

## HOW-TO GUIDE

# Hydropower Infrastructure Safety

A guide for hydropower project developers and operators on delivering good international industry practice



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*Photo Credit: Voith Group*

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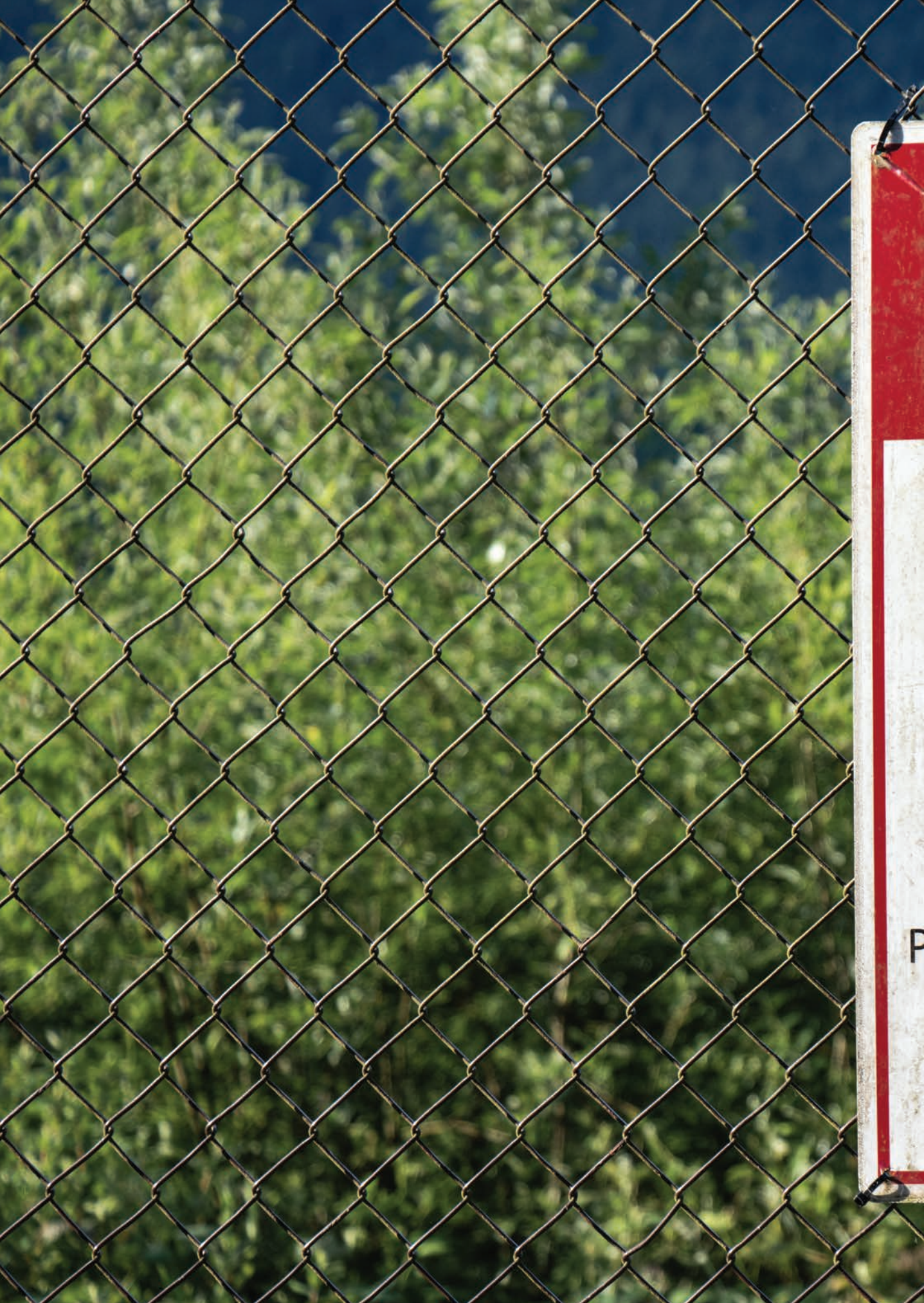


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# Glossary

|                                             |                                                                                                                                                                                                                                                        |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Aggregate</b>                            | Set of rock fragments of different sizes and shapes, used as a component of concrete.                                                                                                                                                                  |
| <b>Anchoring</b>                            | Cable deep-sealed in a wall to stabilise it.                                                                                                                                                                                                           |
| <b>Bearing capacity</b>                     | The ability of an element (often the ground) to support a load.                                                                                                                                                                                        |
| <b>Cascade project</b>                      | A group of hydroelectric projects on the same river, operating in a dependent manner.                                                                                                                                                                  |
| <b>Cofferdam</b>                            | An enclosure built within a body of water to allow the enclosed area to be dewatered for works.                                                                                                                                                        |
| <b>Concrete swelling</b>                    | The excess of free water in the concrete mixture, which causes separation between concrete and excess water.                                                                                                                                           |
| <b>Design flood</b>                         | Value of the instantaneous peak discharge, adopted for the design of a particular project or any of its structures.                                                                                                                                    |
| <b>Digital Elevation Model (DEM)</b>        | A 3D computer graphics representation of elevation data to represent terrain.                                                                                                                                                                          |
| <b>Distinct Element Method (DEM)</b>        | A numerical method used to describe the mechanical behaviour of discontinuous bodies.                                                                                                                                                                  |
| <b>Failure modes &amp; Effects analysis</b> | A step-by-step approach for identifying all possible failure modes in a design, manufacturing or assembly process, or a product or service.                                                                                                            |
| <b>Finite Element Method (FEM)</b>          | A widely used method for numerically solving differential equations in engineering and mathematical modelling.                                                                                                                                         |
| <b>Flushing operation</b>                   | Consists of opening a low-level gated outlet to flush accumulated sediment from a reservoir.                                                                                                                                                           |
| <b>Foundation discontinuities</b>           | Location of significant change in the physical and mechanical properties of the geological formation and foundation conditions.                                                                                                                        |
| <b>Grout curtain</b>                        | A barrier protecting the foundation of a dam from seepage. It can be made during initial construction or during repair, and consists of a row of vertically drilled holes filled with pressurised grout.                                               |
| <b>Hydraulic head</b>                       | Water pressure at one point. Often characterised by a water height or elevation.                                                                                                                                                                       |
| <b>Hydrostatic load</b>                     | The physical force that a mass of water at rest applies to an element.                                                                                                                                                                                 |
| <b>Karstic geology</b>                      | Karst is a topography formed from the dissolution of soluble rocks such as limestone, dolomite and gypsum. It is characterised by underground drainage systems with sinkholes and caves.                                                               |
| <b>Mine tailings dam</b>                    | An earth-fill embankment dam used to store by-products of the mining and mineral extraction processes.                                                                                                                                                 |
| <b>Penstock</b>                             | A water conveyance structure with pressurised water flows (e.g. steel or polymetric pipe resting on concrete supports).                                                                                                                                |
| <b>Piezometer</b>                           | A device used to measure liquid pressure in a system by measuring the height to which a column of the liquid rises against gravity, or a device which measures the pressure (more precisely, the piezometric head) of groundwater at a specific point. |
| <b>Plunge pool</b>                          | A deep basin excavated at the foot of a waterfall (of the dam spillway structure) by the action of the falling water.                                                                                                                                  |

|                                             |                                                                                                                                                                                                                                                                   |
|---------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Pressure head</b>                        | Pressure expressed in units of height of a water column.                                                                                                                                                                                                          |
| <b>Probable Maximum Flood (PMF)</b>         | The largest theoretical flood resulting from a combination of the most severe meteorological and hydrologic conditions that could conceivably occur in a given area.                                                                                              |
| <b>Probable Maximum Precipitation (PMP)</b> | The greatest depth of precipitation for a given duration that is meteorologically possible for a given size storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends.                               |
| <b>Pseudo-static analysis</b>               | A method that considers dynamic forces as being equivalent to static forces.                                                                                                                                                                                      |
| <b>Relative displacements</b>               | Displacements expressed in relation to other points also in displacement.                                                                                                                                                                                         |
| <b>Return period</b>                        | A statistical average period of time, or an estimated average period of time between events.                                                                                                                                                                      |
| <b>Rheological properties</b>               | A branch of physics that studies the way in which materials deform or flow in response to applied forces or stresses. The material properties that govern the specific way in which these deformation or flow behaviours occur are called rheological properties. |
| <b>Risk acceptability criteria</b>          | Criteria defining the overall risk level that is considered acceptable, with respect to a defined activity period.                                                                                                                                                |
| <b>Shear strength</b>                       | The resistance capacity of a material to a rupture, parallel to the direction of the force.                                                                                                                                                                       |
| <b>Soil liquefaction</b>                    | A phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Liquefaction occurs in saturated soils.                                                                                                       |
| <b>Spillways</b>                            | Free or gated structural elements used to discharge water, to manage water levels upstream of the facility.                                                                                                                                                       |
| <b>Stresses</b>                             | Forces passing through an element, expressed as a force distributed over a surface area ( $\text{N/m}^2$ ).                                                                                                                                                       |
| <b>Surge tanks</b>                          | A tank connected to a pipe carrying a liquid. It is intended to neutralise sudden changes of pressure in the flow by filling when the pressure increases and emptying when it drops, and is used to protect the remainder of the hydraulic system.                |
| <b>Switchyard</b>                           | An enclosed area of a power system containing the switchgear (switching equipment used in the transmission of electricity).                                                                                                                                       |
| <b>Tailrace channels</b>                    | A channel downstream from a hydropower plant, through which the turbinised water is discharged after being used.                                                                                                                                                  |
| <b>Time-to-fatigue-failure</b>              | Fatigue failure is the formation and propagation of cracks due to a repetitive or cyclic load. Failure requires a necessary cumulated amount of cycles for a crack to propagate sufficiently within the structure.                                                |
| <b>Total response time</b>                  | Duration of the implementation of actions to minimise the impact of an unfavourable event.                                                                                                                                                                        |
| <b>Turbid discharges</b>                    | Flow of water loaded with fine solids.                                                                                                                                                                                                                            |
| <b>Turbulent processes</b>                  | Fluid motion characterised by chaotic changes in pressure and flow velocity.                                                                                                                                                                                      |
| <b>Upstream water storage</b>               | A reservoir upstream of a hydropower plant, to store water for use when it is more valuable.                                                                                                                                                                      |
| <b>Weirs</b>                                | A low dam (typically within 15 m above the foundation) built across a river to raise the level of water upstream or to regulate its flow.                                                                                                                         |
| <b>Zoned earth dam</b>                      | A dam composed of several zones of material with different characteristics, including permeability.                                                                                                                                                               |



# 1

## Introduction

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**IF YOU SEE ANY  
DAM SAFETY CONCERNS**

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# Introduction

Hydropower projects can have significant implications for public safety. Their infrastructure components, and in particular their dams, need to be sited, designed, built and operated to keep the general public, property (including both private and public assets, and cultural heritage resources), and the environment safe from any adverse consequences. In some cases, hydropower projects may also be able to reduce some pre-existing public safety risks, for example by providing flood mitigation or by improving roads.

Responsible hydropower developers, owners and operators will make decisions with an awareness of public safety risks and opportunities, and in consultation with stakeholders. A systematic process for understanding and managing public safety will facilitate public acceptance, mitigate business risks, and increase the economic viability of a project.



Powerhouse at Kárahnjúkar  
Hydropower plant in Iceland  
*Photo Credit: Landsvirkjun*

## 1.1 This How-to Guide

### 1.1.1 Aim

This How-to Guide aims to increase the knowledge and understanding of measures that can be employed to meet good international industry practice, in conformance with the internationally recognised Hydropower Sustainability Tools (see Box 1).

The guide expands upon the Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIP) and is designed to support practitioners and stakeholders in infrastructure safety issues.

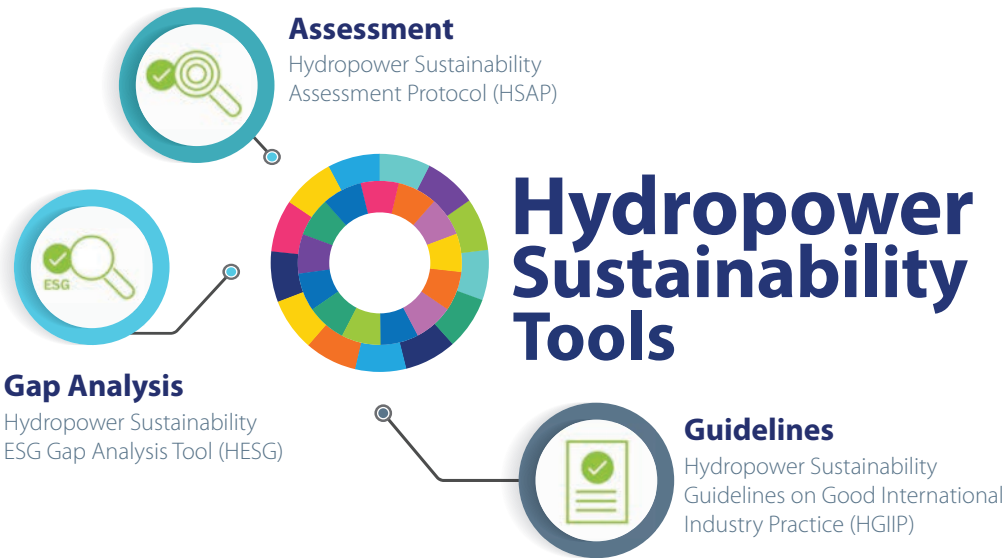
The key decision-makers for infrastructure safety issues are the companies that develop, own and operate hydropower projects, as well as various government agencies that are concerned with safety regulation, water management, emergency response and related issues. Water storage behind a dam and the other components of a project inevitably introduce new risks for communities within the potentially affected region. This guide provides a framework for considering all safety impacts in the decision-making process, throughout the project life cycle. It is intended to assist decision-makers in recognising safety issues caused by a project and managing them responsibly. It can also

help other stakeholders to engage effectively with projects.

Keeping the public safe can be challenging because projects can have multiple components with a variety of safety issues, all with different probabilities of occurrence and resulting consequences. Also, responsibilities can be divided between project owners, regulators, emergency services, and members of the public. While this guide provides an overview of the key safety issues, drawing on technical knowledge from different disciplines, it is not prescriptive in terms of technical criteria, and it does not replace the detailed technical expertise required for the safe design and operations of dams and other infrastructure components.

### 1.1.2 Approach and layout

The approach of this guide is to map out the necessary steps and deliverables that the hydropower developer or operator should take in order to meet good international industry practice related to infrastructure safety, throughout the project life cycle – from early concept through to detailed design, construction, and operation.



The Hydropower Sustainability Tools are governed by the Hydropower Sustainability Assessment Council, a multi-stakeholder group of industry, government, financial institutions, and social and environmental NGOs. The tools are supported by the International Hydropower Association (IHA), the council's management body.

## Sustainability guidelines

The Hydropower Sustainability Guidelines on Good International Industry Practice define expected sustainability performance for the sector across a range of environmental, social, technical and governance topics. Released in 2018, the 26 guidelines present definitions of the processes and outcomes related to good practice in project planning, operation and implementation. As a compendium, the guidelines are a reference document for meeting the expectations of lenders, regulators and consumers. Compliance with each guideline can be specified in commercial contracts between financiers and developers, and between developers and contractors. The guidelines are based on the performance framework of the Hydropower Sustainability Assessment Protocol.



### Infrastructure Safety

The Infrastructure Safety good practice guideline addresses the management of infrastructure safety issues with the hydropower project or operating facility. Adherence with this guideline is measured using the HSAP and the HESG.

## Further information

Visit [Hydrosustainability.org](https://hydrosustainability.org)

## Assessment protocol

The Hydropower Sustainability Assessment Protocol offers a framework for objective assessments of hydropower project performance. It was developed between 2007 and 2010 following a review of the World Commission on Dams' recommendations, the Equator Principles, the World Bank Safeguard Policies and IFC Performance Standards, and IHA's own previous sustainability tools. Assessments are delivered by independent accredited assessors and can examine different stages of a project's life cycle. Evidence collected during an assessment is used to create a sustainability profile and benchmark performance against both good and best proven practice. The assessment protocol was updated in 2018 with a new topic covering hydropower's carbon footprint and resilience to climate change.

## Gap analysis tool

The Hydropower Sustainability ESG Gap Analysis Tool enables hydropower project proponents and investors to identify and address gaps against international good practice. Launched in 2018, the tool is based on the assessment framework of the HSAP's environmental, social and governance topics.

It provides a gap management action plan to help a project team address any gaps and is divided into 12 sections that are compatible with both the IFC Environmental and Social Performance Standards and the World Bank's Environmental and Social Framework.

The guide is presented in five chapters and two annexes:

- **Chapter 1** – Introduction
- **Chapter 2** – Understanding infrastructure safety in hydropower
- **Chapter 3** – Achieving good international industry practice
- **Chapter 4** – Methodologies and approaches
- **Chapter 5** – Conclusions
- **Annex 1** – Bibliography
- **Annex 2** – Project examples

## 1.2 Infrastructure safety in the Hydropower Sustainability Tools

The hydropower sector now has a suite of tools to deliver sustainable outcomes. These tools include the Hydropower Sustainability Assessment Protocol (HSAP), the Hydropower Sustainability Environmental, Social, and Governance Gap Analysis Tool (HESG), and the Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIIP).

A separate topic on Infrastructure Safety is included in all three of the main HSAP tools, each of which corresponds to a project life cycle stage – preparation, implementation, and operation. These requirements on infrastructure safety are also set out in the HESG. They provide definitions of good and best international industry practice in the management of infrastructure safety, in relation to criteria on Assessment, Management, Conformance / Compliance, and Outcomes. Infrastructure safety is always assumed to be relevant, and should thus be evaluated in any HSAP and HESG assessment.

The intent is that life, property and the environment are protected from the consequences of dam failure and other infrastructure risks related to safety.

### 1.2.1 Objectives of this How-to Guide

This guide is designed to help the practitioner to:

- understand potential safety impacts of dams and other infrastructure on the public;

- minimise, mitigate and compensate residual negative impacts, in a cost-effective manner;
- avoid unnecessary negative impacts and enhance positive impacts; and
- achieve and maintain stakeholder acceptance and regulatory approvals related to safety issues.

The objective is to give practitioners the necessary knowledge of how to manage infrastructure safety issues, using a range of strategies and approaches, and how to find further expertise and guidance. It is intended for those engaged in the development and operation of hydropower projects, as well as stakeholders with interests in these projects and in the wider hydropower industry.

### 1.2.2 Scope and limitations

The scope of this guide covers:

- The basic good practice requirements for the management of infrastructure safety, set out in the HSAP and associated tools.
- All stages of a project's life, from the early stage, through preparation, implementation and operation.
- All impacts on public safety, resulting from different project components.
- All locations, sizes and types of projects, including run-of-river, storage, pumped storage, cascade and inter-basin transfer projects.

The geographic scope of safety assessment and management should encompass all significant safety risks and opportunities, including both upstream and downstream areas that could be affected by dam failures and operational flood management, and areas affected by transmission lines, access roads and other components. This could include transboundary safety issues. Where safety issues have multiple or cumulative causes, the hydropower project's specific contribution to the issues should be identified.

This guide does not cover some types of infrastructure that are unrelated to hydropower, such as mine tailings dams.

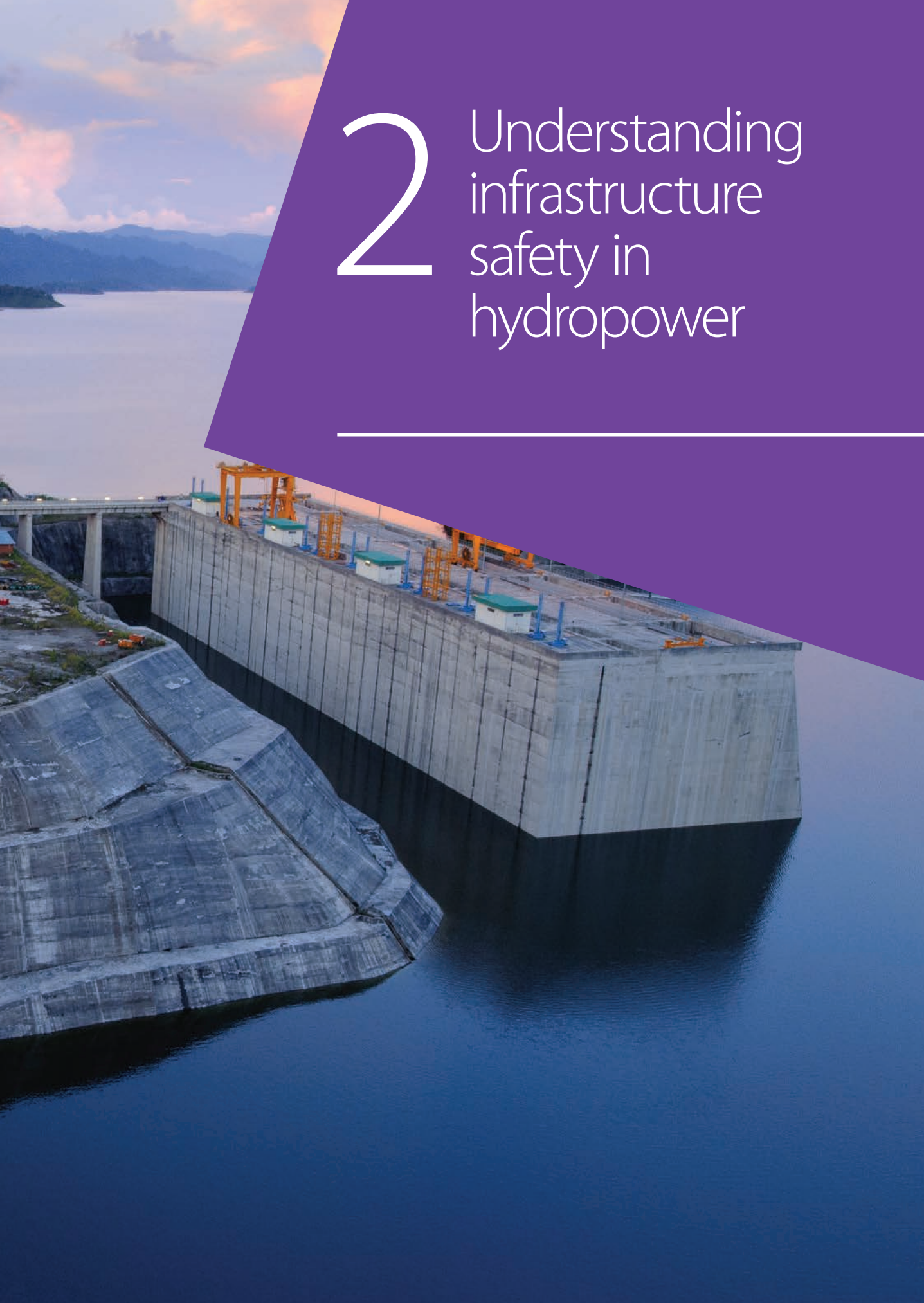
The issues discussed in this guide have a number of overlaps with those in other sustainability topics, including issues related to:

- Communications and consultation (how stakeholders are informed and consulted about safety issues).
- Governance (who is responsible for safety).
- Siting, design and integrated project management (how safety issues are taken into account).
- Hydrological extreme events (how these events are understood and managed).
- Asset reliability and efficiency (how safety-relevant assets are maintained).
- Project-affected communities and livelihoods (how safety concerns of communities are taken into account).
- Labour and working conditions (how occupational health and safety is ensured).
- Public health (how community concerns regarding non-life-threatening issues are taken into account).
- Reservoir management and downstream flow regimes (how operations take safety considerations into account).
- Climate change mitigation and resilience (how the project's safety evolves in a changing climate).



# 2 Understanding infrastructure safety in hydropower

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# Understanding infrastructure safety in hydropower

Infrastructure safety in hydropower seeks to ensure that populations affected by hydropower projects are not put at intolerable risk at any point during the life of a project. While dams are one of the most critical infrastructures with regard to safety, there is a broad range of other risks that need to be taken into account during the life cycle of a project, such that life, property and environment are properly protected.

This section describes the topics and concepts related to hazard, exposure, vulnerability and risk in general, that are applicable to hydropower projects and not limited to dam safety.





Warning before blasting at Devoll hydropower plant in Albania  
Photo Credit: Joerg Hartmann

## 2.1 Hazards, exposure, vulnerability and risk

Public safety risks are a result of hazards, community exposure to such hazards, and the incremental consequences of an incident, such as a dam breach or failure.

A hazard is any source of potential harm, e.g. downstream inundation resulting from a dam breach. Exposed to this hazard are all people and assets in the inundation area. Attribution of a particular hazard to a hydropower project may be straightforward in some cases, but not in others. This may be the case in a small dam failure during a major flood, which may have only small incremental effects on downstream flood levels and velocities.

Vulnerability is the likelihood that harm will occur, and the extent of the harm when something or someone is exposed to a hazard. Some people will find it easier than others to escape a flood, and some buildings will better withstand a flood. Therefore, vulnerability is highly dependent on topography and land occupancy, and escaping a flood is highly dependent on warning systems and the means to escape.

Risk assessment is concerned with (i) identifying hazards, (ii) estimating the probability or likelihood of occurrence of an incident, (iii) estimating the extent and vulnerability to a given hazard, and (iv) estimating the potential consequences of

the incident if it occurs. Risk management is the identification, evaluation and prioritisation of risks, followed by a coordinated and cost-effective application of resources in order to avoid, minimise, monitor and control the probability or consequences of incidents. Residual risks are those remaining after such resources have been applied.

