spalling Reinforcing visible Rust marks	Minor Medium Significant		
Abnormal flow pattern	None Vortices Flow behind concrete structure Other:____________________	Minor Medium Significant		
Flow obstruction/ blockage	None Vegetation Man made structure Agriculture			
Potential for blockage	None Floating debris Overhanging trees Other:____________			
Spillway Control/ Gate Structure (if applicable)			**Recommendation**	**Action Taken**
Abnormal alignment of block joints	Displacement Offset joints Other:____________________			
Concrete condition	Good Fair Poor			
	None Cracks Spalling Reinforcing visible Rust marks	Minor Medium Significant		
Spillway gate issues	None Rust Damage Inoperable Other:____________________	Minor Medium Significant		
Winches/ hydraulic issues	None Rust Damage Inoperable Other:____________________	Minor Medium Significant		
Spillway Chute and Energy Dissipation			**Recommendation**	**Action Taken**
Chute lining	Concrete Rock Rip Rap Grass Earth Other:______________			
Block joint alignment abnormal	Normal Steps at joints Gaps at joints Cracks	Minor Medium Significant		
Chute lining condition	Good Fair Poor			
	None Cracks Spalling Reinforcing visible Voids Rust marks Erosion Leakage	Minor Medium Significant		
Abnormal seepage	None Wet patches Flowing Other:____________________	Minor Medium Significant		
	Clear Turbid			
Abnormal drain condition	None Blocked Clear Flow Turbid Flow Other:____________________	Minor Medium Significant		
Seepage into spillway	None Clear Flow Turbid Flow	Minor Medium Significant		
Slope instability and erosion	None Side slope failure Settlement Cracking Slumping Floor erosion Depression behind walls Other:______________	Minor Medium Significant		
Abnormal condition when discharges are occurring	None Unusual Flow Pattern Erosion Unusual Seepage	Minor Medium Significant		
Downstream energy dissipator (eg. stilling basin) type and condition	Flip bucket Sharks Teeth Concrete Wall Rock lined Natural ground Other:____________________	Good Fair Poor		
Downstream erosion	None Undercutting of spillway structure Erosion of downstream channel Other:____________________	Minor Medium Significant		

Inlet/ Culvert/ Pipe/ Outlet			**Recommendation**	**Action Taken**
Photographs of inlet and outlet	Yes No Photo reference(s):			
Inlet type and location	Tower Walkway Access Weir Wing Walls Concrete Steel Other:____			
Inlet Control Type and Location	Knife Valve Gate Valve Radial Gate			
	Manual Automatic			
	Upstream Downstream			
Inlet Condition	Good Fair Poor			
	None Cracks Spalling Reinforcing visible Voids Inoperable Rusted Not inspected Other:______________________________ _	Minor Medium Significant		
Abnormal conditions at inlet	None Vortices Floating Debris Blockages Slope Instability Other:________________	Minor Medium Significant		
Culvert Type	Pipe Box culvert Concrete Steel Other:____________________			
Culvert Size				
Seepage around culvert	None Damp Wet Soggy Flowing Clear Turbid	Minor Medium Significant		
Culvert features (if known)	Filter Seepage collars Other:____________________________			
Culvert Condition	Good Fair Poor Blocked Not Inspected			
Outlet type and location	Concrete wing wall Concrete Pipe Tunnel Irrigation channel Steel Pipe Rock channel Concrete Channel River Bed Canal			
Outlet condition	Good Fair Poor Blocked Overgrown Drowned Not Inspected			
Abnormal/ turbid outflow	None From natural ground From behind concrete wall Clear Turbid	Minor Medium Significant		
Penstocks and Penstock Slope (hydro-power dams only)			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Abnormal condition of penstocks	None Damage Leaks Dents Rust Missing bolts	Minor Medium Significant		
Abnormal condition of penstock pedestals	None Damage Rust Collapse Cracking Not inspected	Minor Medium Significant		
Slope instability/ cracking	None Slope failure Settlement Cracking Slumping Other:______________________	Minor Medium Significant		
Seepage from slope	None Damp Wet Soggy Flowing Clear Turbid	Minor Medium Significant		
Penstock leakage	None Dripping Flowing	Minor Medium Significant		
Inappropriate vegetation	None Small trees Large Trees Dense vegetation Small bushes	Minor Medium Significant		
Damage from animals or people	None Rutting Pugging Tracking Other:______________________________	Minor Medium Significant		
Downstream Drainage			**Recommendation**	**Action Taken**
General layout photograph	Yes No Photo reference(s):			
Boils, wet conditions, growth of aquatic weeds	None Boils Wet Conditions Aquatic Weeds Other:______________________________ _	Minor Medium Significant		
Formation of local pool or saturated area	None Pool Saturated Area Observations:__________	Minor Medium Significant		
Free flowing passage to downstream	Yes No Observations:________________	Minor Medium Significant		
Depth of water table in vicinity of downstream slope	Observations:________________	Minor Medium Significant		
Condition and maintenance of downstream drains	Good Fair Poor Observations:__________________________	Minor Medium Significant		
Surface drainage	Good Fair Poor Observations:__________________________	Minor Medium Significant		
Relief Wells	Good Fair Poor Observations:__________________________	Minor Medium Significant		
Seepage Measurement - Variations, Colour, Turbidity, Location	Seepage Abnormal variation Colour Turbidity Observations:__________________________ _	Minor Medium Significant		

Landslides and Instability			**Recommendation**	**Action Taken**
Instability photograph	Yes No Photo reference(s):			
Landslide into Reservoir	Landslide material in reservoir Recent failure Landslide ground features Other:____	Minor Medium Significant		
Landslide in Dam vicinity	None Historic landslide evidence Scarps/cracks on slopes Landslide ground features Recent failure	Minor Medium Significant		
Dam foundations	None Low strength material in exposures Adverse geological material in exposures Other:____	Minor Medium Significant		
Reservoir			**Recommendation**	**Action Taken**
General reservoir photograph	Yes No Photo reference(s):			
Abnormal condition	Other:____	Minor Medium Significant		
Erosion or beaching around reservoir rim	None Surface erosion Rilling Channels Gullys Cliffing Beaching Other:____	Minor Medium Significant		
Erosion or beaching around reservoir rim	None Surface erosion Rilling Channels Gullys Cliffing Beaching Abnormal flow patterns Other:____	Minor Medium Significant		
Floating debris in reservoir	None Trees Boom obstructed Other:___________________________________			
Sediment level in reservoir	High Medium Low			
Miscellaneous			**Recommendation**	**Action Taken**
Access to dam	Easy access to dam Difficult access Sealed road/ track Dirt road/ track Foot track only Evidence of slips			
Accessibility around dam	Foot access only Machine access Other:__________________________________			
Nature of downstream river bed	Rocky Gravelly Sands Silts Other:_____________________________________			
General Comments			**Recommendation**	**Action Taken**
Provide overall comment on impressions/ maintenance/ operating regime/ experience of operators/ dam condition/ risk factors/ concerns etc.				
Note any instrumentation or surveillance undertaken				

Major/Main Issues - *Provide overall comment on main issues identified.*	
Issue	Comments

General Layout Sketch

GPS Coordinates

Sketch Signed ____________________

Ref ID	Easting	Northing	Elevation	Note