Once the probabilities and consequences of incidents are understood, decision-makers and stakeholders can start considering what levels of risk they can reasonably tolerate. The definition of acceptable risk is a complex issue and not without challenges. Ideally, the specific risk levels should correspond to the risk that may be tolerated by affected communities, although this may be difficult to establish due to different perceptions of different community groups. Risk tolerance frameworks are based on the fundamental principles of equity and efficiency. Equity is the right of individuals and society to be protected and to be treated with fairness, with the goal of placing all members of society on an essentially equal footing in terms of levels of risk that they face. Efficiency is the need for society to distribute and use available resources so as to achieve the greatest benefit. The conflict between the two is resolved by an appropriate balance between equity and efficiency, in the development of tolerable risk guidelines. It is therefore essential that the risks associated with hydropower projects be evaluated rigorously and managed proactively throughout all stages of the

project lifecycle, such that the risks remain 'As Low As Reasonably Practicable' (ALARP).

## 2.2 Dam safety

### 2.2.1 Types of dams

Hydropower is generated by harnessing the energy of flowing water from natural river systems through turbines and generators. Projects typically include instream structures such as dams or weirs, which provide hydraulic head and/or upstream water storage in a reservoir. They must be able to store water without excessive leakage, be stable with an adequate margin of safety, and be constructed on foundations with an adequate bearing capacity and deformability. They comprise both visible (e.g. above-ground structures) and non-visible components (e.g. foundation cut-offs and grout curtains).

All dams retain water, but not all dams are used for hydropower. Reservoirs can provide water for multiple uses, such as for domestic water supply, irrigation, navigation and recreation, and water regulation for flood protection, drought support, and compensation of irregular inflows or water releases.

The selection of dam type is mainly a function of factors associated with the dam site: topography, hydrology, geology, seismic conditions, and availability of construction materials. Dam types can be classified as follows:

**Embankment dams** are built with natural geomaterials or processed materials, of different types and sizes, which are locally sourced, spread in specified layers and compacted to a specified degree. Based on particle size, they can be classified as earth-fill or rock-fill dams. Earth-fill dams use predominantly soil materials, in which more than 50 per cent of the total volume is formed of compacted earth layers, with materials generally smaller than approx. 7.5 cm. Embankment dams are the large majority of dams worldwide, including some of the most ancient dams. Currently, the highest embankment dam is the Nurek dam in Tajikistan (H = 300 m). There are several types of embankment dams, the main differences amongst

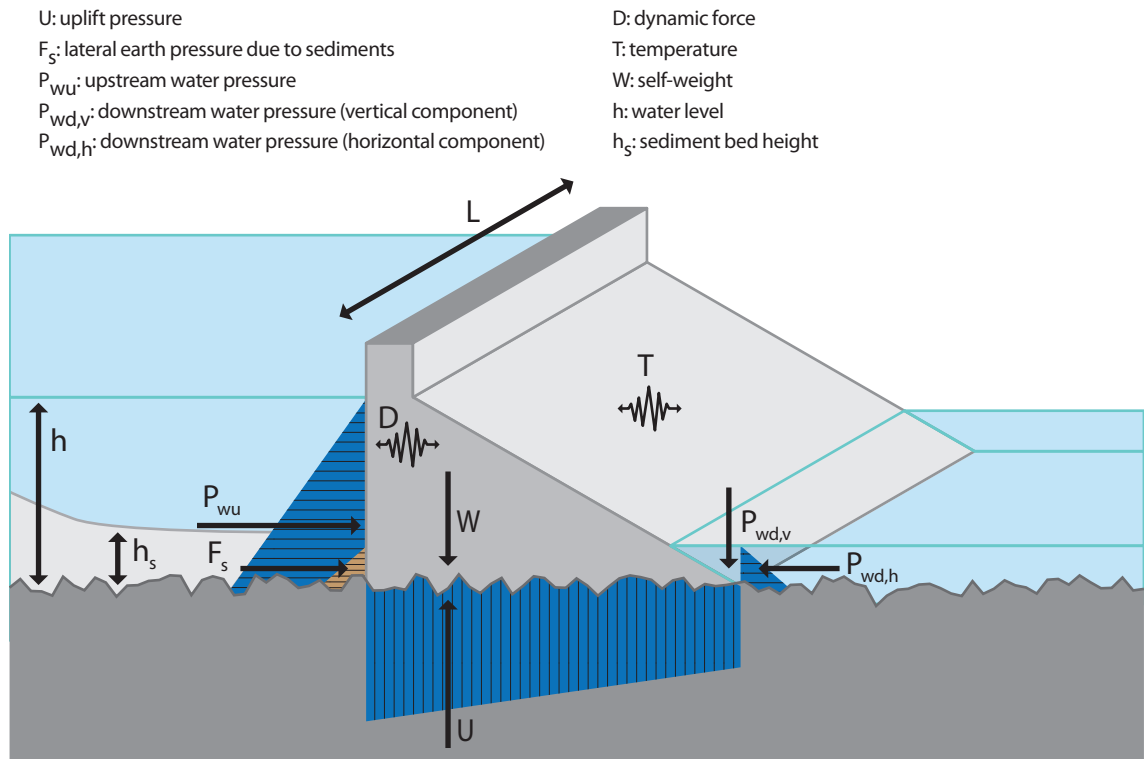
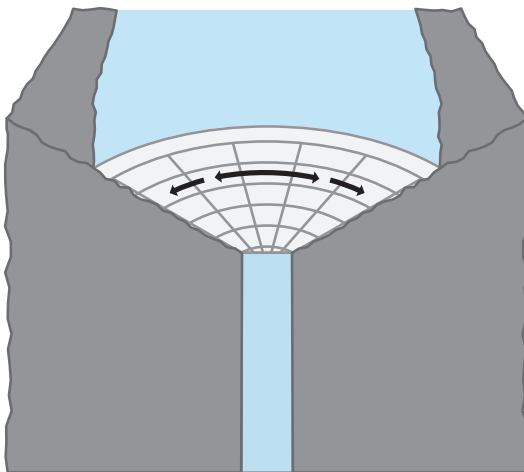
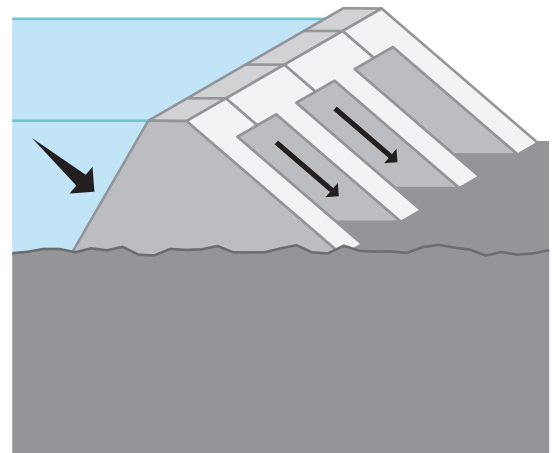
them being the type and location of the impervious elements.

Homogeneous earth dams are generally small to medium-sized structures. The body of these dams is composed of the same type of low-permeability soils with slopes designed to ensure an adequate degree of stability. Good practice for homogeneous earth dams is to include upstream slope protection for waves and a toe drain.

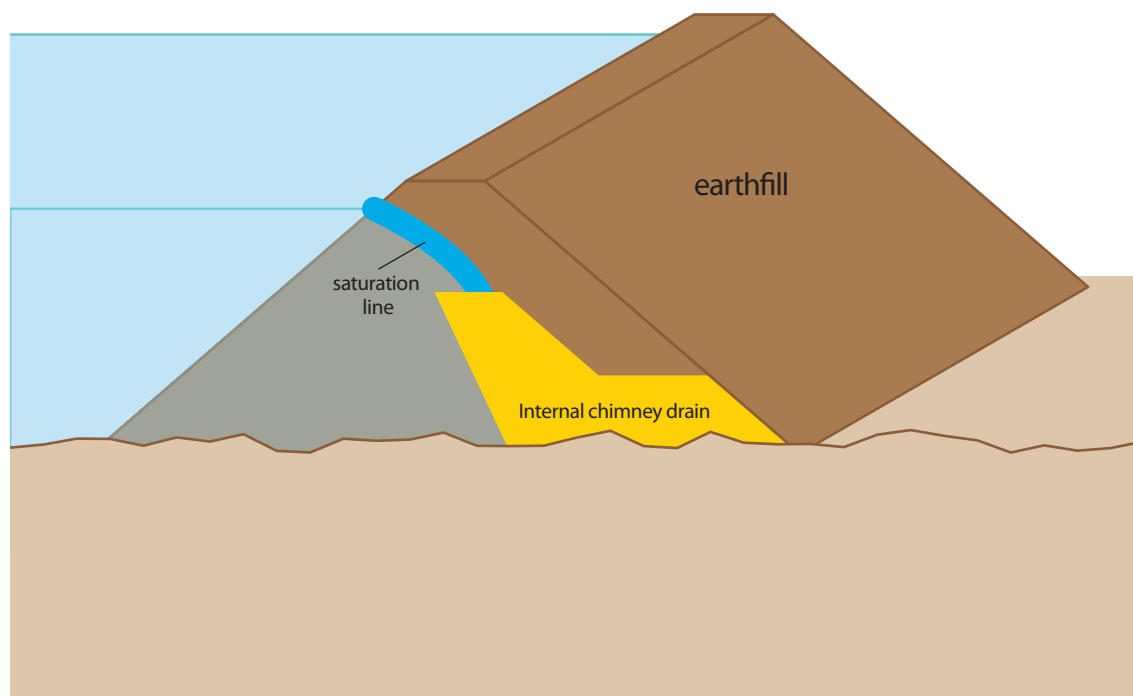
In a zoned earth dam, different types of materials with different granulometries are used (various mixtures of clay, silt, sand, or fine-grained gravel sizes). The dam's impervious element can be constructed using a compacted upstream low-permeability blanket, consisting of low-permeability fill (quite often in clay), asphalt or, less commonly, a geomembrane system or a central low-permeability fill core. Central asphaltic or plastic concrete (usually cement-bentonite based) diaphragms are also used to provide impermeability.

Improvements in the design and construction of embankment dams take advantage of more powerful compaction techniques, increasing the use of larger-sized rockfill material, which can be more stable at steeper slopes than earth-fill dams. Rockfill dams use similar impervious solutions, such as clay-core rockfill dams (CCRD) or asphalt-core rockfill dams (ACRD). The use of an upstream impervious element has become increasingly common, including asphalt-faced rockfill dams (AFRD) and concrete-faced rockfill dams (CFRD). In all cases the watertight element of the dam body is extended through the foundation by means of a cut-off, often combined with a grout curtain.

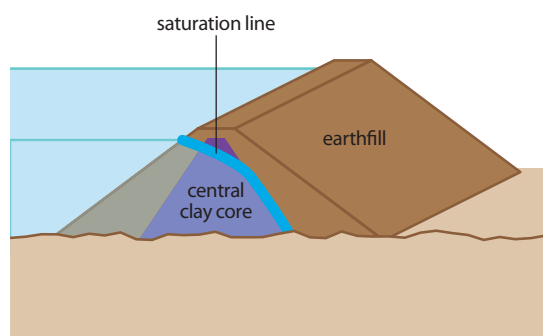
**Concrete and masonry dams** are fundamentally different from embankment dams, since they are more rigid, less vulnerable to overtopping, and require even more stringent design and compliance for their foundation conditions. In brief, they can only be built on fairly good to excellent rock foundations. Currently, the tallest concrete dam is the Jinping-1 dam (H = 305 m), an arch dam in China.

**Figure 1.** Types of dams and illustration of load transfer to dam foundation**(a) Gravity dam (concrete)****(b) Arch dam (concrete)****(c) Buttress dam (concrete)**

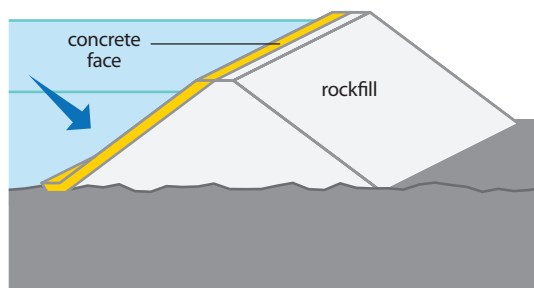
(d) Earthfill dam with an internal chimney drain



(e) Earthfill dam with a central clay core



(f) Concrete face rockfill dam



Gravity and arch dams are the main types of internally vibrated concrete dams, generally designed with vertically spaced joints between construction blocks.

Gravity dams rely on their weight for stability. Hydrostatic loads and induced stresses are oriented vertically to the foundation of each dam block. Some gravity dams are hollowed in the middle and close to the foundation, to reduce concrete volume. For volume reduction, joints can also be enlarged in the downstream areas, leading to the concept of buttress dams, where the downstream buttresses transfer the main loads to the rock foundation.

Masonry dams are mostly gravity-type dams, constructed mainly of stone, brick or concrete blocks, pointed with mortar. They were mainly built in the late 19th and first half of the 20th century, and many of them are still operating.

For narrow valleys, arch dams take advantage of the arch effect to guide most of the hydrostatic load and stresses towards the valley banks. Historically, such dams evolved from a cylindrical plan shape to a double-curvature shape that combines vertical and plan curves, for optimal use of the local site and construction materials. In wide valleys or in specific morphological contexts, multi-arch dams have

been constructed, composed of vaults supported by buttresses.

The arch-gravity dam type combines the behaviour of gravity and arch dams. It enables a reduced concrete volume in comparison to a gravity dam, by making use of the arch effect.

In Roller-Compacted Dams (RCC) a drier zero-slump concrete is used with limited aggregate sizes, enabling a continuous application from bank to bank, and using vibrating cylinders for rolling compaction – a technology somewhat similar to that used in rockfill dams. The first applications of RCC dams were for gravity dams, but arch dams, with small vertical curvatures, have also been built using this method.

Cemented Material Dams (CMD) are a recent development in dam construction and are considered as gravity dams (typically adopting a symmetrical cross-section shape). When compared with concrete and masonry dams, CMDs are less demanding in foundation conditions, and in relation to embankment dams, CMDs are less vulnerable to submersion. Aggregates with adequate granulometry distribution are placed in a first stage. In a second stage, a fluid content cement-based paste is spilled over the aggregates mass to fill the voids. An impervious membrane is placed upstream before impoundment.

Dams with long crest lengths may be a combination of concrete and embankment structures, i.e. **mixed structures**. Some schemes include not only the main dam but also additional dams, often called secondary, saddle, or auxiliary dams.

**Other structures** also retain water, as listed below:

- Concrete spillways, powerhouses and navigation locks.
- Longitudinal dikes and storm surge barriers.
- Cofferdams.
- Open-air surge chambers, tunnels, canals, penstocks and similar structures.

All dams and other water-retaining structures should be designed with the same level of detail and standard of care. The hazard is primarily related to the volume of water stored, whereas the type of structure influences the failure mode and the rate of water release.

The failure of a dam or of any other water-retaining infrastructure can result in fatalities, property loss or damage, damage or destruction of infrastructure, industrial facilities and heritage. Therefore, its economic, social and environmental impacts are generally significant.

### 2.2.2 Modes of dam failure

A failure mode is a specific sequence of events that causes uncontrolled release of water through some component of the dam-reservoir system. Each dam has specific conditions that can contribute towards its potential failure. Lessons learned from past failures provide useful information about failure mechanisms and their main causes. The same cause can be present in the failure mechanisms of different types of dams.

Failures can occur in varying degrees. Minor failures do not necessarily pose immediate threats but can lead to a more significant outcome, such as a dam cracking, breach or collapse. Typically, the three elements of a potential failure mode are: (1) the initiator cause or set of causes, (2) the failure mechanism, and (3) the resulting impact on the structure and on public safety.

Calculating the probability of failure relies on a range of techniques that include engineering judgement, mathematical calculations, statistical analyses, and empirical relationships developed from the study of past incidents.

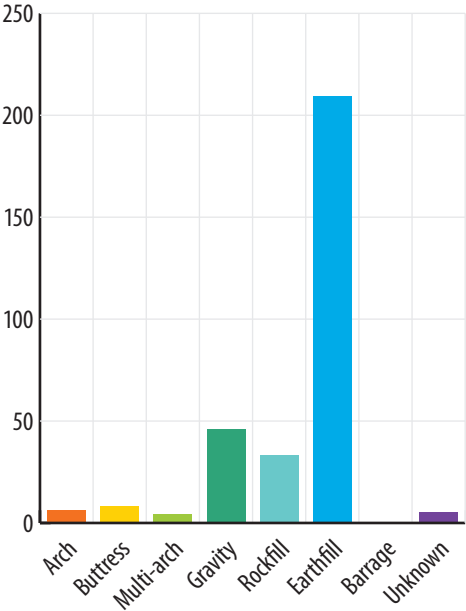
The implementation of effective dam safety-management programmes has had a marked impact on dam safety and public safety, with failure rates dropping significantly over time. However, the average age of dams is increasing, and there is no assurance that positive trends will continue. The key mechanisms which contribute to potential dam failures are discussed below.

Box 2: Dam failure statistics

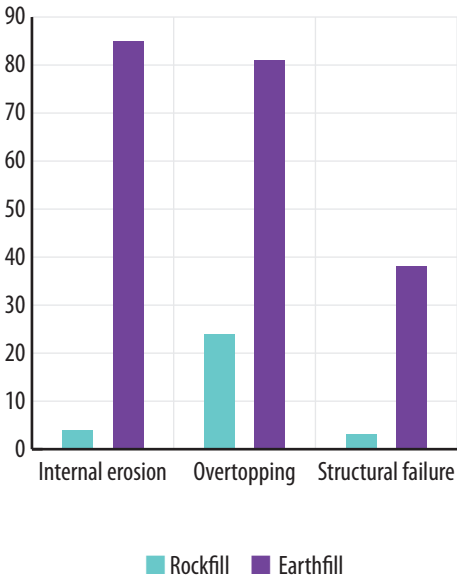
ICOLD’s forthcoming updated Bulletin 99 (originally published in 1995), “Dam Failures Statistical Analysis”, presents data on the number of failures and failure mechanisms for various dam types.

| Dam type        | Existing dams | Failed | Ratio |
|-----------------|---------------|--------|-------|
| VA – Arch       | 890           | 6      | 0.67% |
| CB – Buttress   | 340           | 8      | 2.35% |
| MV – Multi-arch | 105           | 4      | 3.81% |
| PG – Gravity    | 5571          | 46     | 0.83% |
| ER – Rockfill   | 2378          | 33     | 1.39% |
| TE – Earthfill  | 21977         | 209    | 0.95% |
| BM – Barrage    | 224           | 0      | 0.00% |
| XX – Unknown    | 715           | 5      | 0.70% |

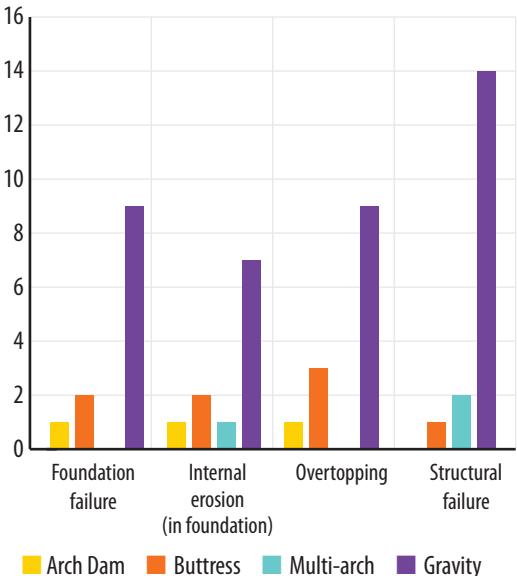
Failure vs dam type



Failure mode vs dam types: Embankment types



Failure mode versus dam types: rigid dams



### 2.2.2.1. Overtopping and erosion/scouring

Dam overtopping is generally associated with inflow conditions exceeding the storage capacity of the reservoir and the outflow capacity of the spillway system, resulting in water flowing over the crest of the dam. This can be due to:

- Insufficient design outflow capacity to accommodate extreme floods such as the design flood or safety check flood, including insufficient freeboard (the difference between dam crest elevation and the reservoir's design floodwater levels).
- Unexpected settlement of the foundation.
- Unexpected settlement of the dam body, in the case of embankment dams, due to dam-face slope instability or piping.
- Inadequate reservoir management strategies, leading to misuse of the available storage at the beginning of a flood.
- Failure of gates to operate on demand (due to lack of maintenance or training, gate jamming, operator error, lack of redundancy in power supply or monitoring equipment, sabotage, etc.).
- Operator error or failure of sensors to detect that a reservoir is reaching maximum capacity, e.g. by continuing to pump into an upper storage (e.g. Taum Sauk pumped storage plant in Missouri).
- Debris blockage of spillway structures.
- Landslide into the reservoir creating an impulse wave.
- Climate change resulting in increased extreme runoff.
- Debris flows, glacier lake outburst floods (GLOFs) or landslide-dam outburst floods (LDOFs) resulting in inflow conditions exceeding the spillways' capacity.
- Upstream dam failure.

Overtopping is an important failure mode for most dams, but in particular for embankment dams. Due to variable settlement along the dam crest and according to inflow intensity, overtopping can occur over either a small or large length of the dam crest. Increased seepage and saturation may trigger mass sliding and additional settlement, and surface flow may lead to erosion of the downstream face and toe of an embankment dam, which may impact the stability of the dam and lead to a breach.

Overtopping may not affect the stability of a rockfill dam if the overtopping height is small. However, should it affect the impervious dam components, stability may be compromised.

Under certain extreme conditions, overtopping of sections of an embankment dam may be planned as an emergency measure to protect the remaining scheme. About 100 earth fuse plugs have been built, mainly in the 1980s in China and the USA, with discharge capacities of up to thousands of m<sup>3</sup>/s and with a height usually between 5 and 10 m. They may be very cost-effective but require specific topographic conditions, and their deployment is therefore limited.

Most dams around the world are embankment dams, and in many cases, the construction of expensive spillway structures may render the project economically unfeasible. One practical way of managing hydrological uncertainty and overtopping risk is to make these dams more resilient to overflow, by installing a protective overlay.

Overtopping of concrete gravity dams can result in sliding failure or overturning failure, due to unbalanced forces acting on the monolithic dam sections. However, the main concern with the overtopping of concrete dams is the scouring erosion of the downstream foundation, which can progress upstream and impact dam stability. Geological faults and rock discontinuities play an important role in this potential dam failure mode.

The overtopping of temporary cofferdams and the flooding of the construction areas may cause schedule delays and can require significant reconstruction of the main dam works, especially for embankment dams.

### Box 3: Failure of the Hell Hole embankment dam during construction

On 23 December 1964, the partially completed Lower Hell Hole Dam failed, causing 37 hm<sup>3</sup> of water and 535,000 m<sup>3</sup> of rock to surge 97 km down the Rubicon River canyon, before terminating into Folsom Lake four hours later.

The dam, located about 113 km east of Sacramento, California, was designed as a 125 m high-zoned rockfill structure. During the first year of construction, progress was slower than anticipated, and the dam was only completed to a height of 67 m before the start of the flood season. In late December 1964, record rainfall of 56 cm over five days filled the reservoir, causing the incomplete dam to fail.

No one was killed as a result of the failure, but rock from the failed dam was carried downstream for miles. Five bridges, including two suspension bridges and the California Highway 49 bridge over the American River, were washed out before the water flowed into the Folsom reservoir. The lack of more severe consequences can be attributed to the remote location of the reservoir, as well as the event occurring during a time of the year when downstream recreational use was low.

Dam safety experts identified the cause of failure as incomplete construction of the dam, coupled with record rainfall. The dam design was not judged to be a contributing factor, and it was subsequently reconstructed in the wake of lawsuits for damages.

#### 2.2.2.2. Overturning and sliding

Overturning and sliding are typical failure modes of gravity structures (concrete and masonry dams).

Overturning occurs when the hydrostatic pressure of the reservoir, acting on the upstream face and at the foundation contact surface (uplift pressures), causes a rigid rotation movement of the dam body around its downstream toe at the foundation contact surface, against the stabilising effect of the dam's own weight. The probability of overturning can be increased by deformation of the foundation dam toe, due to excessive compression stresses and rock weaknesses, and by scouring.

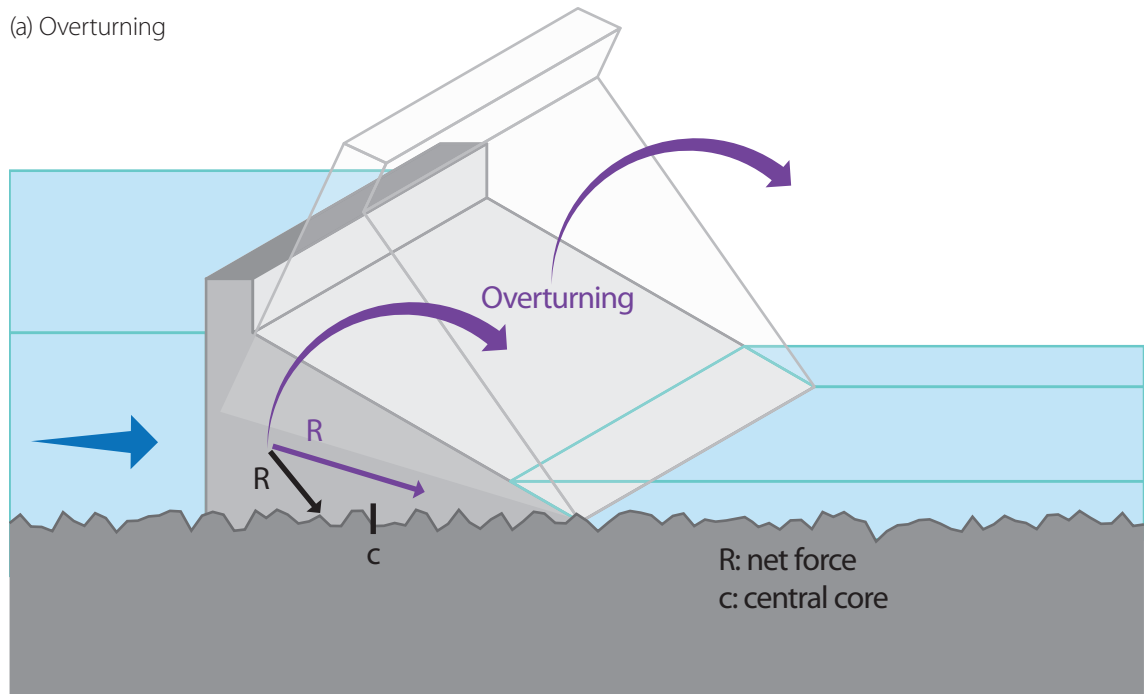
Sliding involves the same type of adverse and stabilising actions. In this case, uplift forces act along a weak sliding surface, which can be horizontal lift joints, dam-foundation surfaces or a set of foundation discontinuities. The sliding failure mode is also relevant for the natural or artificial abutments of arch dams and for the buttresses of multiple arch dams. Potential failure mode scenarios, which include sliding along contraction joints and dam-foundation surfaces, or a set of foundation discontinuities, must also be considered for arch dams.

Embankment dam slopes are prone to mass sliding failure if design loads are exceeded or resistances reduced (e.g. reduction in shear strength of the embankment-fill materials). Sliding failure can be triggered by causes such as excessive pore pressures and hydraulic fracturing within the dam body, soil saturation due to heavy rainfalls, impervious core anomalies, foundation settlement, rapid drawdown of the reservoir, and the effects of animal burrows or vegetation on the embankment. The most usual failure mode for an embankment dam is associated with slope instability, which typically takes the form of a circular or wedge-shaped failure on one of the upstream or downstream slopes, commonly referred to as a 'slide' or 'slump'.

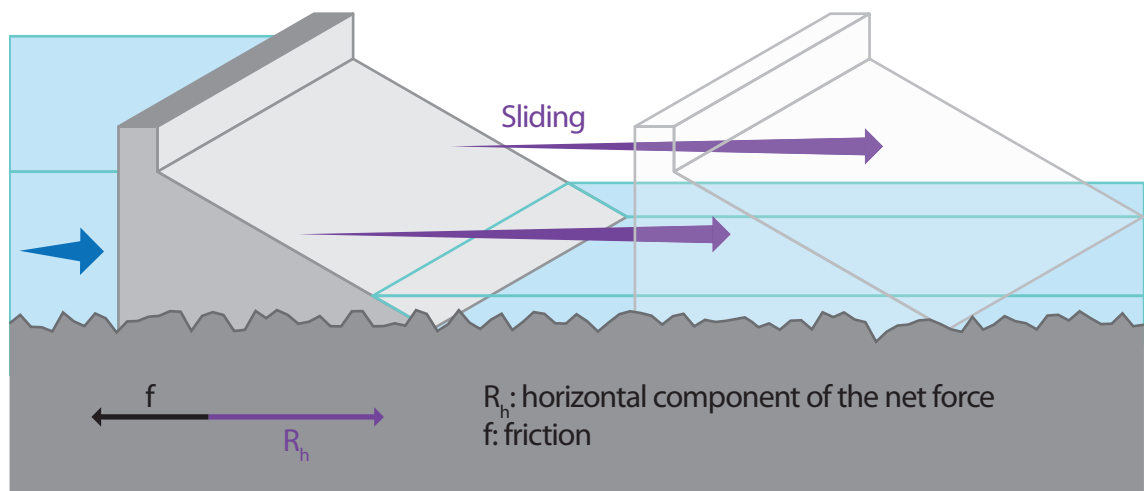
Earthquakes induce cyclical loading, which reduces the resistance to sliding and overturning, and may weaken the mechanical properties of dam materials. In the case of embankment dams, they generate excess external and internal pore pressures, which may lead to dam face slope instability, dam crest settlement and foundation settlement. In the case of concrete dams, they may disrupt the grout curtain, leading to increased uplift loads, or generate tensile stress zones and cracking. Uplift values can be increased when foundation drains become clogged.

**Figure 2.** Overturning and sliding

(a) Overturning



(b) Sliding



### 2.2.2.3. Piping and seepage

Seepage is the flow of water through soil or fissured rock, and controlling its velocity and quantity is one of the most important issues in embankment dam design. Uncontrolled seepage through an embankment dam and/or through its foundation can erode fine soil material, starting from the downstream face or foundation, which can then extend upstream to form a pipe or cavity reaching the reservoir, leading to collapse or settlement of the upper dam body and release of water. This is known as 'piping', and can result in a complete failure of an embankment dam. Excessive seepage can also cause slope failures due to saturation, and reduction of shear strength properties. Structural cracks and sinkholes made by animals are also relevant pathways for seepage development.

In rockfill dams, excessive seepage through the impervious element – e.g. the core wall or the upstream concrete face – can trigger a failure mechanism such as slope sliding or dam toe scouring. In concrete dams, seepage occurs through lift joints, contraction joints or foundation discontinuities.

### 2.2.2.4. Cracking

Cracks can appear in all types of dams. They are usually associated with structural behaviour anomalies, and can be warnings of possible failure modes.

In embankment dams, transverse cracks can appear at the crest, due to movements associated with natural settling, or caused by shrinkage of the materials as a result of severe drying. Internal cracks or excessive movements of the dam or of the foundation can affect the strength properties of the materials. Another failure mode is associated with the rupture or excessive deformation of an impervious upstream face (e.g. concrete slabs or inclined upstream core).

Cracking of slabs in the concrete face of high rockfill dams can be generated by stress concentration, both compressive and tensile, including of thermal origin. The repair of such cracks requires the reservoir water level to be drawn down, which can cause significant economic losses. Past incidents – such as at the Campos Novos dam in Brazil (in 2006)

– have promoted the improvement of watertight joint devices that can accommodate relative displacements between adjacent concrete slabs, thereby preventing cracking.

Many of the visible cracks on concrete dams are associated with concrete shrinkage due to thermal effects, and are usually not very deep and do not affect the structural behaviour of the entire dam. Other cracks can be particularly dangerous, such as those associated with design or construction deficiencies, thermal gradients, concrete swelling phenomena and foundation settlements. Cracks with progressive openings and/or increased leakage can affect dam stability and cause dam collapse.

### 2.2.2.5. Foundation problems

Foundation problems, leading to excessive settlement, sliding or overturning, have been one of the main causes of dam failures, particularly in the case of concrete dams. The foundation of a dam must have mechanical characteristics (strength, deformability and permeability properties) that can sustain the structural behaviour of the dam, and must contribute to the necessary waterproofing of the reservoir.

The foundations of embankment dams are often layers of soil or soft rock. New conditions existing after dam construction and reservoir impoundment – such as induced stresses, hydraulic pore pressures and seepage – can cause foundation erosion and settlement, which may contribute to dam cracking, breaching and failure. Foundation soil liquefaction during seismic events can also be a cause of dam failure.

All foundations for large dams display some sort of geological faulting, and possible "active faults" should be assessed since they can have relevant movements triggered by seismic events. Dam failures can also be caused by instability of the valley slopes or riverbanks near dam abutments, or by erosion at the dam toe. Spillway operation can produce downstream scour and the regressive erosion along faults in the dam foundation.

Sliding of valley slopes (landslides) into the reservoir can cause large impulse waves, additional pressures over the dam, and may lead to dam overtopping. Also, they can cause blockage of the diversion

#### Box 4: Oroville dam and spillways incident, 2017

On 7 February 2017, the service spillway at the Oroville dam, the tallest dam in the USA at 220 m, was discharging about 1,500 m<sup>3</sup>/s, when suddenly a section of the concrete slab located about halfway down the chute gave way, immediately followed by rapid erosion of the foundation and adjacent ground, and progressive failure and removal of the slab in the upstream and downstream directions. Adjusting the flow to control the progression of the damage led the water level to continue to rise in the reservoir. The level rose above the emergency spillway weir for the first time in the project's history, causing severe and rapid erosion downstream of the weir, which could have led to undermining (by scouring) and failure. Hence, 188,000 people were evacuated from the downstream areas. Considered one of the most serious dam safety incidents in United States history, the estimated cost of the repairs and recovery has exceeded USD 1.1 billion.

In this case, the location of the spillway was modified during construction of the dam, moving more than 100 m away from the area with available geological investigations but without conducting equivalent new ones, and the spillway chute cracked due to foundation settlement. An emergency ungated spillway was built at the initially foreseen location, but without sufficient energy dissipation and scour control measures. Although less than 20 m high, the failure of this emergency spillway structure would have released the top layer of the Oroville dam reservoir, representing a significant volume of water, while the dam itself would remain intact.

The forensic investigation report for the Oroville dam spillway incident states that:

*"The Oroville Dam spillway incident was caused by a long-term systemic failure of the California Department of Water Resources (DWR), regulatory, and general industry practices to recognize and address inherent spillway design and construction weaknesses, poor bedrock quality, and deteriorated service spillway chute conditions. The incident cannot reasonably be "blamed" mainly on any one individual, group, or organization."*

tunnels and result in uncontrolled reservoir filling (as at the Ituango project in Colombia, see Box 10). These sliding occurrences can be associated with reservoir-triggered earthquakes, when rapidly filling the reservoir. Foundation failures can also occur for the appurtenant structures (see Box 4).

#### 2.2.3. Consequences of dam failure

The consequences of dam failure must be well understood in order to quantify failure risks and determine mitigation requirements. Dam failures can have catastrophic consequences for downstream areas, caused by the uncontrolled release of all or part of the impounded water from a reservoir, travelling downstream as a flood wave. Failure consequences are generally classified as (i) loss of life, (ii) environmental and cultural heritage losses, and (iii) property, infrastructure and economic losses.

Inundation mapping is used to assess the extent of downstream impacts, and the consequences are then established using tools such as Google Earth, Geographic Information System (GIS) mapping, ground surveys and census information. Various methods exist to estimate the potential number of fatalities and other losses. The consequences of failure of a particular dam can change over time, as land use, infrastructure development and demographic changes over the life of the structure, can affect the downstream areas and the population at risk. Methods for the assessment of consequences are presented in Section 4.2.4.

**Box 5: Failure of saddle dam at the Xe-Pian Xe-Namnoy Project, Laos, 2018**

On 23 July 2018, following heavy rainfall and flooding, saddle dam D failed at the Xe-Pian Xe-Namnoy project in Champasak Province, southern Lao PDR. The project was at a late stage of construction, the reservoir was below its maximum operating level, and the spillway was discharging flows in the range of a 10 to 20-year flood. The failure of the embankment dam by overtopping released an estimated half-billion cubic metres of water downstream, killing between 41 and 71 people and displacing over 6,600, and causing widespread destruction and homelessness in Attapeu Province.

The Independent Expert Panel (IEP) concluded that the main trigger of the failure was a rotational sliding involving the lateritic foundation of the dam, which led to deep sliding along the deepest area of the saddle and the highest section of the dam.

*“The failure could have been prevented by an appropriate treatment of the foundation aiming at providing the required water tightness, filtration and drainage. Furthermore, an early and correct interpretation of the monitoring data and a reinforced detailed visual inspection in the downstream toe region of the embankment, would have allowed to take actions trying to save the Saddle Dam D and/or at least trigger the warning earlier.”*

**Box 6: Malpasset dam failure, France, 1959**

On 2 December 1959, after 9 pm, the Malpasset arch dam in south-eastern France suddenly failed. The breach created a massive wave that was 40 m high and travelled downstream at 70 km/h, destroying the villages of Malpasset and Bozon, as well as a highway construction site. Within 20 minutes the flood wave reached the town of Fréjus and was still 3 m high. The failure caused massive destruction and 423 casualties. Roads and railroad tracks were also destroyed.

This catastrophic failure is credited as being one of the events that has led governments worldwide to develop new regulations on dam safety, and one of the main initiators of two new disciplines: geological engineering and rock mechanics. Aspects such as foundation conditions and abutment stability gained importance in the design process. It is the first and only arch dam to ever have failed.

**Box 7: Banqiao dam failure, China, 1975**

Built in the 1950s and designed to withstand an inflow design flood corresponding to a 1:1,000-year flood, the Banqiao embankment dam failure occurred during Typhoon Nina in August 1975, and is considered one of the deadliest flooding events of all time.

The one-day rainfall of 5 August exceeded the annual average, and it continued to rain heavily for a few more days. On 8 August just after midnight the Banqiao dam failed, causing a flood wave 10 to 12 km wide and 3 to 7 m high to travel downstream at 50 km/h. The official death toll was of about 26,000, although up to 145,000 died from famine and the epidemics that followed. A total of 62 dams failed during Typhoon Nina in China. The flooding affected over one million hectares of farmland and over 10 million people. The event is considered an example of inadequate design flood and lack of hydrological data leading to failure.

## 2.3 Other hazards and safety issues

While dam safety is generally the most critical issue of hydropower infrastructure safety, it is also important that communities are not put at risk by other hazards and safety concerns during the life of a project. This section presents other hydropower-related hazards and safety issues that can arise or be amplified during the implementation and operation of a hydropower project.

A broad range of community safety issues need to be considered for each project stage, namely:

- road safety;
- safety around water bodies associated with the hydropower complex;
- blasting and other construction activities;
- electrical safety;
- natural hazards (natural or amplified by the presence of the hydropower scheme);
- underground geotechnical hazards;
- pressurised conveyance hazards.

Additional low-probability scenarios not covered here, but which can also pose a risk to the overall hydropower complex, the public, and/or the environment, include sabotage, armed conflicts, cyberattacks, water quality impairment from chemical or hydrocarbon spills, discharge of anoxic water from the hypolimnion via low-level outlets, dam failure-induced industrial spills, and others.

### 2.3.1 Road and bridge safety

A hydropower project's first impact on any territory is typically gaining access for site investigations. Initial access routes or pre-existing roads are then upgraded and extended during construction and commissioning, to form a network of different types of roads. They can be divided into three groups: those that fall within the authorities' responsibility, those that are built by the project but handed over

to the authorities after commissioning, and those that are internal within the project premises and will remain the responsibility of the hydropower operator. Some roads are existing roads that require upgrading or new alignments by the project. Other roads may be new, possibly including new bridges spanning the river or reservoir, use of the dam for a road crossing, or short access tracks to transmission towers, etc. Some construction roads may be decommissioned, abandoned, or submerged by the reservoir after construction.

Changes to the road system and to traffic introduce multiple risks for local communities, including accidents with additional vehicles, degraded roads, debris, dust, landslides and other issues during construction, as well as opening access to dangerous locations, transportation of heavy equipment and materials to the project site, etc. All of these issues require adequate mitigation measures, safety management and control.

### 2.3.2 Safety on and near water

Hydropower projects and operations present a number of hazards related to the existence of the reservoir, fast-flowing water, and fluctuating flows and water levels, according to the hydropower plant's operating regime. All of these hazards pose risks to nearby communities and river users, such as dangers of drowning and boating accidents, and they can also affect the environment.

A hydropower plant may be operated as a peaking plant during periods of higher electricity demand, or as a function of water availability in the reservoir. As such, it may abruptly ramp up and ramp down power generation, resulting in rapidly changing flow releases downstream. Fluctuating flows and water levels can travel a significant distance downstream before being attenuated. Furthermore, operating patterns such as this can also cause the reservoir water levels to rise and draw down at regular intervals. The areas around the intake works and spillways located near or at a dam may be subject to higher flow velocities and rotating currents. The reach immediately downstream from a dam is also subject to increases in flows from spillways and gates. Some of these fluctuations in the downstream river reaches are regular occurrences and expected by most downstream communities,

**Box 8: Beas River disaster, India 2014**

Twenty-four second-year engineering students from Hyderabad, and one tour operator on an educational tour, were swept away by a sudden surge and drowned on the Beas River in Himachal Pradesh. This occurred on 8 June 2014, after the upstream 126 MW Larj hydroelectric project had released water without warning. The state High Court found that the deaths had been caused by negligence, and awarded compensation to the victims' families, to be paid by the state electricity board (the operator of the plant), the college and the state of Himachal Pradesh.

while others can be unexpected. However, all of these events can put the public at risk.

Safety booms and signage are placed upstream and or downstream of a dam, to keep the public and boats from approaching the dam and areas of fast-flowing water that pose risks of entrainment. Signage, sirens, emergency planning, and a good communications strategy with local communities and river users, can alert the public of risks related to fluctuating flows and water levels downstream of a dam or a powerhouse. In some jurisdictions, it is a requirement to notify the affected communities of any major changes in flows and water levels, both upstream and downstream of the facility.

### 2.3.3 Blasting and other construction activities

Blasting, drilling, excavation, mucking, concrete and reinforced steel placement, and other construction activities related to hydropower construction (including those involving suspended loads, working at heights, in confined spaces, underground or underwater) can be high-risk activities both for workers and for communities. In most jurisdictions, blasting activities are regulated and must be carried out by specialists with the appropriate expertise and certifications. Explosives storage magazines, when located on site, are typically isolated, gated and surrounded by a protective berm with security and controlled access. A blasting schedule informs the workers and the public of when and where blasts are going to occur throughout the day, and an alert system or siren typically goes off prior to blasting.

Other construction activities also require specialised training and personal protective equipment (PPE) to minimise risks inherent in the activities that are carried out, such as working at heights, welding, working in confined spaces and underground (tunnels, caverns), or electrical work, to name a few.

Risks to the surrounding communities are minimised by controlling access to the construction site, through measures such as gated controlled access, and security, fencing, signage, and local communication campaigns.

### 2.3.4 Electrical safety

Electrical safety is a specialised field, and this section provides only a short summary of some of the main hazards related to electricity and working around electricity.

Electrical current can travel through people, along the ground, through water, and also through trees adjacent to transmission lines. Electrical hazards include downed electrical transmission and distribution lines, due to accidents or during storms, which can pose risks of electrocution to community members and workers.

Working unsafely around electricity can result in serious injuries, ranging from shock to severe burns. Injuries and fatalities can result from contact with low-voltage (up to 750 V) as well as high-voltage electricity. The United States Department of Labour's Occupational Safety and Health Administration (OSHA) lists the following hazards as the most frequent causes of electrical injuries:

- **Contact with Power Lines:** Overhead and buried power lines can be hazards during the construction of a hydropower project.
- **Lack of Ground-fault Protection:** The dynamic, rugged nature of construction work at a construction site can cause wear and tear to electrical equipment that results in insulation breaks, short-circuits, and exposed wires of flexible cords and power tools. If there is no ground-fault protection, these can cause a ground-fault that sends current through the worker's body, resulting in electrical burns, explosions, fire, or death.
- **Path to Ground Missing or Discontinuous:** If the power supply to the electrical equipment at a construction site is not grounded or the path has been broken, fault current may travel through a worker's body, causing electrical burns or death. Even when the power system is properly grounded, electrical equipment can instantly change from safe to hazardous because of extreme conditions and rough treatment.
- **Equipment Not Used in Manner Prescribed:** Always follow the manufacturer's instructions for proper use of equipment.
- **Improper Use of Extension and Flexible Cords:** The normal wear and tear on extension and flexible cords at the site can loosen or expose wires, creating hazardous conditions.

Electrical fires can be caused by overloads on circuits not meant to carry the current flowing through them, and by poor electrical connections. A short circuit occurs when the normal current path is changed, by passing through broken insulation or a bad connection to another conductor. As a result of the short circuit, a very hot spark or electric arc occurs, which can ignite insulation or nearby combustibles. Excessive overheating, severe short circuits, faults in the oil, and lightning strikes may cause transformers to catch fire or explode. Although transformer fires are rare, their impact can be significant. Types of fire protection systems for transformers may include water-based and mist systems (including fire pumps, water-spray fixed systems, or nozzles, valves, valve components and

pipings), and fire detection systems (which include fire detectors, control panels and cabling).

### 2.3.5 Natural hazards

A number of natural hazards such as floods and earthquakes have already been mentioned in Section 2.2.2., as they relate to dam failure modes. This section describes additional natural hazards such as landslides, avalanches and lake outburst floods, which can affect hydropower projects and the safety of the general public around hydropower projects. The construction and operation of hydropower projects can trigger some of these natural hazards or amplify their consequences.

Landslides or landslips are defined as any type of slope failure or downward movement of rock and/or sediment, ranging from a few cubic metres to more than 10 km<sup>3</sup>. The rate of downward movement can range from imperceptible to greater than 100 km/h. Heavy precipitation, earthquakes, retreat of glaciers and thawing of permafrost, and certain human activities are some of the factors that trigger landslides. Hydropower projects can trigger landslides through blasting, excavation, foundation preparation, tunnelling, failure of high-pressure hydraulic tunnels, road building, reservoir level and flow variations, and other mechanisms. Their likelihood of occurrence is higher in steep mountainous terrain, and the risks to communities are thus greatest in populated mountainous regions.

Landslides can affect hydropower projects in a variety of ways. Landslides into reservoirs can cause tsunami-like waves that can capsize boats, erode shorelines, damage infrastructure and overtop the dam (see Box 9). Landslides can block diversion tunnels (see Box 10), block access to the site (affecting the ability to operate safety-relevant equipment such as spillway gates), or block evacuation routes. Large landslides can create natural dams, resulting in Landslide Dam Outburst Floods (LDOF) which can devastate downstream infrastructure, such as at the Sunkoshi hydropower project in Nepal in 2014.

Rock avalanches can produce a significant amount of debris, which bounces down a slope or travels through the air until it lands and fragments into rock shrapnel. While most rock avalanches are relatively

**Box 9: Vajont dam disaster, Italy, 1963**

On 9 October 1963, during the initial filling off the Vajont reservoir in the Italian Alps, and following days of heavy rain, a landslide occurred on the steep slopes of the Monte Toc mountain above the reservoir, causing 267 million m<sup>3</sup> of rock to slide into the reservoir in less than 45 seconds. The rockslide caused an enormous impulse wave in the reservoir, which overtopped the crest of the dam by over 100 m and released over 24 million m<sup>3</sup> of water into the downstream valley. Although the dam remained intact, the floodwave caused the complete destruction of five villages downstream and killed 1,917 people (94 per cent of the community). The flood wave arrived at the first village, Longarone, only four minutes after the landslide occurred.

*“Any dams site investigation should include a detailed study of the proposed reservoir slopes. If old slides or areas susceptible to sliding are identified, a detailed evaluation of their relative stability under reservoir conditions should be required. The lesson afforded by (Vajont) need not be relearned by another generation” – Hendron and Patton, 1986.*

**Box 10: Ituango project, Colombia, 2018**

The construction of the Ituango hydropower project was seriously affected by landslides and tunnel portal collapses in April–May 2018, leading to the partial obstruction of the main diversion tunnel. This caused the water levels behind the unfinished dam and spillway to rise prematurely, long before the scheduled reservoir impoundment. Tens of thousands of people were evacuated from downstream areas, and the powerhouse was flooded in an attempt to release additional water. Flooding from the natural unblocking of the tunnel then destroyed a village, bridges and roads. Cost overruns are reported to have exceeded USD 1 billion.

small, their impacts on a road or an exposed penstock can be significant, such as in the Upper Bhote Khosi hydropower project, also in Nepal in 2015. Other types of landslides are mud and debris flows, where the material is saturated with water.

In high-altitude mountain environments, snow avalanches can occur (sometimes triggered by human activities), with similar consequences to those listed above for some types of landslides. Glaciers can encroach into a river valley and form a dam, and result in outburst floods. Ice jams can cause damage to dams, spillway gates and other hydropower project components.

Significant ice-related hazards result from glacial lake outburst floods (GLOFs). As glaciers recede in response to warming temperatures, their retreat can lead to the formation of pro-glacial lakes dammed

by moraines, which can fail for a number of reasons. GLOF events can involve the discharge of millions of cubic metres of water, with entrained debris, for many tens of kilometres downstream. While there are thousands of glacial lakes in the Himalayas and other mountain ranges such as the Andes, the number of glacial lakes that have been reported to fail is relatively small. Where mitigation of GLOF risks is deemed impractical, an Early Warning System can be installed to give an alert that a GLOF is occurring.

The Himalayas are well known for natural hazards. The devastating 2015 earthquakes in Nepal resulted in direct impacts on hydropower projects, including from debris flows. They also ‘preconditioned’ the steep mountain slopes, which subsequently failed during the monsoon, creating landslides, GLOFs, LDOFs, and other impacts that damaged many hydroelectric facilities.

### 2.3.6 Underground geotechnical hazards

Underground hazards pose significant risks to hydropower projects, during both construction and operation. Even with extensive geotechnical and site investigations, underground risk can never be completely eliminated. Typical underground hazards relate to ground movements due to discontinuities, fractures and faults, karstic geology, groundwater, groundwater pressure, and underground caverns.

Risks can affect different components of a hydropower project that are exposed to different hazards. Some underground works are temporary, such as diversion tunnels, access adits, ventilation/cable adits, shafts, etc. Others represent permanent components of the project, such as the water conveyance tunnels, surge shafts, underground powerhouse caverns, or power cable tunnels.

Underground excavation works can be affected by uncertainty regarding geological features, leading to unexpected water inflows, gas release, rock wedge formation, and potential excavation collapse. Safety is also affected by traffic conditions in confined premises and potential power supply failures, which can impact lighting, ventilation and pumped drainage.

Temporary works such as diversion tunnels are high-risk components of hydropower projects, not only because they convey high-velocity and debris-laden water, but also because they tend to be on the project schedule's critical path. As they are often governed by seasonal river flows, they place the execution team under pressure to complete the task on time.

During operation, the main concerns are high hydraulic gradients, i.e. locations where over a relatively short distance there is an important hydraulic pressure head difference, creating a hydraulic thrust that may dislodge concrete and/or rock masses or soil. This may occur around underground surge tanks, powerhouses and valve chambers, and can lead to surface landslides, hydraulic fracturing of the solid surroundings, underground wedge displacement, and/or inundation of hydropower caverns (powerhouse, valve chambers, etc.).

### 2.3.7 Pressurised conveyance hazards

Above-ground penstocks, as well as high-pressure tunnels and shafts, represent an underrated hazard in many jurisdictions. Their structural failure may lead to uncontrolled water release, often at locations without an existing stream to receive the water. The record of penstock failures includes numerous incidents globally, with several leading to fatalities.

Above-ground penstocks mostly fail due to mass movements and landslides (see Section 2.3.5), while underground hydraulic structures mostly fail where there are large hydraulic gradients (brittle failure) or cyclic loading (fatigue failure). Steel (and other) linings can be applied to withstand high internal hydraulic pressure, as either full or partial linings, including the rock overburden. In the case of lining failure, namely at welding seams, the localised pressure release can lead to hydraulic fracturing and uplift or dislodgement of solid wedges, causing landslides or the collapse of tunnels or cavern boundaries. Failure of the welding seams depends on fracture mechanics and stress concentration, starting from an initially undetected flaw which propagates across the steel plate until the pipe bursts.

The recent use of high-grade steel has contributed to reducing steel plate thickness for large hydraulic heads, thus reducing manufacturing costs but also reducing the time-to-fatigue-failure. Crack propagation and/or increased leakage can affect the stability of hydropower tunnels and shafts, and can cause their collapse. Crack inception is extremely difficult to detect, as site inspections require dewatering and working in narrow underground spaces, often vertical or sub-vertical.

The potential failure modes of such high-pressure tunnels and shafts are difficult to predict, as they also depend on geological features. In 2000, the Cleuson-Dixence penstock above the Bieudron hydropower station ruptured under more than 1,000 m of head. The release of water triggered a landslide that resulted in three casualties, submerged buildings and roads, and blocked the flow of the River Rhone for several weeks.

## 2.4 Contributions to public safety

The first priority in a hydropower project is to identify and mitigate all public safety risks that have been described in the previous sections. However, projects may also provide opportunities to address pre-existing public safety issues in the project area.

### 2.4.1 Flood, drought and wildfire mitigation

In the past, flooding was associated with the highest number of fatalities and injuries among all natural disasters, although those numbers have been significantly reduced since the 1960s (see Figure 3). Flood risks are typically highest in developing countries with limited resources to warn, evacuate or protect communities. Historically, China was the most affected country, especially along the Yangtze River. By contrast, developed countries are reporting fewer flood deaths. For example, the US average over the 2010–2019 period was 104 deaths per year, and most of these occurred while people were driving, often in flash floods.

Drowning accounts for 75 per cent of deaths in flood disasters, and floods also cause death by physical trauma, heart attacks, electrocution,

carbon monoxide poisoning or fire. Floods also have medium- and long-term health impacts. They often have a very high cost (only part of which is insured) and can also damage the downstream environment.

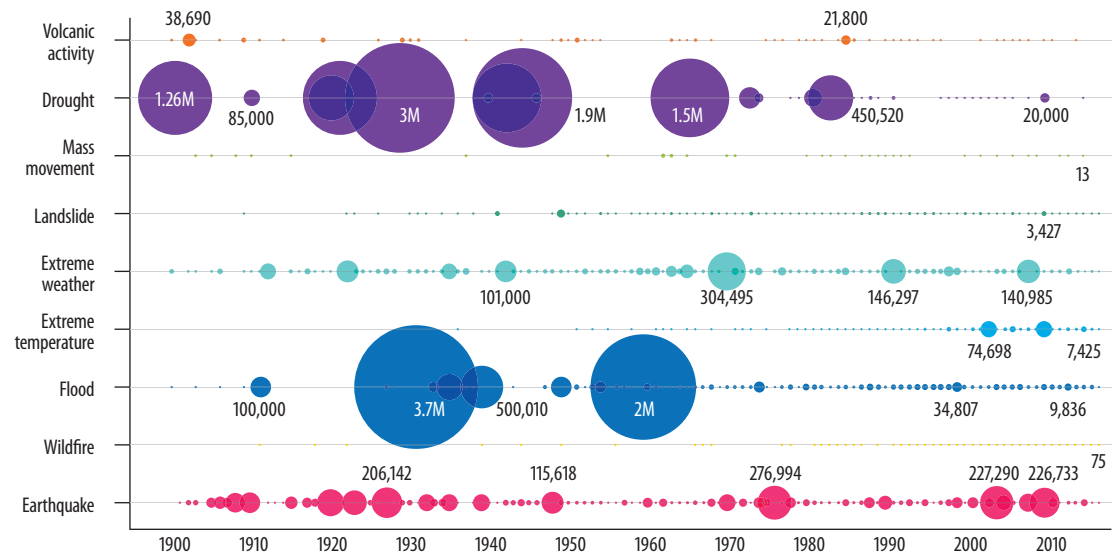
Dams and reservoirs can manage floods to varying degrees, depending on active storage capacity, flood volume, and reservoir operations. The contribution of hydropower projects to flood mitigation is covered in more detail in the How-to Guide on Downstream Flow Regimes (IHA 2020).

Storage of water in reservoirs may also help to mitigate drought risks, another natural disaster with historically high numbers of fatalities. Drought fatalities are typically related to longer-term malnutrition and loss of domestic water supply in some cases, but there can also be immediate safety risks, such as from heat exposure and wildfires.

Wildfires are a good example of the complex interrelations between hydropower projects and public safety hazards. Hydropower projects can cause wildfires through the negligence of personnel, for example, or through electrical infrastructure, such as transmission lines in close vicinity of vegetation. Hydropower projects can also be threatened by wildfire, especially components such as work camps and access roads. Finally,

**Figure 3.** Global deaths from natural disasters (1900–2016)

Source: <https://ourworldindata.org/natural-disasters#number-of-deaths-by-type-of-natural-disaster>



hydropower projects can help mitigate the risk of wildfires, either passively – by acting as firebreaks, by being used as a source of water, or by improving access and communications in an area – or actively, when project emergency staff and equipment support firefighting.

## 2.4.2 Traffic and other safety improvements

Compared to flood risks, traffic risks are several orders of magnitude higher. Globally, approximately 1.35 million people die in road crashes each year, and an additional 20-50 million suffer non-fatal injuries, often resulting in long-term disabilities. More than half of all deaths occur among pedestrians, cyclists and motorcyclists. More than 90 per cent of all road fatalities occur in low- and middle-income countries.

In many cases, hydropower projects require new roads or upgrades to existing roads and bridges, such as for heavy equipment transportation. This can be an opportunity to address key risk factors, including unsafe road design and conditions, unsafe vehicles, speeding, non-use of seatbelts and helmets, driving under the influence of alcohol, inadequate post-accident care, and lack of enforcement of traffic rules. This would generally be done in cooperation with the local police and roads departments. Both the general public and project staff and contractors will benefit from improved safety on access roads.

Improved road infrastructure can also have secondary safety benefits for the local population, such as better access to a hospital, improved access for emergency services, and better evacuation routes.

Depending on the relevant pre-existing safety risks in an area, project staff and equipment can also contribute to preventative and emergency safety management in various areas (fire, ambulances, search and rescue, landslides, water recreation, etc.).

## 2.5 Legal, regulatory and bank safeguard instruments for infrastructure safety

Hydropower projects, like other industrial facilities, are subject to generic public safety and liability regulations. Additionally, some jurisdictions have specific laws and regulations that owners and developers of dams must comply with during the various stages of a project. Some jurisdictions have non-legislated dam safety guidelines, sometimes issued by professional organisations, while others have no specific regulatory framework at all.

Comparative studies have shown that existing legal and regulatory dam safety frameworks have the following commonalities: the paramount objective is the safety of people and property in relation to the risk imposed by dams, and dam surveillance is critical. Legislation may include dam definition and classification schemes according to size (height of dam, volume of water impounded), hazard or consequences of failure, and design criteria. This may require dam safety frameworks, programmes or management systems.

Where specific legislation on dam safety is not available or is outdated, dam owners or government entities may need to comply with a financing institution's standards, adopt ICOLD standards and guidelines, or adhere to other national standards. Legal frameworks for dam safety establish minimum standards, as well as the roles and responsibilities for ensuring the safe development and operation of dams. In addition, legislation defines the standard of care, liability in case of dam failure, and the criteria applied to distribute such responsibility among the stakeholders.

In some jurisdictions, authorities and emergency services have an important role during emergencies (e.g. flooding), and will work in close collaboration with dam owners to control and activate the emergency response measures. In some instances, they may take over the control of a facility and even issue directives that may cause unsafe conditions (e.g. requesting to retain higher water levels to avoid flooding downstream, or for environmental reasons). Hydropower projects may also have transboundary impacts, and some transboundary water

resources agreements between countries include responsibilities and measures to jointly prepare and respond to emergencies. There are many examples around the world of transboundary basins that span countries with different legal systems, which may have implications for liabilities.

Financing arrangements for large dam projects can be complex and involve government and utility financing, as well as contributions from international and multilateral development banks, export credit agencies and commercial banks. While some banks adhere to international standards such as the Equator Principles, which are underpinned by the IFC Performance Standards (in which community safety is considered under Performance Standard 4 and worker safety under Performance Standard 2), these do not include any specific requirements for dams. Therefore, these financial institutions will rely on teams of independent engineers to review dam design prior to financial close, and conduct periodic monitoring during construction. IFC's "Hydroelectric Power, A Guide for Developers and Investors", issued in 2015, includes the "requirement to design, build, operate, and decommission structural elements according to Good International Industry Practices (GIIP) and that competent professionals should be in charge of design and construction, and, in high risk situations, external experts should review throughout the stages of the project".

In the World Bank's Environmental and Social Framework, the Environmental and Social Standard 4 (ESS4), which relates to Community Health and Safety, includes an annex specifically dedicated to the Safety of Dams. This discusses requirements for new dams, dams under construction and existing dams, including the review of site investigation, design, construction, and the start of operations, by independent panels of experts. The World Bank's "Good Practice Note on Dam Safety" was issued in 2020 "to enhance the quality of practice without creating new requirements for the application of the new ESF". Other banks either follow World Bank Group directives, combine them with other guidelines, or in some cases issue their own requirements, such as on the role of independent panels of experts.





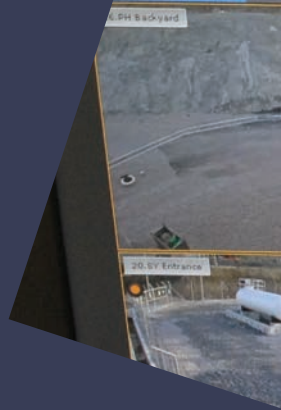
# 3 Achieving good international industry practice

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# Achieving good international industry practice

The safety of all stakeholders affected by hydropower projects, including the general public in the vicinity of a project, has become an increasingly important concern, leading to more systematic and comprehensive management. While it has long been accepted that the developer or operator has primary responsibility for the occupational health and safety (OH&S) of project staff and contractors, the development of good practices regarding the safety of external stakeholders has lagged behind OH&S practices. Even today, in some projects and jurisdictions the approach to infrastructure safety can still be quite narrow: for instance, regulatory approval of a dam may be taken as sufficient, safety risks other than dam failure may not be considered, opportunities for positive contributions may be disregarded, safety management may be conducted without proper coordination with public agencies, or transboundary issues may be disregarded.





Remote camera supervision  
at Devoll hydropower plant  
in Albania  
*Photo Credit: Joerg Hartmann*

A lack of comprehensive safety practices is clearly not acceptable by today's standards, and there is now sufficient industry experience to deliver better outcomes for both new and existing projects. The Hydropower Sustainability Tools provide definitions of current good practices for infrastructure safety. This chapter links safety issues to the Hydropower Sustainability Tools, which are structured by different stages in the project life cycle, with different criteria for each stage. Thus, Chapter 3 provides a structured overview of the steps that should be taken to achieve good practice, while the following Chapter 4 will present methodologies and approaches in detail.

The responsibility for taking these steps and achieving good international industry practice lies with the developer or operator of a hydropower project, even if certain tasks can be outsourced to consultants and contractors, or if government agencies assume certain roles.

### 3.1 Infrastructure safety in the project life cycle

As a hydropower project moves through the different stages in its life cycle, safety considerations also evolve. Siting, design and operational options (and their safety implications) are progressively narrowed down as a project moves through the preparation, implementation, and operation stages.

Figure 4 below provides an overview of the most important considerations at each stage.

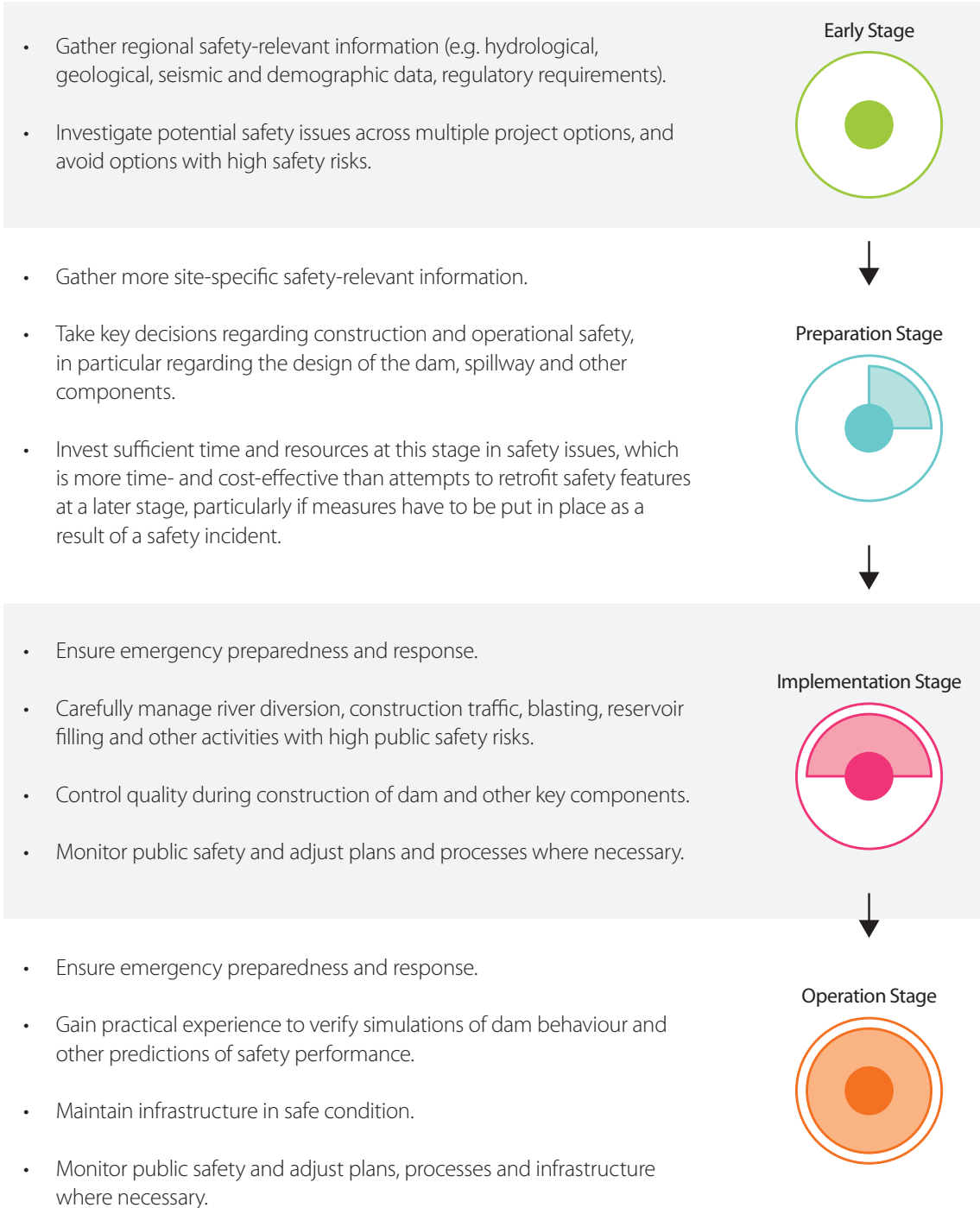
The following sections review each stage's tasks in more detail.

#### 3.1.1 Early stage

In the Early stage, investigations will begin to consider factors that will ultimately be part of the considerations for infrastructure safety. The following steps should be taken with respect to safety:

- Identify and compare safety issues for potential sites, designs and operations at a pre-feasibility or scoping level, without detailed data. This high-level evaluation of safety issues, and examination of experiences from other project developers with respect to infrastructure safety, should help inform the consideration of project options.
- Identify regulatory requirements and institutional responsibilities regarding infrastructure safety, dam licensing and emergency planning requirements.
- Consider trends that may influence safety over time, such as demographic and land-use

**Figure 4.** Project life cycle stages with key public safety considerations (ES, P, I, O)



changes, changes in hydrology, or changes in power markets that will influence operations.

Key information sources may be hydropower masterplans, river basin development plans, national dam safety plans, and regional hydrological, climatological and geological studies. The focus in this stage is on understanding different options for sites and designs. If significant adverse safety issues are identified, it is necessary to consider realistic alternatives to the initial project concepts.

A preliminary gap analysis may be undertaken to identify the surveys and studies that would become necessary in the next stage. If baseline information is limited and longer time series are required, it is advisable to start monitoring programmes already at this stage, such as by installing flow, weather and seismic monitoring equipment.

If a promising project site and type has been identified, the project moves into the Preparation stage.

### 3.1.2 Preparation

Short-term infrastructure safety risks that can arise during preparation activities could relate to, for example: temporary labour camps, access roads, site investigation facilities such as test wells, helipads, fuel storage, and power supply – some of which may be in previously undeveloped locations and may require protection against community interactions.

The main safety-related focus during the preparation of a hydropower project should be oriented towards delivering a safe design, safe construction plans, and a preliminary operations concept.

This will typically be achieved through a range of studies, which are part of different workstreams, such as engineering, environmental or social. In most cases there is not one single integrated document combining all safety aspects. It is advisable, however, to at least summarise public safety issues in the environmental and social impact assessment (ESIA). Following typical ESIA methods, this summary should contain:

- documentation of the current baseline conditions;
- identification of potential changes, both negative and positive, to conditions in the vicinity of project infrastructure;
- potential mitigation measures to address any potential negative impacts; and
- potential enhancement measures to increase any potential positive impacts.

Regardless of the format of preparatory studies, good practice requires that the following substantive steps should be covered:

- Consider all potentially affected areas for which changes in public safety can be attributed to the project (e.g. through dam-break studies).
- Consider options for design, construction methods and operations in terms of their implications for different safety issues.
- Where safety issues are the result of multiple projects (e.g. in a cascade), consider the cumulative impacts and mitigation options.
- Consider all stages of the project, including average, infrequent and extreme conditions. The assessment should thus include special events and periods such as earthquakes, ice jams in cold regions, landslides, debris flows, reservoir filling, extreme hydrological conditions such as floods, and potential long-term trends due to climate change (e.g. increasing flood peaks and fire risks).
- As the Preparation stage progresses, increasingly revise and inform the safety assessment through other elements of the feasibility studies, such as hydrological and hydraulic modelling. The team preparing the ESIA should work in parallel and closely with the design and construction specialists, in order to understand specific safety aspects of the various project components and inform the engineering plans. An iterative approach with coordination between the different workstreams is vital for achieving successful outcomes, including a willingness to review project objectives in a flexible manner.

In reality, preliminary engineering studies often precede environmental and social studies by years, making iteration, flexibility and design adjustments difficult – this is one of the most frequent causes of unsatisfactory outcomes. In some jurisdictions, it has become mandatory to conduct both technical design and ESIA studies in parallel.

- Follow a methodological and defensible process to determine links between engineering plans and safety objectives, and to achieve safety commitments.
- Address trade-offs among competing safety and other objectives (such as cost control) and seek outcomes with the lowest impact and highest benefit. This may require a process of engagement with external stakeholders such as regulators and emergency services.
- To deliver on safety commitments, choose a suitable design, construction plan, and preliminary operations concept. Build flexibility and adaptive management over time into these plans.
- Where appropriate and cost-effective, identify additional measures to protect public safety. Safety risks can rarely be eliminated completely, and residual risks and impacts often remain. There may also be opportunities to address pre-existing safety issues.

These processes will take time, and in some cases (where few baseline data are available) years. They will therefore have to be programmed as early as possible, in order to avoid an assessment process being cut short as developers or authorities grow impatient. They may also deliver unwelcome messages for project developers and other energy sector stakeholders, through adjusting expectations for power generation and loss in revenue, or increased costs, if sensitive safety risks are identified. Developers and authorities must resist the temptation to limit investigations during the feasibility stage, which could lead to optimistic early budgeting, and significant cost overruns and/or under-investment in infrastructure safety when the project is built.

In some extreme cases, projects may be abandoned or moved to alternative sites. It is therefore of the utmost importance to clearly communicate uncertainties, risks and liabilities regarding public safety, using non-technical language and conservative methodologies. In some jurisdictions, the study of potential dam failure and its consequences (e.g. inundation maps, assessment of life and property at risk) has become mandatory as a prior condition for firm concession agreements and obtaining construction permits.

Parts of the assessment process can be very sensitive and lead to the public rejection of projects, if outcomes are unfavourable or not well communicated. This refers primarily to dam failure-related issues, such as inundation maps and emergency response plans. It can be difficult for downstream authorities and communities to understand the implications – such as failure probabilities – of different project options. However, developers should not avoid communicating these issues in the hope that they will not become a concern. In the age of social media, it is important for the developer to present accurate information to the public, in order to pre-empt the rapid dissemination of misleading information. Insufficient communication may also impede establishing adequate restrictions on land use downstream of the dam, leading to occupation of downstream areas, and increasing the vulnerability of the downstream population to a potential dam-break event.

The results of these evaluations in the Preparation stage should be appropriately documented. They should be consistent between the various studies, and in particular, include detailed design decisions. The respective compliance obligations will be formulated by regulators and should provide clarity on how compliance commitments will be monitored. Any responsibilities and liabilities of the owner/operator, contractor and other stakeholders also need to be documented. This information is then taken into account in the investment decision at the end of the Preparation stage.

During the Preparation stage, many developers rely heavily on consultants for specialised studies. Financiers and contractors may provide additional contributions from their experience, if involved early enough in the preparation process.

### 3.1.3 Implementation

In the Implementation stage, areas of focus are construction-related safety risks, and the preparation of safe operations. Project commissioning is included here, as the final phase of the Implementation stage.

An emergency preparedness and response mechanism must be functional from the beginning of any construction activities.

Public safety needs to be considered and ensured in the construction of all project components, such as access roads, quarries, spoil areas, camps, workshops, cofferdams, dams/weirs, tunnels, penstocks, surge shafts, transmission lines, and chemical and hazardous material storage areas. Applicable methods include public access restrictions, quality assurance and control, training of workers/code of conduct, supervision (e.g. of traffic speed), and slope stabilisation.

In most cases, a specific plan with associated commitments for distinct stages (e.g. the closure of the river diversion, reservoir filling and test operations) will be required. This process also needs to be well documented for future reference. Responsibilities for decision-making must be clearly defined, as some contractors and developers may have incentives to fill the reservoir as rapidly as possible in order to complete the commissioning process.

The first filling of a reservoir is a particularly sensitive operation in terms of public safety. It is the first occasion where the dam, its foundation and the entire reservoir area will be exposed to the upstream hydraulic load from the storage of water. This has to be managed in a highly controlled and methodical process (including periods where static water levels are maintained to allow for the structural accommodation of the dam and its foundation, and for the proper balance of groundwater levels), and must include a comprehensive surveillance programme with continuous monitoring. A significant proportion of all dam failures occur during first filling.

Provisions must be made, and equipment must be available to suspend the filling process at any time in case of potential danger, such as landslides,

rockslides, dam settlement, unprecedented ground motion, high uplift pressures on the dam foundation, or high seepage flow discharges. The first filling of pressurised waterways (tunnels, shafts) and surge tanks must also follow a similar procedure.

During implementation, various measures relating to safe future operations should be put in place, depending on the characteristics of the project. These always require adherence to design and quality standards, and may include measures as diverse as instrumentation, reinforcement of bridges, signage and fencing, or joint preparedness drills with public emergency services.

As construction of a project takes several years, new issues may emerge over that time, new information can be gathered, and safety plans updated accordingly. At the end of the Implementation period, the reservoir will be filled, and the project will be ready for commissioning.

### 3.1.4 Operations

An emergency preparedness and response mechanism needs to be functional throughout the operational lifetime of the project.

Operational decisions will be made by a combination of local, regional and central office staff of the hydropower company, and external agencies, which may include power system dispatchers, dam safety authorities, a different dam owner (in case the dam is owned by a different entity, such as an irrigation district), and others. The following steps should be taken with respect to infrastructure safety:

- Monitor and document safety-related issues and compare with those planned and predicted during the preparatory studies. There should be clarity regarding dam instrumentation and other monitoring facilities and systems, their design, and responsibilities for their installation and maintenance among the owner/operator (most likely responsible for compliance monitoring) and public authorities, who will have a broader role in monitoring other safety issues.

- Choose indicators that are practical, clearly attributable to project operations, and meaningful for stakeholders. Include key predefined parameters regarding dam behaviour, slope stability, flood patterns, traffic accidents and others. Monitoring efforts should be commensurate with any identified risks or opportunities, as identified in the project preparation documents. Some parameters may be measured continuously, while others can be revisited on a less frequent basis (seasonally, annually, etc.). The definition of plausible threshold values to define alarm levels is key, in order to inform adequate responses and eventually trigger the emergency response structure.
- Analyse monitoring data for trends and examine significant divergences from predictions, to identify causes and effects. Parameters for monitoring may change over time, as some data series may be found to be less useful for analysis, and other issues may emerge. However, to ensure continuity, they should only be changed with good justification.
- Maintain all infrastructure components in a safe condition, through a systematic asset management programme (note: asset reliability and efficiency are addressed as a separate but related topic in the Hydropower Sustainability Tools).
- Based on monitoring and evaluation results, make adjustments as is feasible within constraints such as the project design, licence conditions, and power purchase agreements. At longer time intervals, there may be opportunities for a systematic re-evaluation and improvements of infrastructure and operations. These could be triggered, for example, by a re-licensing process, a change in dam safety regulations, a new technology, or a major event such as a flood, earthquake, ice jam or landslide. As a more specific example, if it is determined that a landslide into the reservoir was the result of rapidly changing soil saturation in the slopes, an adjustment could be made to limit reservoir level fluctuations or the maximum operational level.

As the average age of hydropower plants increases, their monitoring, maintenance and periodic rehabilitation should accommodate changes in safety regulations and expectations.

## 3.2 International good practice requirements for infrastructure safety

### 3.2.1 Assessment

Assessment includes all data collection and interpretation to support safety-relevant decisions, through all stages of a project. Data can include results of technical investigations (e.g. climatic, hydrological, hydraulic, geological, geotechnical, seismic, glacial, and material properties), monitoring data, as well as visual assessments and verbal feedback from stakeholders, which can be followed up with focused quantitative surveys and analysis.

The assessment effort is typically most important during the preparation of a project, when all relevant dam and other infrastructure safety risks throughout the project cycle have to be systematically analysed, using appropriate expertise. This requires specialists with proven experience in designing and constructing projects of a similar complexity, and with competencies in engineering safety and key risk areas.

Since dam safety is paramount, all potential failure modes should be identified and addressed in the dam design and operational rules. Regional circumstances will influence the degree to which different types of risks require consideration. For instance, cascading dam failure may be of importance in river basins with multiple dam developments. The consequences of dam failure should be analysed before an investment decision is taken, and they should inform emergency response planning.

All regulatory requirements for the jurisdiction, and relevant design standards for the infrastructure and risks, should be identified, documented and met.

**Table 1. HSAP and HESG Assessment criteria on the topic of infrastructure safety**

| Criterion  | Infrastructure Safety Requirements                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Assessment | <p><b>Preparation Stage:</b> An assessment has been undertaken of dam and other infrastructure safety risks, with appropriate expertise, during project preparation, construction and operation, with no significant gaps.</p> <p><b>Implementation Stage:</b> Dam and other infrastructure safety risks relevant to project implementation and operation have been identified through an assessment process. Also, safety monitoring is being undertaken during the project implementation stage, as appropriate to the identified issues.</p> <p><b>Operation Stage:</b> Routine monitoring of dam and infrastructure safety is being undertaken to identify risks and assess the effectiveness of management measures. Also, ongoing or emerging dam and other infrastructure safety issues have been identified.</p> |

Assessment during preparation should also include temporary risks related to site investigations. This should consider the likelihood of community impacts, and options to avoid or minimise safety incidents.

The assessment process continues during project implementation, when specific safety issues relevant to implementation and operation are identified. Furthermore, safety monitoring is undertaken commensurate with the identified issues. Monitoring for quality assurance and quality control is essential to ensure that the infrastructure is constructed to design standards, and that any issues arising (e.g. variations in materials specifications, or fault zones in excavation areas) are detected and addressed.

During operations, routine safety monitoring should be undertaken to identify risks, to assess the effectiveness of management measures (such as emergency response measures), and to ensure safety objectives are achieved. Assessment requirements may change over time based on changing regulations, new safety issues emerging (e.g. from demographic changes or cumulative impacts), or stakeholders' expectations. Responsibilities for the monitoring and evaluation of various safety issues should be clearly allocated (e.g. among the owner/operator and government authorities) and documented.

### 3.2.2 Management

Management is responsible for addressing any significant issues that are identified through the assessment process, in all stages of the project.

In the Preparation stage, comprehensive dam and other infrastructure safety management plans and processes should be developed for project implementation and operation, and these plans and processes then need to be in place during the later project stages. Plans should outline what actions will be implemented and how responsibilities are allocated, important timing requirements, budget allocations, and reporting and review procedures. This may take the form of a structured safety programme, at least for the subset of measures related to dam safety. During operations, the plans should be periodically reviewed and updated.

Throughout the project cycle, plans and processes should be designed in conjunction with the relevant regulatory and local authorities, and enable the communication of public safety measures to internal and external stakeholders. Emergency response plans should address all emergency risks and should include awareness and training programmes, as well as emergency response simulations and mock drill exercises.

Additionally, because of their critical importance, in the Preparation stage, plans for dam safety should be independently reviewed, and in the Implementation stage a formal construction quality control programme should be in place.

Table 2. HSAP and HESG Management criteria on the topic of infrastructure safety

| Criterion  | Infrastructure Safety Requirements                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Management | <p><b>Preparation Stage:</b> Dam and other infrastructure safety management plans and processes have been developed for project implementation and operation, in conjunction with relevant regulatory and local authorities, with no significant gaps. They should provide for communication of public safety measures. Emergency response plans include awareness and training programmes and emergency response simulations, and dam safety is independently reviewed.</p> <p><b>Implementation Stage:</b> Processes are in place to address identified dam and other infrastructure safety issues, and to meet any safety-related commitments relevant to the project implementation stage, including providing for communication of public safety measures. A formal quality-control programme is in place for construction. Safety management plans for the operation stage have been developed in conjunction with relevant regulatory and local authorities. Furthermore, emergency response plans include awareness and training programmes, and emergency response simulations.</p> <p><b>Operation Stage:</b> Dam and other infrastructure safety management plans and processes have been developed in conjunction with relevant regulatory and local authorities with no significant gaps, and provide for communication of public safety measures. Emergency response plans and processes include awareness and training programmes and emergency response simulations.</p> |

3.2.3 Conformance/Compliance

During the Implementation and Operation stages, any processes, objectives and commitments relating to infrastructure safety should be met. To achieve good practices, compliance and conformance are required of all parties with responsibility for a project, not just of the developer and operator.

Primarily, the safety programme needs to be compliant with relevant legal or administrative requirements, as expressed in licence or permit conditions or stated in legislation. Compliance requirements might relate to, for example, standards to be met, the frequency and type of monitoring to be performed, and reporting to be submitted by the owner to the regulatory authorities.

Conformance refers to any relevant plans that provide details on how the project will achieve compliance (e.g. budgetary allocations, designation of roles and role expectations, and provision of internal training), and in some cases these plans may go beyond compliance requirements. Commitments to stakeholders (including, in some cases, to lenders) may be expressed in regulatory requirements or in company policies and statements.

Meeting design standards is of particular importance to infrastructure safety, and quality control and independent review processes should be thorough and credible, including documentation to verify that all design standards have been fully met.

Table 3. HSAP and HESG Conformance/Compliance criteria on the topic of infrastructure safety

| Criterion               | Infrastructure Safety Requirements                                                                                                                                                                                                                         |
|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Conformance/ Compliance | <p><b>Implementation and Operation Stage:</b> Processes and objectives relating to safety have been and are on track to be met, with no major non-compliances or non-conformances, and safety-related commitments have been or are on track to be met.</p> |

Table 4. HSAP and HESG Outcomes criteria on the topic of infrastructure safety

| Criterion | Infrastructure Safety Requirements                                                                                                                                                                                                             |
|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Outcomes  | <p><b>Preparation Stage:</b> Plans avoid, minimise and mitigate safety risks with no significant gaps.</p> <p><b>Implementation and Operation Stage:</b> Safety risks have been avoided, minimised and mitigated with no significant gaps.</p> |

3.2.4 Outcomes

Outcomes are essentially the combined result of all activities described above, under Assessment, Management, and Conformance/Compliance.

During the Preparation stage, safety-relevant plans should aim to avoid, minimise and mitigate safety risks. Plans should include mitigation measures with clear responsibilities and allocated resources, which are directly linked to all risks that have been identified, through appropriate expertise. During Implementation and Operation, those plans should be implemented, resulting in safety risks being effectively avoided, minimised and mitigated. The safety programme should reduce safety risks to a justifiable level of residual risk.

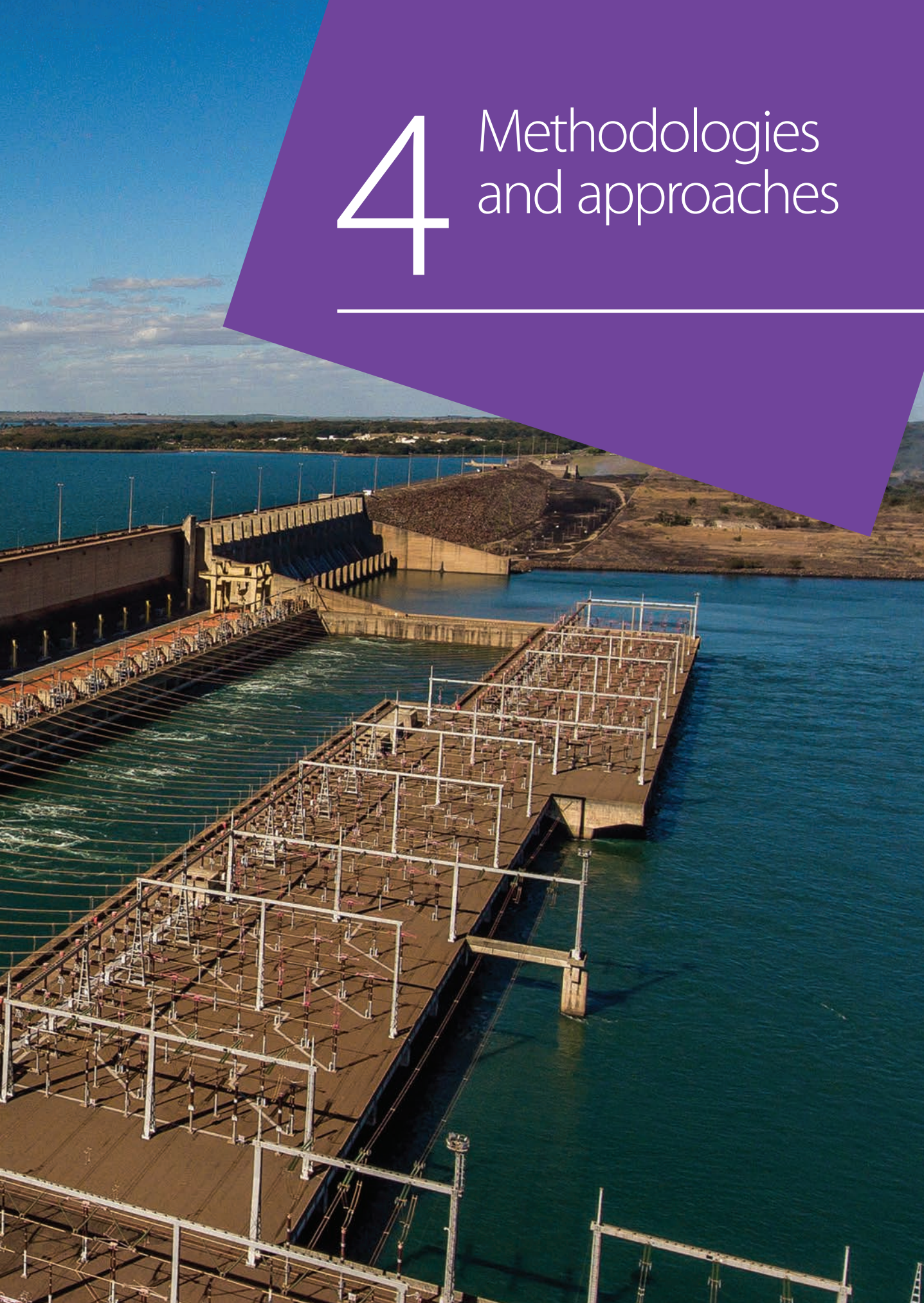
Evidence of successful safety management should be provided by monitoring reports that track performance against commitments and objectives, and have a systematic approach to data collection and analysis, regarding safety incidents, near misses, and trends. Ideally, the safety programme should reflect a continuous improvement approach, and should be adapted to ensure that incidents that have occurred are unlikely to be repeated.



Ilha Solteira hydropower plant located on the Paraná River, between the municipalities of Ilha Solteira and Selvíria, with installed capacity of 3,444 MW. It is currently undergoing the largest hydropower modernization project in Brazil.  
*Photo credit: Henrique Manreza*

# 4 Methodologies and approaches

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# Methodologies and approaches

This chapter describes practical approaches to prepare, implement and operate safety-relevant infrastructure. It starts with general approaches to risks, followed by methodologies to ensure dam safety and the safety of other components, and then discusses a series of approaches that apply across all project components.

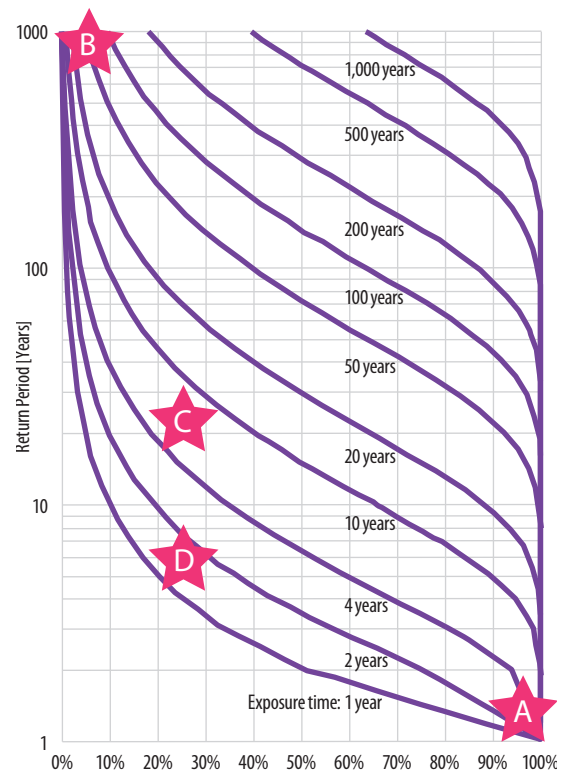
## 4.1 Assessing risks and risk tolerance

Risk management is based on an understanding of probabilities and consequences, and risk probability matrices can be applied to all aspects of infrastructure safety. Such matrices allow the determination of risk and its sensitivity to various factors. For instance, the risk level for diversion works is sensitive to the exposure duration in years, and this constitutes a planning risk, since construction delays will cause an increased likelihood of the event's occurrence.

The following risk probability matrix includes four examples of the likelihood of an event with a given probability (return period  $T$ ) occurring during a given time window (exposure duration  $n$ ).

- **Case A:** Example of road traffic with a short return period (i.e. there is a significant probability of serious accidents) over a long exposure duration (over a concession term, for example).
- **Case B:** Example of extreme floods or earthquakes with long return periods (e.g. over 100 years) over long exposure durations (over a concession term, for example).

**Figure 5.** Example of a Risk Probability Matrix



- **Case C:** Example of river diversion works (coffer dam) for the construction of an embankment dam, with an intermediate return period (e.g. 25 years) and an exposure duration which is a function of the duration of the construction phase.
- **Case D:** Example of river diversion works (coffer dam) for the construction of a concrete dam, with a short return period (e.g. five years) and an exposure duration which is a function of the duration of the construction phase.

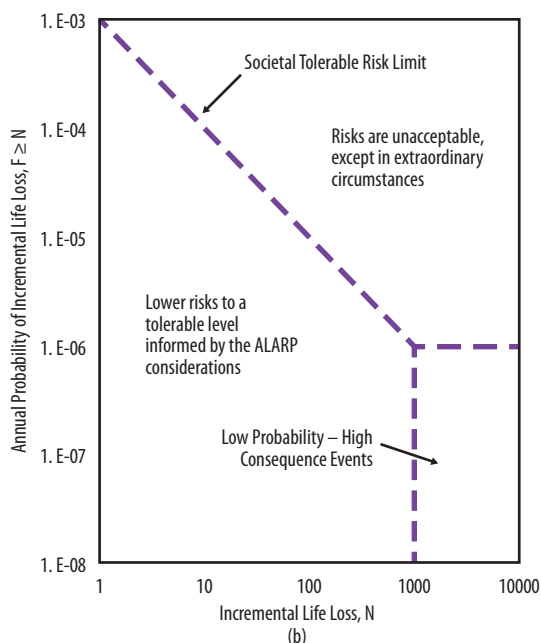
In quantitative or semi-quantitative risk analyses, it is standard practice to prepare a risk register listing hazards and risk factors, and to estimate the frequency of occurrence and consequences of any resulting incidents. Life-safety risk analyses for dams, and for a number of other engineering and societal activities, evaluate the frequency of occurrence in terms of the annual probability of failure, and the associated annual number of fatalities.

Another method of assessing and prioritising risk qualitatively and quantitatively is to identify key failure modes, by following the FERC's PFMA (Potential Failure Mode Analysis) process and identifying the consequences of failure, in order to develop a matrix for each of the specific failure modes identified. This enables better prioritisation and tailored remedial solutions based on the specific failure mode.

Risk acceptability criteria, or limits of tolerability for a range of engineering and societal activities, are the subject of some controversy. However, guidance is available from organisations such as the Canadian Dam Association and others, which can be used to guide the development of risk tolerability criteria in risk assessments.

As an example, Figure 6 illustrates the USACE's societal tolerable risk limits, showing the distribution of the estimated annual probability of potential life loss from dam failure. This is displayed as an F-N chart, which is a plot of the annual probability of exceedance (greater than or equal to) of potential life loss (F), vs. incremental potential loss of life (N) associated with the incremental flood risk.

**Figure 6.** USACE Societal Guideline for Incremental Risk



## 4.2 Keeping dams safe

### 4.2.1 A systematic Dam Safety Programme

A safe dam does not present unacceptable risks to life, property or the environment. Ensuring dam safety requires the collective application of engineering principles and experience, through all phases of a project, from the original design to construction and operations. This includes quality control, maintenance, surveillance and emergency planning. A dam safety programme includes an assessment of risks to the public resulting from dam failure and operational errors, and the mitigation – to the extent that is reasonably possible – of any unacceptable risks.

Accomplishing these purposes requires commitments to continually monitor, evaluate and document the design, construction, operation, maintenance and rehabilitation of the dam and associated infrastructure, and to maintain up-to-date emergency preparedness and response plans for each dam and the associated public. It also requires a document control and filing

system to manage information – from the design through construction and operation phases – which concerns inspections, the history of the dam (e.g. rehabilitation works and changes in instrumentation), and the training records of the personnel who inspect, evaluate, operate and maintain the facilities and structures.

All of these actions are part of a Dam Safety Programme or Dam Safety Management System. All dam safety programmes include a range of complementary components, as shown in Figure 7.

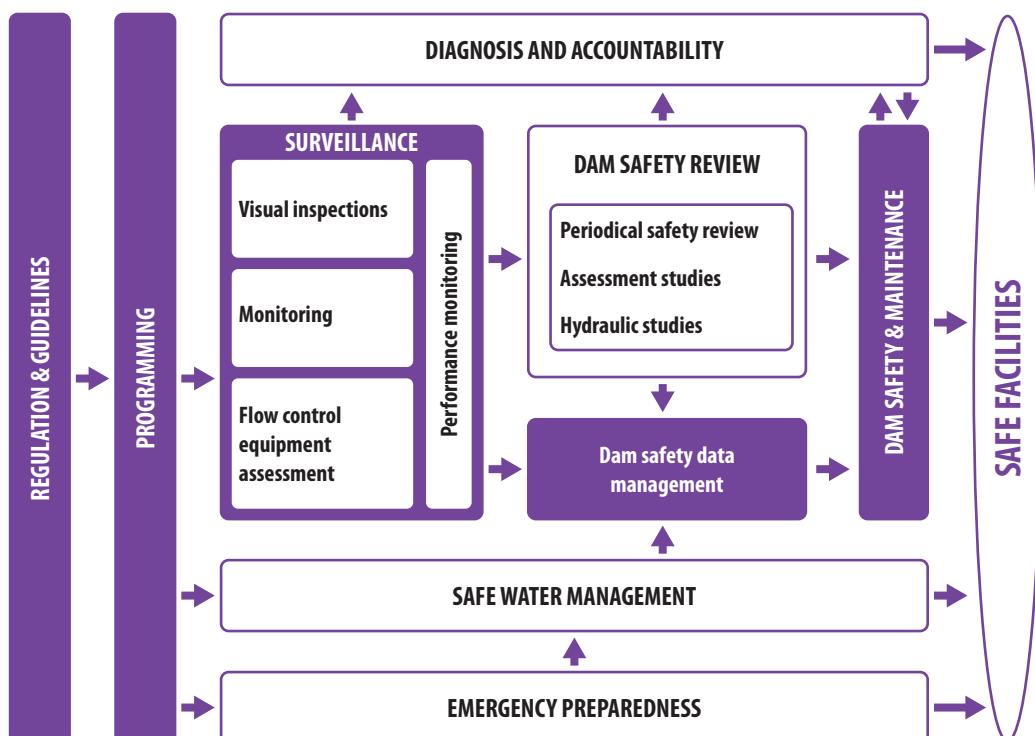
Dam safety guidelines for hydropower projects have been developed and improved upon continuously for many decades by organisations such as ICOLD, and by more regionally based organisations such as the Canadian Dam Association, USBR, and the US Army Corps of Engineers in North America, as well as regional ICOLD groups such as EURCOLD. Governmental agencies and ICOLD National Committees of several countries have developed dam safety regulations and guidelines.

These entities are well positioned to ensure that guidelines are kept up to date, made available to practitioners, and adhered to in practice. Dam safety management is the ultimate responsibility of the dam owner. The Dam Safety Programme components should follow a holistic approach, including the dam owner's operations staff, independent technical subject matter experts and the regulatory authorities.

The following Sections 4.2.2.–4.2.5. describe individual components of a Dam Safety Programme, such as the preparatory studies, designs, failure consequence evaluations, inspections and reviews. Other components, which apply not only to the dam but to all aspects of hydropower projects, are covered under the cross-cutting issues discussed in Section 4.4.

**Figure 7.** ICOLD: Components of a Dam Safety Programme

Source: ICOLD Bulletin 138, *Surveillance: Basic Elements in a Dam Safety Process* (2009)



**Box 11: The Pillars of Dam Safety according to ICOLD (2019)**

*Source: ICOLD, World Declaration on Dam Safety, 2019*

With almost a century of commitment to dam safety, and acknowledging that zero risk does not exist, ICOLD recognises several overarching pillars of dam safety:

- Structural integrity of dams is the keystone to dam safety.
- Routine surveillance and maintenance programmes are necessary for early detection.
- Instrumentation and monitoring programmes are essential throughout the life of a dam.
- Design-intrinsic risks need to be adequately addressed.
- Natural hazard risks change with time, and thus should be regularly reviewed and updated.
- Emergency planning is of the utmost importance for all dams.
- Adequate training of operators is part of a comprehensive safety programme.
- Sharing lessons learned is of benefit to the entire industry, making all dams safer.
- A comprehensive dam safety approach will allow minimisation of risks.
- A dam owner has the ultimate responsibility for its dam.
- The role of regulatory authorities is of paramount importance.
- An international perspective on dam safety can be enlightening

## 4.2.2 Understanding site conditions: preparatory studies

### 4.2.2.1. Hydrological studies

A thorough understanding of the hydrology of the region and the watershed is fundamental to hydropower design and operations, both in the planning phase and throughout the life of the dam.

Basin hydrology has an inherent level of uncertainty, as it is based on streamflow and precipitation records obtained from gauging stations within the dam catchment. A longer period of record, typically at least 30 years, should be available to adequately define the patterns and trends of the flow regime. In more remote regions or countries lacking resources to install hydrometric networks, shorter or discontinuous periods of record may be all that are

available, and statistical methods need to be used to extend or 'infill' the data series, in order to produce a record that can be used for design purposes.

For ungauged catchments, regional methods can be used in hydrologically homogeneous regions. Frequency analysis offers a number of techniques for studying the statistical properties of flow and precipitation series. Because dam design is concerned with designing a structure that can withstand or safely pass flood flows, a subset of annual maxima (maximum flow events) is used to determine the magnitude of the flood in design calculations. For dams with high or significant hazard or consequence, this may range from the 1:1,000 or 1:10,000-year flood up to the probable maximum flood (PMF), which is based on the site's probable maximum precipitation (PMP) event.

Depending on the jurisdiction or standard used, the design flood can be referred to as the 'Inflow Design Flood', 'Safety Flood', the 'Standard Project Flood', etc. Typically, the applicable framework will identify the return period of the relevant flood (i.e. 1:100 or 1:1,000-year flood, PMF, etc.). This may be a function of the hazard or consequence classification of the dam (higher hazard or consequence dams will be designed to safely pass higher return-period floods).

The design of temporary structures for the construction stage (cofferdams and diversion tunnels) typically uses a lower return period, depending on how long the structure is expected to be in service (usually a few years), such as the 1:25-year flood. The design flood used for these structures is best determined through a risk assessment, as mentioned earlier in this guide, which also takes other parameters into account – for example, schedule risk, geotechnical risk, ice jam floods, landslide risk, etc. These temporary structures merit attention, as their construction can be on the project schedule's critical path, and their failure could result not only in public safety risks, but also in significant setbacks to a project. In some cases, the selection of this flood event may be contingent on acceptance by the insurer.

All hydrology studies need to take into account the potential effects of climate change on temperature and rainfall intensity and quantity, extended drought periods, snowpack and snowmelt, glacier melt, glacier lake outburst floods (GLOFs), and other extreme events. Other changes over time within the dam's catchment (changes in land use, development, forest fires, etc.) can change how rainfall is converted into runoff. This occurs through changes in processes such as interception, infiltration and percolation, surface or depression storage within the catchment, evaporation from water bodies and evapotranspiration from vegetation, sediment transport and erosion, and runoff travel time. Upstream dams and reservoirs and their normal operations also need to be taken into account.

Hydrometric stations should be installed during project preparation and maintained during construction and operation (when they do not exist on the river system or in the watershed), in order to build a record of flows and calibrate hydrologic

models, and to provide advance information on expected inflows during the operation stage.

The project's hydrology should be reviewed periodically, to ensure the dam can still safely pass the design flood, even if the magnitude of this flood has changed. It is increasingly critical to design resilient projects that can adapt to flow changes. The Hydropower Sector Climate Resilience Guide offers guidance on identifying, assessing and managing climate risks to enhance the resilience of hydropower projects. Periodic re-evaluations should also include the exposure of changing downstream populations-at-risk (PAR), upon which the original project risk level is often based.

#### **4.2.2.2. Geological and geotechnical studies**

An accurate assessment of the geological and geotechnical context of the site is an important precondition for the design and construction of a safe project. Every site's foundation conditions and available construction materials are unique, and therefore the extent and nature of required geological and geotechnical investigations are also site-specific.

These investigations are usually carried out in several phases associated with the sequence of engineering decisions which must be made. Accordingly, preliminary investigations involve the assessment of several alternative sites, feasibility investigations enable the selection of a dam type and infrastructure layout that is best suited to a site, and design investigations give the engineering team information for more detailed analyses and final design. These studies should provide complete mapping and zoning of the foundation and surrounding areas of the dam and other infrastructure, in terms of mechanical and hydrogeological properties. This will inform the selection and design of foundation treatments (consolidation, water tightness and specific fault treatment), and for slope stabilisation (grouting, anchoring or other measures), as necessary. At the end of each of the above-mentioned stages, complete reports should be issued, containing detailed descriptions of the investigations and findings.

During the construction stage, conditions should be confirmed and updated. Unexpected variations may require prompt additional investigations to prevent costly delays. In the operation stage, data and reports from previous stages are invaluable for understanding and rectifying any problems that may occur.

Typical methods and techniques that are applicable to dams, as well as other structures such as spillways, powerhouses, tunnels, etc., include the following:

- Topographical surveys, digital surface and elevation models and imagery (aerial photos, orthophotos and satellite imagery) support the geological mapping, enabling the detection of large morphological features that are difficult to identify on the ground, such as faults and localised geological formations.
- Trial or test pits at the dam site and in borrow areas are essential for embankment dams, but may also be dug for concrete dams when the rock substratum is not very deep. In some cases, it may be preferable to dig trenches along carefully chosen alignments, along or crossing the valley axis. Pits enable direct observation and sampling for laboratory testing.
- Investigations for large projects may include exploratory adits or galleries, which provide a better understanding of rock formations, joints and faults, and enable in-situ mechanical rock tests and hydrogeological assessments.
- Seismic wave velocities are relatively quick and easy to measure, mainly in rock foundations, and can provide valuable information about rock weathering, faults, and degree of cracking. These techniques are suitable for feasibility studies to help select a dam location, and they enable design studies to define excavation depths and dam foundation levels.
- At sites with a risk of underground cavities, high permeability and/or loss of bearing capacity (such as karst formations, former mines or quarries, soluble rocks), microgravimetry can detect anomalies in the gravity field.
- Core sampling by drilling provides knowledge of the lithological structure of the various

foundation layers. This technique makes it possible to conduct investigations in every type of terrain, at greater depth than with test pits, and with more reliable water testing than can be done in pits (although restricted to fewer points). It also allows video observation inside the boreholes, and the recovery of undisturbed samples from the ground.

- Boreholes enable deformation tests along their length, and seismic wave velocity measurements between boreholes and the surface (enabling indirect mechanical zoning). Special techniques of borehole execution allow the extraction of integral samples, for a better understanding of foundation discontinuities. Boreholes also provide important hydrogeological information, and permeability tests in boreholes enable the permeability zoning of the foundation.

Any laboratory and in-situ tests should be performed by accredited laboratories and companies, according to recognised standards and specifications, and summarised in a report.

A survey of the complete reservoir area should be carried out, starting with aerial, satellite or drone imagery, followed by site visits to detected critical locations, and where necessary, specific investigations. The focus should be on the sliding stability of the reservoir bank slopes, and instrumentation can be installed to understand and control potential slope instabilities.

Ideally, borrow areas to provide materials for embankment dams, and quarries to provide aggregates for rockfill or concrete dams, shall be identified within the reservoir area. The properties of materials need to be analysed to ensure safe construction. A particular concern is the selection of aggregates to prevent concrete swelling phenomena, such as alkali-aggregate reactions, which represent one of the major problems affecting concrete dams. Thus, suitable tests before the beginning of construction are required.

#### **4.2.2.3. Seismic studies**

Seismic studies are required to predict earthquake hazards at the site, as well as to provide seismic parameters for the selection of the dam type, and

the structural design of the dam and other project components. Any geological condition at or near the site that might indicate recent fault movement or seismic activity should be investigated. The presence of an active fault (fault with evidence of repeated movements in the past) can preclude the construction of a dam, if no adequate solutions can be designed to accommodate the estimated movements associated with the fault.

As listed in ICOLD Bulletin 148 on selecting seismic parameters for large dams, a seismic hazard assessment requires the following:

- identification of potential sources of earthquakes;
- evaluation of the characteristics of each potential earthquake source, such as geological conditions, magnitudes and rates of activity; and
- estimation of ground motion amplitudes or intensities at the dam.

Specific geologic information for the site is necessary, in order to ascertain the ground movement expected and the potential for primary or sympathetic fault movement through the foundation. The studies should be tailored to local conditions, the size of the dam, its intended functions, and the consequences of damage or failure of the structure. Some sites require consideration of a large regional study area, to encompass all significant geologic features.

The compilation of historical earthquake data helps to identify the seismicity patterns of an area and provides a basis for estimating the probability of future earthquake motion. Earthquake catalogues existing in different countries and data from international agencies provide information on earthquake magnitudes, epicentre locations, and other parameters such as focal depth and fault mechanism. Seismic history and geologic considerations may be used to quantify the rate of seismic activity (number of events per year) for the

### Box 12: Standard earthquakes to be considered in seismic studies

*Source: ICOLD Bulletin 148 (2016) – Selecting Seismic Parameters for large dams. Guidelines.*

- **Maximum Credible Earthquake (MCE)** is the event that would produce the largest ground motion expected at the dam site, based on the seismic history and the seismotectonic region framework. It is estimated based on deterministic earthquake scenarios, but if this is not possible, a probabilistic approach linked to a long return period (for example, 10,000 years) can be used.
- **Safety Evaluation Earthquake (SEE)**, also (previously) designated Maximum Design Earthquake (MDE), is the earthquake ground motion that a dam must be able to resist without the uncontrolled release of the reservoir. For a large dam, it can be associated with an event with a return period of 10,000 years.
- **Operating Basis Earthquake (OBE)** is the seismic event that is expected to occur during the dam lifetime. Its probability of occurrence is about 50 per cent during a service life of 100 years.
- **Reservoir-Triggered Earthquake (RTE)** represents ground motion triggered at the dam site by the filling, drawdown, or the presence of the reservoir. It has been generally linked to dams higher than approximately 100 m or to large reservoirs (capacities greater than 500 hm<sup>3</sup>), and to new dams located in tectonically sensitive areas.

In many cases a 'verification earthquake' is also considered, with a return period greater than the OBE. In line with some codes for buildings' seismic design, parameters associated with an earthquake with a return period of 949 years (corresponding to a 90 per cent probability of not being exceeded in 100 years) are often used.

area and, if possible, for each recognised active fault or tectonic province within the area.

Seismological studies result in the definition of seismic actions – in particular, the intensity, shape and duration of seismic vibrations at the site. This can be accomplished by using either a deterministic or a probabilistic seismic hazard evaluation (refer to Box 12 for more information on the standard earthquakes to be considered in seismic studies).

The data obtained in seismic studies should be also used in the design of appurtenant structures and other project infrastructure, according to the potential hazards they can induce.

## 4.2.3 Designing for safety

### 4.2.3.1. Hydraulic design

Hydraulic design applies to several components of a hydropower project, including the spillways, water conveyance structures (pressurised and not pressurised), intake and outlet structures (designed to safely convey water, sediment, logs and other debris), navigation locks, and fish ladders and passages. It also provides the definition of levels for different components, for protection against flooding.

All dams must be protected by a spillway that is intended to discharge inflows in excess of the storage capacity, which must be safely conveyed downstream and released without presenting any danger to the dam foundation, dam side abutments, or any other neighbouring infrastructure (e.g. nearby powerhouse or road).

Spillways are designed to ensure that the dam is not overtopped, with a defined amount of freeboard, and considering flood routing through the reservoir. Freeboard is the height of the dam crest above the maximum operating level, and the required freeboard depends on wind and wave conditions at the dam, and the risks of overtopping (higher for embankment dams). In most jurisdictions, spillways are designed for several design scenarios, including at least one ‘design’ scenario for which good performance must be guaranteed, and in some instances, one ‘safety-check with maximum flood’ scenario, for which some damage or loss of

efficiency may be accepted, as long as there is no uncontrolled release of water and dam stability is not endangered.

The capacity of a spillway needs to be adequate to safely pass floods, from the first filling of the reservoir throughout the life of the plant. Spillway capacity must be periodically reassessed considering updated (and extended) hydrological records, as well as progress in hydrological engineering, public safety awareness and risk management practices.

There are many types of gated and ungated spillways, depending on the inlet structure (ogee, labyrinth, piano keys, round, etc.), conveyance structure (chute, shaft, siphon, or simply free ballistic trajectory in air), and outlet structure (ski-jump, roller bucket, flip bucket, hydraulic jump stilling basin, impinging jet lined pool, or simply plunging impact on downstream riverbed). Gates for spillways can also vary significantly, including radial (or tainter), vertical lift, flap gates, etc. Design considerations include operating condition, costs, the available space, the need to avoid flow separation, inefficient use of the available hydraulic surfaces, and cavitation, as well as to ensure sufficient energy dissipation, and others.

There are several design standards for the different types of spillway. An earth or grass-lined spillway may not be reliable under sustained flow and should not be used as a single spillway, but must be combined with additional spillway structures.

Bottom outlets are important structures, particularly for the safety of storage dams, and are designed for a series of safety-related tasks, including i) controlled first filling of the reservoir and loading of the dam and foundation, ii) emergency drawdown of the reservoir if necessary, iii) maintaining the reservoir at a given water level if necessary, for dry or wet inspections and for safety issues, and iv) releasing sediment. These outlets are gated structures operating under high heads. The design must foresee adequate flow convergence at the inlet, high velocities without excessive abrasion or cavitation during opening, and flow release without damages to the downstream river. Water release outlets at different elevations may be necessary.

Debris management can be an important aspect of operations in some watersheds. Most powerhouse intakes and some spillways are equipped with trashracks to avoid entrainment of debris. Adequate width of the spillway bay, as well as distance from catwalks or any platforms, is important to avoid clogging and reduction of spillway capacity, as this may lead to high water levels (and even dam overtopping) for flood events that could otherwise be safely conveyed through the spillway structures. Ice jams can present similar risks. Debris or log booms upstream of the dam can prevent the blocking of and damage to gates, spillways, intake works, and the dam itself. Some booms are designed to direct logs to chutes that pass logs downstream.

The design of spillways requires specific expertise related to free surface flows with three-dimensional features that are difficult to predict, as well as of air-water mixing and turbulent processes occurring in the energy dissipation structures or plunge pools. Desk-based studies leading to the initial definition of hydraulic geometries are generally complemented with physical modelling studies in specialised laboratories. These studies allow the validation and optimisation of the hydraulic design, and are generally conducted between the investment decision and the early years of construction. Keeping a physical model available throughout construction can be advisable, in order to assess civil works methodologies for specific work fronts in or close to the river, to optimise design solutions after geological findings during the works, or to evaluate equipment suppliers' variant proposals.

The development of computational sciences today allows some hydraulic modelling studies to be carried out earlier, and for different geometries to be screened with a lower level of effort than in physical models. Computational modelling tools provide promising results for low-velocity unaerated flows (such as those in reservoirs), approach channels to intakes and spillways, tailrace channels from powerhouses, and river hydraulics. However, this type of modelling cannot yet reliably reproduce the complex features of highly turbulent air–water flows, as are encountered in many dam spillways.

#### 4.2.3.2. Structural design

This section is mostly concerned with concrete dams, while embankment dams are covered in the following Section 4.2.3.3., as their potential failure modes and design requirements are primarily addressed through geotechnical design.

Structural design includes the analyses and verifications that assure a structure's capacity to support all loading actions it can be subjected to, without loss of equilibrium and without total or local ruptures. This concerns both the stability of the structure as a whole and partially, and the assessment of spatially distributed stresses and displacements.

In the simplest formulation, structural design requires the verification that resistant parameters are higher than the corresponding action loading effects, with an adequate 'margin of safety', and involves defining structural materials' properties, response parameters and partial safety factors.

Safety must be checked for a complete range of operating scenarios, including a combination of different loading conditions (e.g. different water levels in the reservoir) that are associated with usual, unusual and extreme actions, according to their probability of occurrence. The safety evaluation earthquake (SEE) and the probable maximum flood (PMF) are examples of extreme actions.

The requirements to withstand different failure modes (see Section 2.2.2.) are then analysed. The most common concrete dam failure modes (mainly for gravity dams) are as follows:

- **Overtopping:** To ensure stability, the adverse turning effects around the downstream toe of the dam – caused by the hydrostatic pressure acting on the upstream face of the dam, and by uplift pressure acting on the dam base – should not be greater than the stabilisation effect of the structure's weight. The safety factor is defined by the ratio between the stabilising and the overturning effects.
- **Sliding:** Relevant stability considerations concern the dam–foundation surface, foundation discontinuities, and lift joints. The destabilising actions are the tangential forces

caused by hydrostatic pressure, while the resistant forces are those mobilised by cohesion and friction. These two parameters depend on the geo-mechanical properties of both sliding surfaces, and friction is caused by the action of the dam weight or loading stresses, reduced by water pressure (e.g. uplift effects).

The main issues to consider in structural analyses are the structure's weight, and water, thermal, seismic and sedimentation actions:

- **Hydraulic loads:** Upstream-downstream flows through the dam body and its foundation (through cracks and/or pores) cause hydraulic gradients (pressures and velocities), which are analysed using hydraulic models. Limit levels associated with usual, unusual and extreme operational conditions in the reservoir shall be considered, including flood management scenarios, ice, and waves due to reservoir landslides or wind action. Hydraulic loads should include forces applied by spillways, bottom outlets and intake gates, as well the associated hydrodynamic effects.
- **Thermal loads:** Concrete hardening is an exothermic chemical reaction which causes temperature to rise and acts on contraction joints by closing them, mainly during construction. The rise in temperature depends on factors such as cement content, thermal concrete properties, concrete temperature placement, the concreting schedule, and pre-cooling operations. This issue is particularly relevant in RCC dams, due to the continuous and fast concrete placement. Concrete post-cooling is performed by circulation of refrigerated water in pipes installed during construction. Temperature gradients can cause internal stresses and cracking, and therefore, coupled thermal-structural analysis is necessary to design dams and plan their construction, including post-cooling operations. Such analysis can also be required to analyse thermal loads during the first filling and first years of operation. During the operation stage, the ambient air and reservoir seasonal temperature variation should be considered in the analyses, as should solar radiation.

- **Seismic loads:** Seismic study results, such as peak ground motion, can be sufficient for simplified structural analyses (pseudo-static methods), and dynamic finite element response analyses may be performed using response spectra. However, acceleration time histories from earthquake records are required for most dams in high hazard or consequence classes.
- **Sediment loads:** Sediment deposits accumulated near the dam's upstream face can place a considerable load on the dam. The definition of this action requires analysis of the type of sediments and the mechanisms of sediment deposition, through hydraulic computational models and bathymetric surveys.

For the purposes of structural analysis, these loads can be combined to develop the above-mentioned usual, unusual and extreme scenarios.

Further requirements for structural analysis are material properties, and in particular the mechanical and rheological properties of concrete. Mass concrete used for dam construction has special features that differ considerably from concrete used for other structures, such as reduced cement content and larger aggregate size. Different types of concrete are used in different parts of the same dam, according to resistance and water tightness requirements.

Concrete mix design and composition studies should be performed during the design and construction stages, supported by laboratory and field tests of experimental mixes. Deformability, strength and creep, including the estimated evolution over the structure's lifetime, are the most relevant parameters for structural design. The same parameters should be known for the foundation materials, from the geological and geotechnical investigations.

The finite element method (FEM) has become the most commonly used tool for stress and displacement analysis in dam design, and for dam safety assessments during the operation stage. The fast development of computational algorithms enables geometrical modelling associated with finite element mesh generation, as well as non-linear material behaviour analysis (which is important for considering creep

effects and cracking). Spillway structures, dam galleries, construction joints and other geometric particularities can be incorporated in the structural model.

The distinct element method (DEM) can be used for stability analysis regarding foundation failure scenarios. The use of DEM combined with FEM models allows the representation of different weak surfaces, such as complex rock jointing patterns or the concrete-rock interface, including hydraulic pressures (uplifts).

For seismic structural design, various types of dynamic analyses can be performed, ranging from a simplified rigid-body pseudo-static analysis (as in the case of some gravity dams), to more elaborate procedures, such as analysis by the finite element method, including reservoir interaction (particularly for high hazard and consequence dams).

#### 4.2.3.3. Geotechnical design

Geotechnical engineering is based on the fields of soil and rock mechanics. In a hydropower project there can be a large number of structures requiring geotechnical design, including embankment dams, foundations of concrete dams, abutments, open-cut and underground excavations and slope stabilisation, tunnelling, and underground caverns.

Modern geotechnical design codes adopt the limit state design (LSD) concept, also known as the load and resistance factor design (LRFD). A limit state is a condition of a structure beyond which it no longer fulfils the relevant design criteria. Serviceability limit states (SLS) are associated with usual operating scenarios, and ultimate limit states (ULS) with potential failures modes. Suitable safety factors should be adopted according to the limit state under analysis. Results should be interpreted with caution, as they depend on the accuracy of the actions and geotechnical parameters, and the quality of dam construction.

Embankment dam design includes consideration of the properties of the available construction materials, based on the results of the geological and geotechnical investigations, and the construction strategy.

The main actions to be considered in the design of an embankment dam are the weight of the materials and any type of loads directly applied to the structure, such as earth pressures, water pressures (including those associated with percolation in the dam body and foundation), loads due to construction methods, expansions and retractions due to water contents and temperature variations, creep and consolidation effects, as well as seismic actions. These actions can lead to the verification of the following limit states:

- Failure or excessive deformation of the dam and its foundation, where resistance is provided by the strength of soil or rock (e.g. material shear strength and cohesive properties).
- Loss of equilibrium of the dam structure or its foundation, due to uplift by water pressure or other vertical actions.
- Slope ruptures on dam faces or on the crest, as well as ruptures due to surface and foundation erosion.
- Hydraulic lifting, internal erosion and piping in the dam or foundation, caused by hydraulic gradients.
- Failure or excessive deformation in structural components built with other materials, such as upstream slabs in rockfill dams.

As mentioned previously, earthquakes can provoke either loss of stability due to the decreased strength of the embankment or foundation materials (e.g. liquefaction due to pore pressure increase), or excessive deformations (slumping, settlement, cracking of the embankment, and planar or rotational slope failures). In order to predict dam behaviour during earthquakes, simplified methods (e.g. derivation of seismic load factors from specified peak ground-motion parameters) may be adequate if the embankment materials are not susceptible to loss of stiffness and strength, and the hazard and consequence ratings are low. For other dams, dynamic analyses (based on finite element models) using acceleration time histories are required for the SEE. Taking advantage of the available software, factors such as the vertical component of ground motion or hydrodynamic effects of the reservoir water can be considered, particularly for high

embankment dams and for dams with high and steep faces.

#### 4.2.3.4. Instrumentation

This section specifically addresses the instrumentation of the dam, as a subset of safety monitoring approaches that has very specific objectives and requirements. A more general discussion of monitoring, analysis of monitoring results and adaptive management – which applies to all components of a hydropower project – is provided in Section 4.4.6.

A global monitoring plan for the life cycle of a dam may include the definition of parameters to be measured, selection of devices and procedures for their installation, data gathering and validation methodologies, organisation of results in a digital database, and type and frequency of site inspections and reports. Specific monitoring plans may be set up during construction, first filling of the reservoir, and the initial operation period (usually five to seven years). In this section we focus on the instrumentation plans.

The purpose of instrumentation is to enable the assessment of the dam's behaviour and to identify potential key failure modes before they progress to a point where stability is at risk, thereby providing time for corrective or remedial measures.

A wide range of instruments are used at hydropower schemes. Some instruments, such as permanently installed cameras, can help with remote surveillance of the dam and powerplant, while also ensuring the security of the installations (monitoring of intruders), and the safety of workers and visitors. General considerations for instrumentation include the following:

- Many countries have legislation, guidelines or specifications concerning dam safety, which include instrumentation plans. The instrumentation plan may have to be approved by local authorities, to verify compliance with regulations, and/or be reviewed by independent experts.
- Any weak point or gap in monitoring can affect overall dam safety. Plans can incorporate several systems, and redundancy should be included in the most important data, to compensate for any damage to devices.
- Plans should be reviewed and adapted following unexpected circumstances, events or variations during the construction and first filling of the reservoir. During operation, safety assessment reports may identify further needs for repair or other adaptations.
- Threshold alarm levels should be developed for all instruments. These levels should be designed to first identify when more frequent monitoring is needed, then when detailed assessment is required to identify a suspected problem and develop contingency solutions, and finally, when immediate remedial action should be taken to implement the contingency solution.
- Reliability should be the most important criterion in the selection of the monitoring devices and methodologies. The devices, as well all other components such as cables, connections, switches and power supply (if necessary), should be of the appropriate quality and withstand local weather conditions.
- Instrumentation should be installed by technicians or companies with recognised expertise, and be adequately controlled.
- The construction schedule should consider appropriate timing for the installation of the instrumentation, in particular the embedded devices.
- The expected lifetime of the devices should be in line with their particular objectives.
- When automatic data acquisition is used, manual readings of the main devices should be maintained at a certain frequency in order to detect malfunctions.
- Data analysis should be performed by experienced engineers in design and safety assessment.
- Budgets need to be available to maintain and replace (when necessary) any instrumentation during the operation stage.

**Table 5. Significant parameters for the monitoring of dam and foundation behaviour***Source: ICOLD Bulletin No. 158*

| Concrete dam                                                   | Embankment dam                                              | Foundations                                                                             |
|----------------------------------------------------------------|-------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| Structural deformations                                        | Deformations of the dam body                                | Deformations<br>Abutment movements                                                      |
| Special movements (cracks, joints)                             | Special displacements (links with a concrete structure)     | Special displacements (cracks, diaclasses)                                              |
| Dam body temperature                                           | Dam body temperature to detect seepage (possible)           | Dam body temperature to detect seepage (possible)                                       |
| Uplift pressures (contact concrete-foundation and in the rock) | Pore pressures in embankment dam body and piezometric level | Pore pressures<br>Deep body uplift pressure<br>Piezometric level<br>Phreatic line level |
| Seepage and drainage rates                                     | Seepage and drainage rates                                  | Seepage and drainage rates and resurgencies (sources)                                   |
| Chemical analysis of seepage water<br>Turbidity (possible)     | Chemical analysis of seepage water<br>Turbidity             | Chemical analysis of seepage water<br>Turbidity                                         |

The instrumentation system must be designed to gather data describing the actions, the behaviour of the materials, and the structural response of the main structures. Table 2 lists the most relevant parameters for the monitoring of concrete and embankment dams, and their foundations, as recommended by ICOLD.

For concrete dams, the main instruments are the following:

- Plumb lines suspended from the crest, inverted plumb lines anchored in the foundation, or a combination of both, enable the measurement of relative or 'absolute' displacements at several levels, along vertical shafts.
- Biaxial or triaxial joint or crack meters monitor relative movements of contraction joints or cracks, and clinometers are used for rotation measurements.
- Piezometric and drainage networks installed in the dam foundation are used to measure uplift

and water flows, providing information about grout curtain efficiency.

- Rod extensometers installed in the foundation, dam–foundation interface or dam body, to enable deformation and displacement measurements.
- Strains, stresses and temperatures can be measured by embedded devices, including devices based on electrical resistance and vibrating wires, and more recently, fibre-optic sensors.
- Creep cells allow periodic tests to understand the evolution of concrete deformation.
- Seismometers measure earthquake-induced acceleration and are usually installed near the dam foundation for characterisation of the action, and in the upper zones of the dam for the evaluation of structural response. These are advisable in high potential hazard dams, and if any potential active faults have been identified nearby, or in reservoirs with high water volumes

located in sensitive seismic zones. In such cases, Structural Health Monitoring Systems (SHMS), using highly sensitive accelerometers, enable the evaluation of the dam's dynamic characteristics and their variations over time (damage detection).

For embankment dams, the main instruments include:

- Hydraulic or pressure cells that measure pore pressure in permeable materials, while vibrating wire piezometers are preferred in impermeable materials (clay, rock, concrete). Standpipe (or Casagrande) piezometers can measure the hydraulic pressure at the bottom of a borehole, and where feasible, open pipes can measure water levels in the dam body.
- Settlement gauges and hydraulic settlement cells that measure dam settlement. Multipoint settlement systems are established by connecting several hydraulic settlement gauges connected to a reference tank located on higher stable ground. Each settlement gauge is a pressure transducer with vibrating wire, or capacitive technology, mounted on a plate with a protective cover.
- Inclinometers measure relative displacements in structures along a borehole, by means of a sensor probe.

Reservoir levels are usually measured with staff gauges or scales installed on dam faces, and by sensors with Automatic Data Acquisition Systems (ADAS).

Seepage is measured in different ways. In concrete dams, water infiltrations are directed through galleries towards discharge measurement devices. In embankment dams, infiltrations can be collected in drainage systems located downstream of the core or the upstream impervious curtain, and directed to measurement stations (calibrated weirs). Distributed fibre optic systems can provide information about temperature distribution, which is related to seepage, and allows leakage detection inside the dam. Boils, whirlpools, sinkholes, turbid discharges, increasing seepage with time (unrelated to reservoir levels or rainfall) are all indicators of a developing and internal erosion issue.

For all types of dams, geodetic surveying is used to measure displacement, and includes precision triangulation, geometric levelling and precision traverses. As they use assumed fixed stations and fixed reference targets, these methods are able to determine absolute and not just relative displacements. Precision has been enhanced through improvements in devices, application methods and calculation algorithms, including through integration with the Global Positioning System (GPS) and other Global Navigation Satellite Systems (GNSS).

Data obtained from the various instruments need to be documented, analysed and interpreted through qualitative and statistical analysis, and through calibration of the dam structural model. The main challenge in data analysis is the integration of all the information, although there have been important advances in numerical models, risk analysis, big-data analysis and artificial intelligence. New developments in sensors and data transmission enable the automatic acquisition of readings from almost all types of devices installed at a dam. ADAS are being installed in many dams, enabling automatic data transmission, remote access, and warnings about malfunctions or the passing of predefined thresholds.

During recent years, a number of new instrumentation techniques have been applied to dams. These include thermal imagery, acoustic monitoring, robotic total stations, laser scanning and digital imagery (drone- or satellite-based), remotely operated or autonomous underwater vehicles, satellite synthetic aperture radar (SAR), ground-based interferometric synthetic aperture radar (GBinSAR), ground penetrating radar (GPR), and multi-beam bathymetry. Robustness, effectiveness and reliability of new technologies must be carefully tested. It is also necessary to ensure data continuity, and correspondence with previous data collection techniques.

#### 4.2.4 Evaluating the consequences of failure

Dam safety and risk management requires an understanding of the consequences of potential hazards and incidents. Dam failure consequences are typically assessed by dam-break analyses, and

hydraulic modelling to simulate the dam breach and flood wave that travels downstream. This is typically an interdisciplinary effort between hydrological/hydraulic, civil engineering and geology/geotechnical experts.

The losses attributed to the dam failure event are referred to as the 'incremental' losses resulting from the release of the volume stored behind the dam, as compared to the losses caused by the same event without a dam breach (i.e. without additional release of impounded water). Failure consequences are typically assessed for both flood and non-flood cases. Inundation mapping based on a failure occurring during a flood may show areas that would be inundated without a failure, and additional inundated areas with the failure. The incremental flooded area between the two floodwater levels is the area where the incremental losses occur. For failures not associated with a flood, inundation mapping shows only one inundation floodwater level, corresponding to the flood wave resulting from the release of water impounded by the dam.

The evaluation of failure consequences is typically done in four steps:

1. Identification of the most plausible failure mode through detailed analysis of potential trigger events, preparation of failure trees, and empirical assessment of probabilities of occurrence.
2. Modelling of the dam breaching sequence, to obtain a failure hydrograph.
3. Modelling of the propagation of the failure hydrograph both downstream and upstream, considering the fast reservoir drawdown.
4. Preparation of inundation mapping for several scenarios (failures associated with and not associated with floods), and estimation of consequences using topographic, land-use and occupation maps, in order to assess damages and potential loss of life.

Identification of the most plausible failure modes requires a holistic view of the entire dam system (dam structure, foundation, reservoir and surrounding environment), as well as an understanding of the dam behaviour that is

rooted in detailed analysis of the relevant data and documentation on dam design, construction and operation. The identification of the potential triggering events can be based on evidence, on legal requirements (in terms of design floods, seismic loading, etc.), and on interpretation of the overall context. As a general principle, systematic approaches based on a thorough assessment of the failure modes presented in Section 2.2.2. are preferred, including the possibility of cascading events.

Breach formation and development processes are closely linked to the type of dam and failure mode. For concrete dams, breach formation should correspond to the brittle rupture of the dam in part or totally (including, in specific cases, the foundation), leading to an uncontrolled release of the water stored in the reservoir through a breach of hypothetical geometry. The fast disappearance of the dam is normally modelled as the fast (quasi-instantaneous) removal of a gate or concrete block. The resulting hydrograph presents a steep rising limb, with water levels at the dam breach being in the order of 4/9 of the dam height at the breach location.

For embankment dams, breach formation is generally of two types: either the creation of an initial breach at the dam crest (due to settlement, face slide, or by overtopping), or due to piping through a weak section of the dam. From the initial breach, the hydraulic flow section develops progressively by scouring and/or erosion (following typical sediment transport dynamics) and channel side-slope failure. Breach formation takes more time for embankment dams than for concrete dams: this is generally in the order of tens of minutes for low dams, extending to several hours for dams over 15 m high, which allows some time to trigger evacuation procedures. Commercial software for the modelling of breach formation is widely available.

Commercial software for computational propagation modelling of the dam-break hydrograph uses 1D, 2D and 3D solvers. In most applications for large dams, modelling involves the development of a 1D or 2D hydraulic model of the downstream valley. In some cases, sediment flow simulation is included when the reservoir contains

considerable sediment deposits, and/or when sediment deposition along the downstream valley may lead to increased flood levels.

Inundation maps for several flood scenarios, including extreme floods, can be created by superimposing the modelling results onto georeferenced maps, including infrastructure such as bridges, roads, buildings, and other features. Mapping should include flood characteristics such as arrival time, time to peak, arrival flow velocity, maximum flow velocity, and maximum water level and flow depth, at relevant river cross-sections.

The assessment of consequences can then be done by cross-correlating the flow characteristics with vulnerability features of the inundated zones (i.e. houses at risk, infrastructure at risk, etc.). Typical assessment criteria for population at risk include maximum tolerable flow depth, maximum tolerable flow velocity, maximum tolerable specific flow, and others. These criteria may consider the likelihood of the failure occurring by day or at night, during weekdays or on weekends, etc. Typical assessment criteria for buildings consider the impact force as a function of flow characteristics with regard to the type of structure (i.e. whether it is more or less permeable to flow).

Understanding the failure consequences is a prerequisite for emergency planning (see Section 4.4.1).

### **4.2.5 Inspecting dams and reviewing their safety**

The most basic level of inspections are regular routine visual inspections (daily, weekly, monthly). More thorough periodic inspections, checks and functional tests will be conducted as required at longer intervals (annually), complemented by formal external reviews every 5-10 years, which can vary by jurisdiction.

Regular routine visual inspections are an integral part of a dam safety programme. In jurisdictions where dam safety is regulated, the number of visual or formal inspections may be a function of dam classification, where higher risk or consequence dams would require more frequent inspections. Inspections and performance monitoring should

be carried out by technical specialists and qualified engineers who are familiar with the dam and its behaviour, and can detect any changes and anomalies.

At a minimum, a complete inspection should be carried out annually and include the use of a standard checklist, photographs, and notes on observations, in order to detect any relevant phenomena and characterise the condition of the structure for follow-up. It should correlate qualitative information from visual inspections (presence of cracks, seepage areas, surface sloughing or spalling, settling) with quantitative data from instrumentation (movement detection, crack measurements, piezometer measurements, surveying, etc.). A visual inspection and functional testing of flow control equipment and the emergency power supply to that equipment is required, to ensure its operability and full discharge capacity in the event of a flood or other incident. Discharge works include the different types of gates, outlets, valves, lifting devices, stop logs, etc. Merely visual inspections of the discharge works do not allow the verification of electrical and mechanical function and operational safety, as some parts – such as bottom outlets – may not be frequently in use. Some inspections can be carried out during maintenance activities, but these should be complemented by additional investigations, as necessary, when deficiencies are detected.

Safety Assessment Reports should be issued at the end of construction, first filling of the reservoir, and the first period of operation. During operations, a periodic Dam Safety Review (DSR) should be carried out by a third party (independent engineers or dam safety regulator staff) every 5-10 years (this can vary according to jurisdiction), depending on the dam behaviour, classification, potential failure modes, and regulatory requirements – or after relevant events such as floods or earthquakes. The DSR should cover condition assessments of all dam components (main dam, auxiliary dams and other water-retaining structures), and involves:

- a comprehensive review of design, construction and monitoring records;
- site inspection and interviews with the operating staff;

- verification of the functionality of the dam surveillance and monitoring instrumentation;
- functional testing of discharge facilities;
- dewatering or underwater inspections when necessary, to ensure all possible deficiencies are covered;
- review of the design criteria and assumptions used for design related to hydrology, hydraulics, geotechnical aspects, structural stability, discharge capacity and flood routing, in order to note any discrepancies with current standards or requirements;
- review of the project's hydrology, incorporating additional data obtained since the last review, and noting any hydrologic trends, including potential long-term trends due to climate change, in order to verify the flood routing and discharge capacity of the structure;
- review of the downstream area and people at risk (PAR), as these can change over the life of a project;
- review of sedimentation, to understand live storage volume and potential blockages;
- review and verification of the dam's or other components' stability and foundation conditions, including the verification of safety factors;
- diagnosis of the behaviour of the dam compared to the expected behaviour (for that type and age of dam, for example);
- review of the O&M manual and the reservoir management or operations plan;
- review of emergency planning procedures and documentation;
- verification that previously identified deficiencies have been corrected or are planned to be corrected;
- recommendations for improvements, repairs or rehabilitation, and for further investigations to ensure ongoing safety;

- formal reporting.

Dam Safety Reviews (DSR) may include workshops for hazards, failure modes and consequences analysis, using the Potential Failure Modes Analysis (PFMA) or the Failure Modes and Effects Analysis (FMEA) frameworks, among other methodologies.

## 4.3 Keeping other project components safe

### 4.3.1 Securing roads and bridges

Road safety is a critical aspect of any infrastructure project, and it is good industry practice to prepare a Road Safety Plan, including hazard identification and risk assessment, to minimise risks to the public and workers. The preparation and implementation stages of a hydropower project require the transportation of heavy equipment, and heavy loads of materials and workers to the site.

Measures to minimise risks from traffic accidents include: adequate road design (including protected walkways for pedestrians), signage, barriers, traffic safety personnel (flaggers), enforcement of speed limits and drug and alcohol bans, monitoring of vehicle conditions, monitoring of vehicle speed and location using GPS devices, driver training, separation of light and heavy traffic, dust suppression (for air quality and visibility), community road-safety awareness training, etc. Alternative routes for construction traffic that minimise the interaction with local communities can be identified. Heavy traffic can be restricted at certain times with heavy local road use (e.g. around school or harvest times). Some projects have offered bus services to keep private vehicles and pedestrians off the roads during the construction stage.

All roads (and bridges) must be designed, built, operated and maintained to assure the safety of all users, whether the operator's personnel or any members of the general public. Often there are no specific enclosure barriers or fences, or it is impractical to control occasional visitors or frequent users. Thus, members of the public may be using project infrastructure unknowingly. Roads to remote locations may provide benefits to communities, but they may also open access to potentially unsafe

locations. In such conditions, the developer must clarify the responsibilities and liabilities regarding road and bridge safety for the general public. If there is any doubt, perhaps because of the limited capacity of public authorities, the developer should take action. Guidance on road safety is available from a range of national and international organisations.

### **4.3.2 Preventing safety concerns from electrical installations**

Switchyards, substations and transmission lines are an inevitable feature of hydropower projects. The majority of transmission lines are aerial overhead lines, running long distances, with spaced poles or towers aligned along a deforested corridor. Clearing of the transmission-line corridor is a preventative measure against forest fires and transmission failures. This requires the regular mobilisation of resources for maintenance and clearance of vegetation, including of the access roads for equipment, and it needs to be planned and conducted with an awareness of public safety. A few recent examples of underground and underwater lines exist, which involve special safety requirements.

Direct contact with transmission lines must be restricted to trained and authorised personnel, and only when following strict OH&S procedures related to power lines. Direct access to substations and powerhouses must be restricted. Measures to reduce the risk to communities and workers also include fencing, gated access, signage, electrical safety and awareness training, proper PPE, and a comprehensive OH&S programme, which in many jurisdictions is required by governmental departments responsible for labour. Guidance on electrical safety is available from a range of national and international organisations.

### **4.3.3 Managing quarries, borrow and spoil areas safely**

The significant hazards that exist at quarries, borrow, spoil and muck areas involve material handling by mobile equipment operators, and pedestrian and vehicle interaction with trucks and other vehicles that are involved in transporting the mined quarry

and borrow materials and the spoil/muck material. Other hazards are associated with crushing, screening and conveying processes, improper loading and dumping procedures, overloaded haulage vehicles and improperly secured loads, working at heights, working under suspended loads, lack of dust control (affecting visibility of drivers and equipment operators, as well as causing potential environmental issues), and contact with power lines, etc. Haulage roads need to be properly designed and maintained, to avoid collisions and rollovers.

Project owners need to take appropriate precautions to protect workers and the public, because quarries, borrow, spoil and muck placement areas can be located outside the restricted project construction areas. This can be done by ensuring that equipment, vehicles and protective devices are well maintained and used as per the manufacturer's instructions, providing appropriate supervision and PPE for workers, implementing traffic control procedures, and ensuring that all workers receive appropriate training and site orientation. Supervisors should check that all workers are trained for the work they do, ensure workers comply with health and safety legislation and are wearing appropriate PPE, and hold daily occupational health and safety meetings to review any hazards, incidents and near misses. They should also provide procedures for vehicle and equipment operation, traffic control and any lockout and tagout procedures, and take every precaution to protect the workers and the public.

The stability of quarry walls and the slopes of spoil areas needs to be ensured, including after construction, when the general public are more likely to access them. This requires appropriate shaping, drainage and revegetation.

### **4.3.4 Keeping the reservoir safe**

Safety issues on and near water have been described in Section 2.3.2. This section deals with design and operational measures to reduce such safety risks at the reservoir upstream of the dam, while the following section addresses design and operational measures for downstream reaches. Note that Section 4.4.2. also describes additional measures, such as access restrictions, signage and

alarms, that are applicable to all infrastructure components.

Key safety issues in the reservoir are boating, fishing, swimming and diving accidents, as well as jumping or falling from heights. These risks can be mitigated through the following measures:

- Safety-oriented design of components that are necessary in any case, such as trash racks, spillway gates, boat ramps, mooring facilities, portages and boat lifts, booms, bridges and overhead cables – and on larger reservoirs, shipping lanes, ports, locks and other shipping facilities. All these components need to be designed with safety in mind (e.g. railings and fences, boat ramps at a sufficient distance from intakes, booms in highly visible colours, overhead cables with sufficient clearance, anti-sliding surfaces).
- Components specifically installed for public safety, such as life preservers, throw bags, railings and barriers, buoys, safety ladders, nets, and other escape devices (see also Section 4.4.2. below).
- Operational measures, including limited and controlled rates of reservoir level changes, visual inspection of the area upstream of gates and intakes before opening, and permanent guards, patrols or radar to monitor the reservoir – in particular, the section immediately upstream of the dam and intakes.

These measures will always need to be project-specific, as hazards are also project-specific. There can be slippery surfaces, strong but poorly visible currents over spillways and into intakes, and hazards that are hidden under water. For example, where trees have not been removed prior to filling of the reservoir, they may remain a boating hazard for decades, especially in shallow areas. Thin ice that people can break through is an issue in some areas of the world, and during some seasons. In the Kárahnjúkar project in Iceland, people started snowmobiling in the spillway, which required additional fencing and signage. Some measures may be temporary, such as boat barriers that are installed seasonally or during spilling and flushing operations, or measures associated with seasonal

snowmobile trails that may traverse a frozen reservoir.

The responsibilities for safety at the reservoir need to be clear. The hydropower operator may be directly responsible only for the area immediately around the dam, while local authorities or other government agencies may be responsible for safety on the rest of the reservoir. However, hydropower operations can contribute to dangerous conditions throughout the reservoir (for example, when the water level is lowered under a thin ice surface). In some cases, public agencies may not have the resources to effectively protect the general public, and the dam operator may agree to step in and make such resources and equipment (such as boats) available. Users themselves will also have a responsibility to understand and mitigate the dangers inherent in their activities, such as hypothermia. Public safety then becomes a joint responsibility of all stakeholders.

#### 4.3.5 Protecting downstream reaches

Sections 2.2.3. and 4.2.4. have addressed the downstream consequences of dam failure, which can be catastrophic. Section 2.4.1. and the IHA How-to Guide on Downstream Flow Regimes (2020) also address the potential of hydropower operators to contribute to flood management. Here we focus on the safety risks associated with normal operations.

In and immediately downstream of diversion weirs, spillways, fish passages and tailraces, there may be dangerously swift currents and turbulent water conditions. The risks of low-head structures are often underestimated, but they can create hydraulic conditions such as standing waves or 'rollers' that can trap people. The design of the hydraulic structures should aim to minimise hazards from turbulence, or to adequately secure the premises.

Peaking, spilling and flushing operations can create rapidly changing flows and water levels, thus affecting river users such as fishermen or people washing clothes on the riverbank. These can be mitigated through a combination of measures (see also Section 4.4.2.). There can be limits on ramp-up/down rates and specific gate-opening procedures (often mandatory for safety devices such as spillways). Releases can be preceded by a visual

inspection of downstream areas to ensure that no people are exposed, or they can be announced by visible and audible alarms.

As with the reservoir, responsibility (and liability) for public safety downstream of the facility must be clarified. In principle, the project should be responsible as far downstream as there are new safety risks arising from operations. In practice, responsibility for public safety downstream of the facility will be shared between operators, public authorities and river users.

## 4.4 Addressing cross-cutting issues in public safety

The following Sections 4.4.1.-4.4.6. cover a range of issues that apply not only to dam safety, but to the safety of all components of a hydropower project. In practice, the focus may be on the dam, and many of these issues should be included in a dam safety programme, although there is a case for broadening this to a general public safety programme.

### 4.4.1 Preparing for and responding to emergencies

Emergency planning is a good example of the focus on dams in hydropower safety. Although there may be significant public safety risks not related to the dam itself – and there are examples of accidents with multiple fatalities caused by boating, road traffic, or downstream releases – most emergency plans focus exclusively on dam failures.

In some jurisdictions, emergency management plans may be called ‘disaster management plans’, or separate disaster management plans may be required that focus on disaster response. Many such plans, whether called emergency or disaster plans, are concerned with managing external impacts on the project and its personnel, and not on the project’s impacts on the general public. This approach is based on the assumption that if a dam can be kept safe and operational during a disaster, there are no public safety implications. In many cases, this will be an over-simplification. As emphasised throughout this guide, hydropower projects can create other hazards, amplify the

impacts of natural hazards, or can assist with the management of external hazards.

The following general principles, as defined in the guidelines of several countries, apply to emergency management to ensure dam safety (and by extension, to other significant public safety risks associated with hydropower projects):

- The dam owner’s dam safety management system should include an emergency management programme that addresses prevention, mitigation, preparedness, response and recovery.
- This programme should consider all hazards relevant to potential emergencies involving a dam.
- During all phases of emergency management, the dam owner should collaborate and communicate with relevant external agencies and stakeholders to clarify responsibilities and appropriate procedures. Effective procedures should be in place for use by external agencies with responsibilities for public safety within the floodplain.
- The effectiveness of the emergency management programme should be validated and continually improved through regular exercises, tests, training, updating, and lessons learned.

Emergency management should result from a risk assessment process that identifies hazards and vulnerabilities. Eliminating and reducing hazards and minimising communities’ vulnerabilities, while also increasing effective mitigation strategies, leads to more manageable emergency responses. All identified hazards should be covered in the emergency management framework, including all scenarios that could result in an uncontrolled or unforeseen release of water and/or dam failure, as well as other emergencies such as (but not limited to) events involving powerhouse breaches, environmental spills, fires, and situations requiring rescue and medical aid.

The risk assessment specifically for the dam evaluates how it would respond to hazards, the potential failure modes that may develop, indicators

of imminent or developing failure, and the likely consequences of the various failure modes or uncontrolled releases of water. Inundation mapping from dam-break analyses is used to determine the population and property at risk under certain scenarios. These should include non-flood (sometimes referred to as ‘sunny day’) and flood scenarios for dam failures, sequential dam failures in a cascade, as well as floods that do not result in dam break.

Emergency plans should be shared with, or preferably, developed jointly with communities (such as downstream local governments and emergency services), and need to clearly specify the different scenarios for which responses are being prepared. Emergency maps are used by dam owners, emergency planners and first responders, to provide information that is vital for timely warnings and evacuation routes. They can be used by communities for zoning and infrastructure planning, and to build long-term resilience. Emergency maps should include information such as worst-case inundation boundaries, flood travel times (which determine warning timeframes), identification of critical locations at risk (including schools, parks, campgrounds), transportation infrastructure (roads, bridges, rail), and they should clearly identify evacuation routes and critical infrastructure (emergency services, hospitals, fire stations, etc.) (more detailed information on inundation mapping is included in Section 4.2.4.).

Preparing an emergency plan will include classifying the emergency events and defining different activation levels or thresholds. Each activation level is associated with specific occurrences or conditions that would trigger a number of specific responses, including communication pathways and tools to be used. In developing response actions, it is important to ensure that the total response time to an imminent event is less than the estimated time to impact (e.g. flood arrival time).

Once the emergency plan is prepared, it is important to maintain a state of readiness, monitor and manage changes, and conduct regular exercises, drills and education campaigns with the various stakeholders. Mapping should be kept up to date and include changes to land use and new developments, with amendments made during periodic dam safety reviews. Routinely testing

the plan and communication protocols is key to maintaining readiness.

In the shorter term, personnel responsible for emergency management (working for the operator and the authorities) need to keep track of any developing situations – such as floods, wildfires, landslides, glacial lake formation, earthquakes, civil unrest, and others – that could affect safety and require preparation. In particular, flood forecasting allows local authorities and dam owners to anticipate and prepare for hydrologic conditions, and implement measures to prevent damages. Flood forecasts may trigger the need to spill water and draw down reservoir water levels, to allow the reservoir to better accommodate and route an incoming flood. Any situation requiring the draw-down of the reservoir is also an opportunity to carry out visual inspections, when it is safe to do so, of reservoir banks and dam sections that are typically submerged and not regularly inspected. Flood forecasts may also trigger other preparations, such as closing roads or access to the reservoir, requiring staff to remain on site, or informing grid operators of an impending shutdown of the plant.

#### **4.4.2 Restricting access, displaying signages and sounding alarms**

Despite all the above-mentioned design, operational, quality control and maintenance programmes, some residual public safety risks will always remain. This section covers mitigation measures related to such residual risks.

The general public, and especially visitors from outside the area, often do not understand the inherent risks associated with a hydropower facility. Educating and informing them about safety risks should be a priority, so that they can adapt and modify their behaviour accordingly. Information and warning signs should be easily understood (e.g. using pictographs, local languages and non-technical terminology) and be clearly visible. Signs and other safety-relevant project components may have to be lighted at night.

Verbal messages, brochures, radio announcements and other communication measures can support signage, but they may not reach all stakeholders. Visible and audible warning signals (such as

**Figure 8.** Public safety around dams: Trevallyn, Australia *Photo Credit: Joerg Hartmann*

flashing lights and sirens) can be used to announce regular events such as gate openings and peaking releases, and/or exceptional events (emergencies). The effectiveness of such measures can decline over time, as the public becomes complacent or desensitised to the hazards, or as usage of an area changes.

Access to areas with high safety risks, such as powerhouses, intakes, switchyards and other structures, should be controlled and restricted, where necessary. Access restrictions can range from simple fences and railings to more complex systems, such as using access card readers or camera supervision. These may also be required where there is a significant risk of vandalism, sabotage or terrorism. Access restrictions have to be balanced with the public interest in having access and the public benefits from access, whether for transport (e.g. where a road crosses the dam) or for visits to the facility, which may be of high public interest. Some dam reservoirs are major recreational and

tourist attractions, and some access roads and bridges are highly important to local communities.

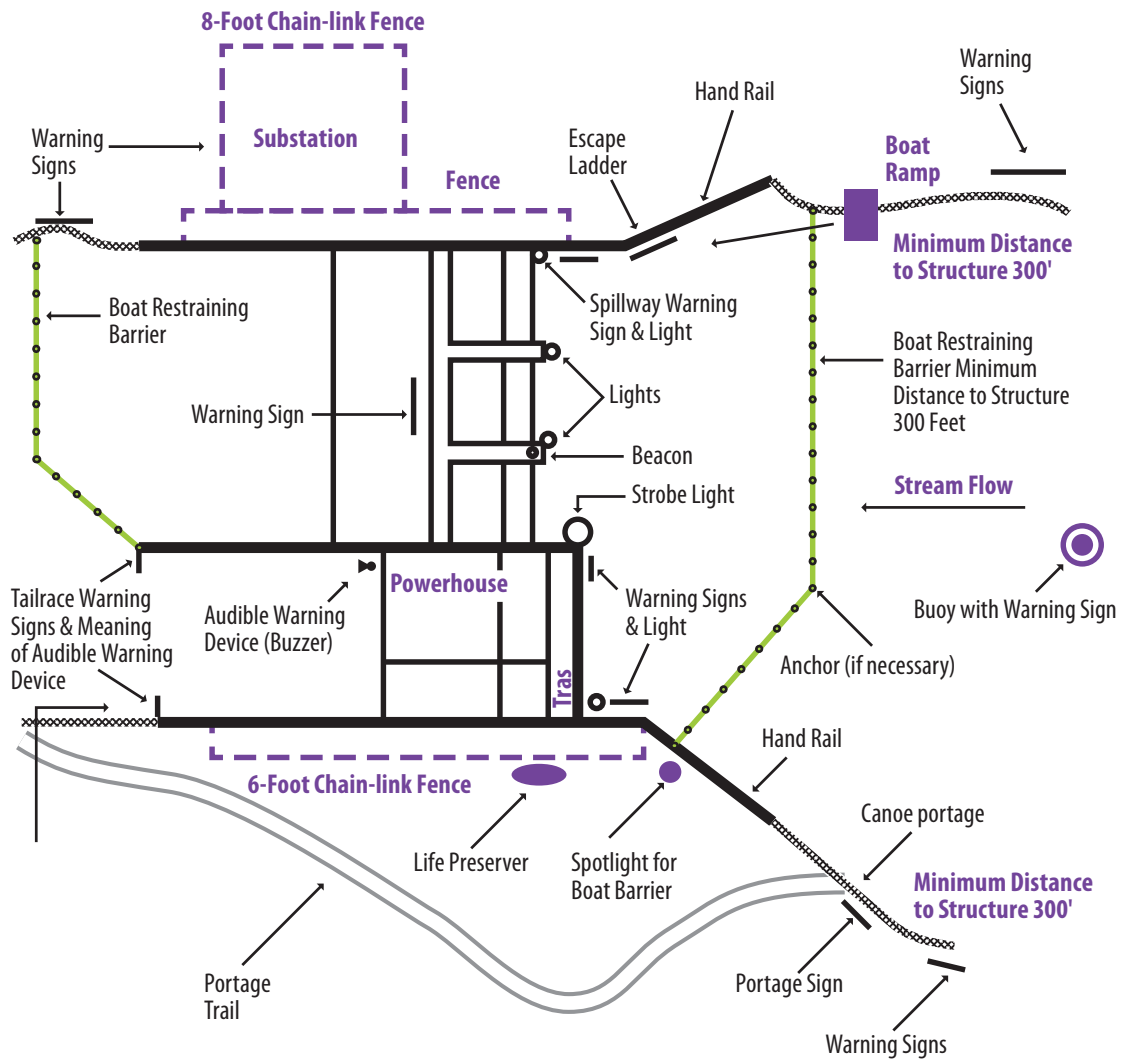
The figure below is an example of possible public safety measures around dams, recommended for situations of heavy recreational use. Stream flow is from the right to the left.

While it may be technically possible to operate many hydropower facilities remotely, public safety can require a minimum presence of personnel, who are able to interact with the public and intervene in emergencies.

#### 4.4.3 Engaging with stakeholders

Key stakeholders for infrastructure safety are local communities, visitors, local authorities and emergency services, and regulators. As emphasised throughout this Guide, stakeholder acceptance and regulatory approvals regarding safety issues need to be achieved and maintained, even as stakeholder

**Figure 9.** Safety measures around dams (FERC, USA, 1992)



expectations and regulatory requirements change over time. Responsibilities and liabilities of different stakeholders, and commitments to stakeholders, need to be clearly documented. Safety monitoring systems need to be designed to be meaningful and accessible to relevant stakeholders.

All these require a process of building awareness with stakeholders, through information sharing and consultation, and in some cases joint through activities such as emergency training and simulations. Mutual support between project staff and local emergency services is the best approach to build cooperative relations and interoperability. For example, where projects have ambulances and fire engines, these can assist in emergencies

outside the project boundaries, while the local fire department can be invited for annual emergency trainings in the powerhouse.

Effective emergency preparedness requires that stakeholders who could potentially be affected – and in particular, their local governments and emergency services – are aware of risks and planned responses in advance (i.e. sufficiently early before river diversion, reservoir filling, major spills, and other project milestones). Effective emergency action requires that communication lines with these stakeholders and responsibilities for next steps have been agreed, and are straightforward and clearly understood.

As described in Section 3.1.2., communication regarding safety issues (in particular, about dam failure probabilities and consequences) can be sensitive and challenging. There is often reluctance on the part of dam owners and operators to publicly address dam failure hazards or to make emergency preparedness and action plans publicly available. Stakeholder engagement can be even more complex in the case of cascades and transboundary rivers. However, in general, transparency is the best approach. Social media is an effective means of communicating with stakeholders. For example, a simple text-messaging group that involves key staff from the hydropower project, hydrometeorological stations, weather and emergency services can greatly improve communication and response times in a river basin. Making real-time flow and water-level data available online, and announcing operational plans well in advance, also builds trust in other river-users.

The relationship with dam safety regulators should be as constructive as possible, and be seen as an opportunity to gain experience and build capacity on both sides.

#### 4.4.4 Ensuring quality control

Quality control programmes must be implemented as good practice in hydropower projects during the complete lifetime of the project. Quality control should be enforced during all procurement stages for engineering services, contractors and suppliers.

Quality control can be of two types: i) focusing on internal procedures, or ii) on the procurement of goods and services, including construction materials and services. Regarding procedures, the developer should establish from the early stages a quality management system that guarantees the proper organisation of project data and documents, as this is paramount for later stages.

Quality control of goods and services should begin with a proper review of hydrological, geological and topographic data, and adequate specification, procurement and control of site investigations. During project construction, the proper testing and certification of construction materials and specialised work is required. For instance, for concrete dams, traceability of relevant components

for concrete production, from aggregates to water and cement characteristics for each batch, must be properly monitored and recorded, and provide a clear indication of the material sources, as well as the final location of placement within the project.

Specific issues such as concrete production, embankment compaction, steel welding, shotcrete spraying, cement grout properties, and instrumentation commissioning, must be the object of specific quality-control procedures and protocols, as part of an overall programme.

Quality control is closely linked to project and risk management. Auditing must be carried out to assess if the allocation of responsibilities to different stakeholders is clear, has minimum overlap, and no gaps or blind spots. Auditing must also assess compliance with the contractual scope of works and specifications. Unforeseen situations not fully covered in the contractual scope and specifications need to be identified and managed, before they lead to safety issues and other adverse consequences.

#### 4.4.5 Implementing a maintenance programme

Maintaining all project components in good operational condition is crucial for safety. This may be obvious for directly safety-related components such as dam instrumentation and spillway gates. Maintenance of the dam itself includes any preventative measures identified in maintenance manuals, as well as corrective action noted in inspection reports. This could include regular minor repairs, filling of cracks, lubrication of gate bearings, painting, housekeeping, and vegetation and animal control. Major deficiencies may require major rehabilitation or replacement efforts, with significant costs.

The relation between good maintenance and safety applies equally to other components and equipment in a hydropower plant, such as hydrometric stations, weirs, intakes, trashracks, desanders, tunnels, surge shafts, penstocks, valves, tailrace channels, plunge pools, navigation locks, and fish passages. Even associated infrastructure may be safety-relevant. For instance, the lack of maintenance of a transmission line may trigger

plant outages, resulting in rapid changes to water levels. A lack of maintenance of an access road (or of vehicles and boats) may interfere with emergency operations.

Each operator should define a project-specific maintenance programme that is aligned with the business plan and operational standards. Maintenance of different components can be done on a regular basis (scheduled maintenance) or on demand (risk-based maintenance). Continuous monitoring of the operating assets is required, although with variable degrees of inspection frequency. In many companies, particularly those that manage a fleet of hydropower stations, maintenance is embedded into an overall asset management framework, based on the ISO 55000 series standards for asset management. Asset registers and records of conditions and repairs for each asset help to prioritise maintenance measures.

According to the topic O-7 Asset Reliability and Efficiency of the HSAP, good practice requires:

- **Assessment:** Routine monitoring of asset condition, availability and reliability is being undertaken to identify risks and assess the effectiveness of management measures, and ongoing or emerging asset maintenance and management issues have been identified.
- **Management:** Measures are in place to address routine monitoring and maintenance requirements of the operating facility, in accordance with the overall electricity generation and supply strategy of the owner/operator.
- **Conformance/Compliance:** Processes and objectives relating to asset maintenance and management have been and are on track to be met, with no major non-compliances or non-conformances, and any asset-related commitments have been or are on track to be met.
- **Outcomes:** Asset reliability and efficiency performance is in line with the objectives of the owner/operator and any asset performance guarantees, with only minor gaps.

Proper documentation of all project documents, as designed and as built, is a precondition for effective maintenance. Operation and maintenance manuals are generally developed during the implementation stage, and may need to be updated periodically. Additional guidance on maintenance is available from a variety of sources, including equipment manufacturers and many jurisdictions.

#### 4.4.6 Monitoring, analysis and adaptive management

Good practices require continued monitoring, analysis and adaptive management of all aspects of hydropower, including infrastructure safety. Because of the longevity of hydropower projects, conditions of the project and around the project continue to evolve over time. It is not sufficient to collect data, as the data need to be understood, and conclusions need to be drawn and acted upon.

It is the responsibility of the owner/operator of a hydropower project to ensure that adequate and up-to-date information is available. Information can be obtained from a variety of sources, both internal and external, and useful information depends on project-specific requirements. Sources of information and data are often summarised in monitoring plans, and data are recorded at the project control or operations centre. This information may include:

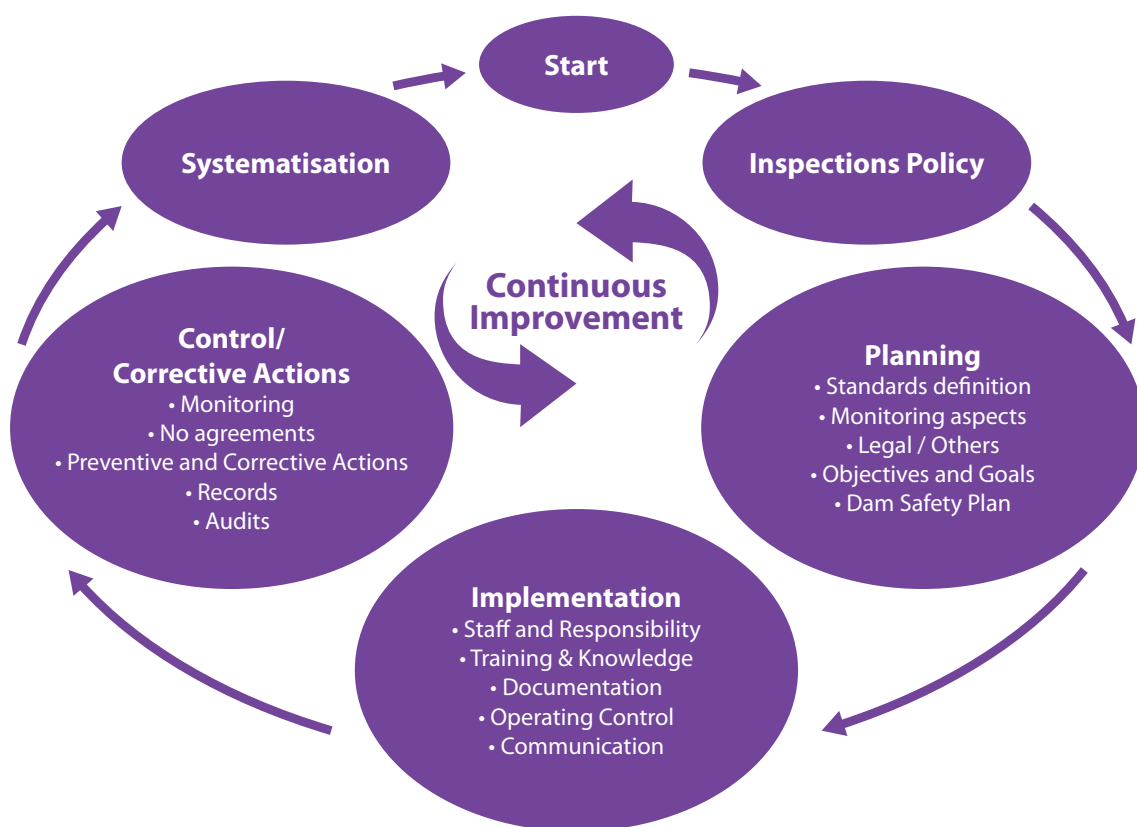
- Data from dam instrumentation (see Section 4.2.3.4.) and instrumentation of any other infrastructure components, such as spillway gates or penstocks.
- Periodic inspection reports (see Section 4.2.5.) and maintenance records (see Section 4.4.5.).
- Information on weather, climate, runoff, flood conditions and seismic activity, from hydrometric and seismic stations, and from new models for the area.
- Information of any natural hazards and disasters in the vicinity of the project.
- Surveys of slope stability around the reservoir, upstream land-use changes, and emerging landslide, GLOF, and similar risks.

- Bathymetric surveys of the reservoir, to understand any reduction of the reservoir's live storage volume (for flood management) and any potential blockages of outlets, intakes and spillways.
- Bathymetric surveys of the area immediately downstream of the project, to understand scour, and further downstream, to understand changes in the river channel morphology.
- Information on public presence in the area, including areas immediately surrounding the project infrastructure (from cameras, surveys of recreational users, radar to identify watercraft, etc.), and demographic changes in potential downstream inundation areas.
- Stakeholder mapping and surveys, specifically to understand public expectations and inform emergency planning.
- Information on personnel training and expertise regarding safety.
- Information on any lessons learned from emergency drills and simulations.
- Information on new upstream and downstream infrastructure such as dams and diversions, river basin management and development plans, allocation of water rights, etc.
- Information on lessons learned from similar dams, new guidelines and legislation, and new technologies for surveillance, repairs, etc.

The implications of this information for safety management need to be analysed and interpreted by internal experts or specialised consultants. This may involve comparisons with original studies, identification of trends over time, and forecasts.

**Figure 10.** Continuous improvement of the dam surveillance system

Source: ICOLD Bulletin 158, *Dam Surveillance Guide*



According to the ICOLD World Declaration on Dam Safety (2019), a monitoring programme is essential throughout the life of a dam in order to

a) determine behaviour during construction, b) assess performance during first reservoir filling, c) compare actual performance with design, d) characterise long-term behaviour, e) provide early warning of abnormal conditions, f) capture and analyse the response to events such as large floods, earthquakes, etc., g) predict future performance of the dam, and h) demonstrate safe management of the dam to regulatory authorities.

Furthermore, monitoring and analysis of aspects that are not directly related to the dam will typically be done in conjunction with the relevant public authorities. For example, the analysis of traffic or boating accidents can reveal unsafe locations.

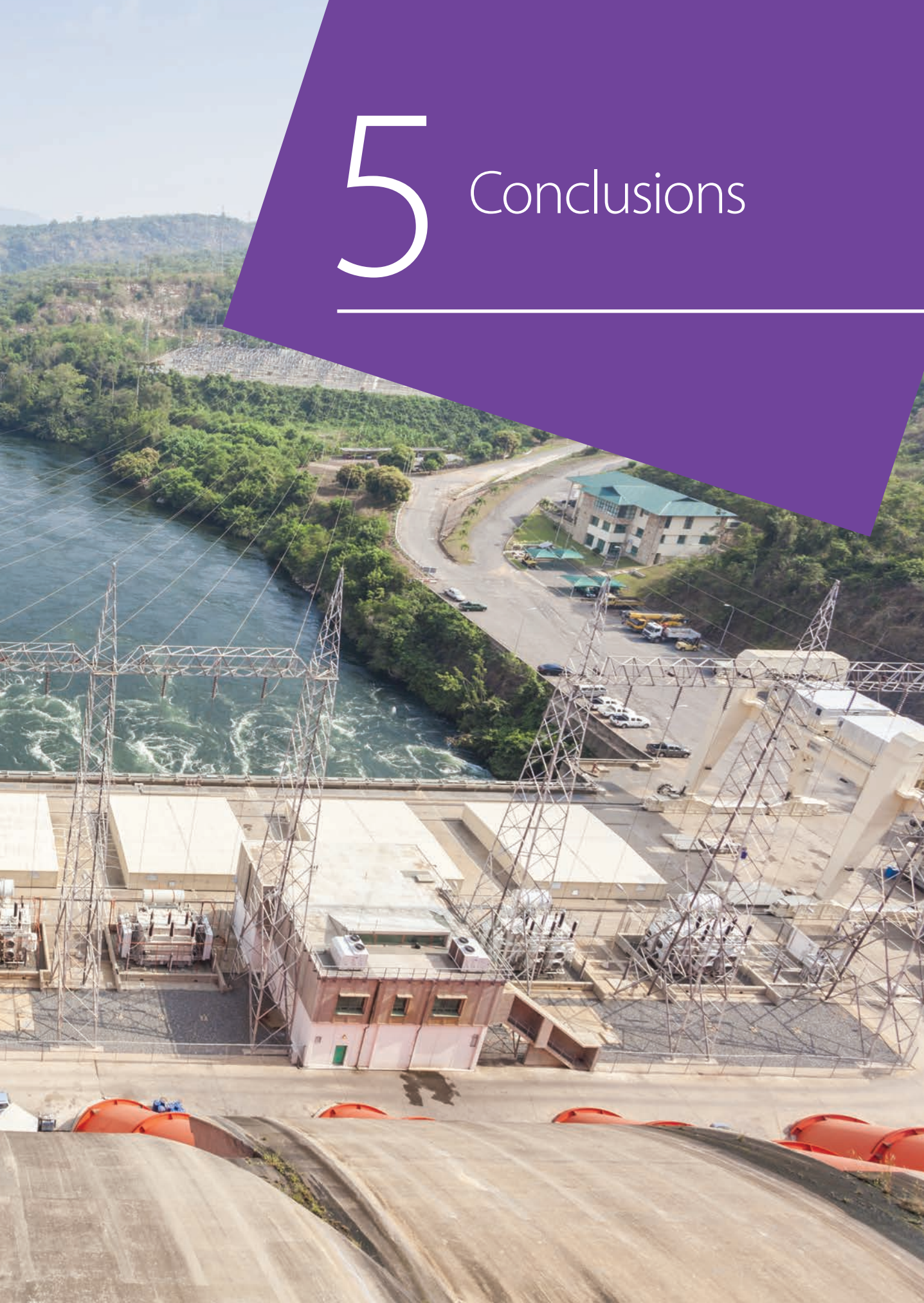
The analysis of information is intended to reveal emerging safety risks and opportunities, to identify actions to mitigate those risks or make use of those opportunities, and to update designs, operations and maintenance plans, and emergency plans accordingly.

Every safety framework or programme should undergo systematic continuous improvement to evolve with new information and lessons learned, as shown in Figure 10 for one aspect of safety management: the surveillance of the dam.

A successful project is one that is resilient and robust in the face of change, and/or in adapting to change. Adaptive management is a systematic process for improving management policies, plans and practices. Adaptive management can be at the project level, or at the level of an entire portfolio of projects. Hydropower projects need to be both resilient and adaptive, to continue to operate safely over long periods of time, in a continually changing context.



# 5 Conclusions



# Conclusions

Dam-related hazards can cause large numbers of fatalities, can be very costly, and may undermine public confidence in the hydropower sector, resulting in a loss of the industry's social licence to operate. Hydropower project developers and operators therefore have a regulatory, business and ethical responsibility to ensure the safety of communities surrounding projects. Communities are typically not in control of project decisions, and thus become 'involuntary risk bearers', on whom risks are imposed by third parties (e.g. national authorities and hydropower companies). Developers, owners and operators should also aim to reduce pre-existing public safety risks – for example, by managing floods through reservoir storage. Public safety should be one of the priorities of any hydropower project.

This guide has presented an overview of potential infrastructure safety hazards and good practice approaches to managing safety issues throughout the project life cycle. Infrastructure safety, and in particular dam safety, is an inherently complex issue which must be continuously studied and improved. There will always be





Explosive transportation truck  
at a project in Bhutan  
*Photo Credit: Bernt Rydgren*

trade-offs between safety and other objectives, including cost control. Also, because all hydropower projects are unique, the hazards, exposure and vulnerability of communities, as well as the most appropriate solutions, will always have to be site-specific. However, much has been learned over the past century, and there is now a broad consensus regarding safety-related principles and methods. It is acknowledged that continuous improvement is both possible and necessary, and, as a consequence, leads to a better safety record.

Looking forward, challenges are already evident through the ageing of the world's hydropower fleet, a lack of experience in some regions, hydrological risks related to climate change, some new projects located in less favourable sites (as many of the best sites have already

been developed), and the greater exposure of populations and property, caused by demographic and economic growth.

Safety-related expectations of communities and regulators are bound to increase, and what is today considered an acceptable level of risk may not be acceptable in the future. In general, developers and operators should aim to keep risks 'As Low As Reasonably Practicable' (ALARP). This applies both to the higher-consequence but low-probability risk of dam failure, and to the lower-consequence but often higher-probability risks resulting from communities interacting on a daily basis with project infrastructure such as roads, transmission lines and reservoirs.

## Annex 1

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Annex 2

# Project examples

From assessments using the Hydropower Sustainability Assessment Protocol

| Project                                               | Reservoir volume<br>Dam type<br>Dam height                                                                                  | Infrastructure Safety Issues                                                                                                                                                                            | Key Management Measures                                                                           |
|-------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Blanda<br>150 MW<br>Operation stage<br>Iceland        | Main dam:<br>426 million m <sup>3</sup><br><br>Rockfill<br>44 m                                                             | Hazards include flooding, severe weather, public access to waterways.<br><br>Contributions to search and rescue capabilities.                                                                           | Comprehensive dam monitoring system, public access restrictions, emergency response procedures.   |
| Devoll<br>256 MW<br>Implementation stage<br>Albania   | Banje / Moglice dams:<br>350 million m <sup>3</sup> / 392 million m <sup>3</sup><br><br>Rockfill / rockfill<br>80 m / 150 m | Seismic safety, safety on waterways, reservoirs and public roads, slope instabilities and geotechnical problems, stability of old Banje dam core.<br><br>Contribution to flood forecasting and control. | Comprehensive design, construction and emergency response plans.                                  |
| Hvammur<br>82 MW<br>Preparation stage<br>Iceland      | 15.5 million m <sup>3</sup><br><br>Rockfill<br>32 m                                                                         | Hazards include flooding (including upstream dam break), ice jams, earthquakes, volcanic eruptions (including under glaciers).<br><br>No contributions to public safety.                                | Comprehensive design, construction and emergency response plans.                                  |
| Kaunertal<br>1,015 MW<br>Preparation stage<br>Austria | New Platzertal upper reservoir dam:<br>42 million m <sup>3</sup><br><br>Rockfill<br>119 m                                   | Complex scheme with multiple components.<br><br>Avalanches, rockfalls, debris flows, safety risks on public roads.<br><br>Contributions to public safety (e.g. road safety).                            | Detailed analysis and comprehensive plans for design, construction and operations.                |
| Trevallyn<br>96 MW<br>Operation stage<br>Australia    | 12.3 million m <sup>3</sup><br><br>Concrete gravity<br>33 m                                                                 | Categorised as an extreme hazard dam, upstream of Launceston.<br><br>Risks for people in gorge downstream of dam.<br><br>Some contribution to flood control.                                            | Updates of flood-risk assessments and instrumentation.<br><br>Cooperation with local authorities. |

| Project                                                     | Reservoir volume<br>Dam type<br>Dam height                                                        | Infrastructure Safety Issues                                                                                                                                   | Key Management Measures                                                                                                   |
|-------------------------------------------------------------|---------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| Teesta-V<br>510 MW<br>Operation stage<br>India              | 8.5 million m <sup>3</sup><br>Concrete gravity<br>89 m                                            | Flooding, earthquakes, landslides and debris flows.<br>Peaking operations<br>Some support to public safety services.                                           | Regular safety inspections.<br>Some dam break and GLOF studies, but need to be updated.<br>Warning systems.               |
| Kárahnjúkar<br>690 MW<br>Operation stage<br>Iceland         | 2,100 million m <sup>3</sup><br>Concrete-faced rockfill dam<br>198 m                              | Complex system with multiple components.<br>Extreme weather conditions.<br>Some contributions to public safety.                                                | Dam instrumentation, inspections, remote cameras, emergency preparedness, warning systems.<br>Some non-conformances.      |
| Jostedal<br>288 MW<br>Operation stage<br>Norway             | 350 million m <sup>3</sup><br>Rockfill<br>51 m                                                    | Dam break and road safety risks, extreme weather.<br>Contribution to flood control (multi-purpose scheme).                                                     | Strong regulation.<br>Inspections, instrumentation, signage, emergency response plans.                                    |
| Santo Antonio<br>3,568 MW<br>Implementation stage<br>Brazil | 2,710 million m <sup>3</sup><br>Concrete gravity, combined with earthfill embankment dams<br>14 m | Main failure modes piping or overtopping of embankment dams.<br>Log jams.<br>Contributions to traffic safety                                                   | Comprehensive assessments and design.<br>Emergency preparedness.                                                          |
| Romanche-Gavet<br>94 MW<br>Implementation stage<br>France   | Low diversion dam, small storage capacity                                                         | Sudden flow increases in bypass stretch.<br>Category C diversion dam, low risks.<br>Some contributions to public safety.                                       | Energy dissipation to reduce variability of flows, warning waves.<br>Appropriate construction and design risk management. |
| Walchensee<br>124 MW<br>Operation stage<br>Germany          | Low diversion dams                                                                                | Complex system with several remotely operated diversions.<br>Surge tank and penstocks between Walchensee and Kochelsee.<br>Some contribution to flood control. | Asset monitoring and maintenance, signage, emergency response plans and simulations.                                      |
| Kabeli-A<br>38 MW<br>Preparation stage<br>Nepal             | 670,000 m <sup>3</sup><br>Concrete barrage<br>14 m                                                | Low risks from dam failure.<br>No contributions to public safety.                                                                                              | Appropriate design and operational plans, warning systems and emergency plans.                                            |
| Semla IV<br>3.5 MW<br>Preparation stage<br>Sweden           | Concrete dam, small storage capacity                                                              | Improvements to public safety through reconstruction of existing dam.<br>Category 3 dam with negligible risks.                                                 | Engineering of rehabilitation measures.<br>Few public access restrictions, signage or other precautions.                  |

| Project                                             | Reservoir volume<br>Dam type<br>Dam height                                                                               | Infrastructure Safety Issues                                                                                                                                                                                    | Key Management Measures                                                                                                                                                                                                    |
|-----------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Jirau<br>3,750 MW<br>Implementation stage<br>Brazil | 2,747 million m <sup>3</sup> Earth-riprap with asphalt core dam, concrete sections for powerhouses and spillways<br>63 m | Dam failure, though designed with high safety margins.<br><br>Increased road traffic.<br><br>Limited storage compared to river flows (42 hours of average inflow).<br><br>Minor contributions to public safety. | Comprehensive assessments and design.<br><br>Emergency preparedness and response in coordination with downstream Santo Antonio project.                                                                                    |
| Chaglla<br>456 MW<br>Implementation stage<br>Peru   | 345 million m <sup>3</sup><br>Concrete-faced rockfill<br>202 m                                                           | Risks related to dam break, dam releases, 23 km access roads and the TL, landslides and rockfall, navigation in the reservoir.                                                                                  | Comprehensive assessments, design, construction and emergency plans.<br><br>Innovative approaches to public safety during construction.<br><br>Some non-conformances, late preparation of operation stage emergency plans. |
| Keeyask<br>695 MW<br>Preparation stage<br>Canada    | 81 million m <sup>3</sup><br>Earth fill embankment dams combined with concrete gravity sections                          | Risks related to dam break (including risks to downstream dams), roads and transmission lines.<br><br>Extreme weather.<br><br>Road improvements.                                                                | Appropriate safety-relevant plans.<br><br>Independent review confirms that project meets CDA guidelines, but no plans for review of emergency preparedness plan.                                                           |





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The International Hydropower Association (IHA) is a non-profit organisation that works with a vibrant network of members and partners active in more than 100 countries.

Our mission is to **advance sustainable hydropower by building and sharing knowledge** on its role in renewable energy systems, responsible freshwater management and climate change solutions.