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ICOLD

**Committee L Tailings Dams and Waste Lagoons  
Tailings Dam Safety**

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## PREFACE

**PLEASE HOLD THIS SECTION UNTIL THE BULLETIN IS COMPLETED**

Where jurisdictions have existing Guidelines covering the scope of this Bulletin, it is hoped that these may be adapted to include these ICOLD Guidelines as a base document, with appropriate addendums to focus on specific additional requirements of those jurisdictions. Where there are currently no Guidelines then jurisdictions may develop their own unique Guidelines based on this Bulletin

These Guidelines draw on existing documents, recognised as “leading practice” within the mining industry. For this Guideline, “Leading Practice” is defined as practice that “has consistently shown results superior to those achieved with other means, and that is used as a benchmark”. It is important to include a proviso that “leading practice” evolves to become better as improvements are developed. This is particularly relevant for tailings dams where understanding and technologies continue to develop.

ICOLD have produced many Guidelines that are applicable to various aspects of tailings dam management. These are listed in Section XX. National and Industry Guidelines have also been drawn upon for this Bulletin and are good references for further details. These are listed in XXXX

**Table 1-1 Summary of Key References (Incomplete)**

Reference	Bulletin Section No.	Items of Key Interest
ICOLD/UNEP Bulletin: Improving Tailings Dam Safety (2011): <i>Critical Aspects of Management, Design, Operations and Closure</i>		
Mining Association of Canada – Towards Sustainable Mining		
Site Characterization of Dam Foundations - Engineers and Geoscientists of British Columbia, V1.2 (2016)		Site characterization planning process and key components
Eurocode 7		
ICOLD Bulletin XXXX (2020). Tailings Technology Update		Classification of tailings types and typical parameters for each tailings type. Technologies for tailings processing and dam construction.
ICOLD Bulletin 153 Closure		Stages of closure and guidelines for closure design.
Mining Association of Canada – Operations Maintenance and Surveillance Manual		
UNEP APELL Handbook (Reference <a href="http://apell.eccentre.org/ResourceDetailInfo.aspx?ReadDetails/id=105">http://apell.eccentre.org/ResourceDetailInfo.aspx?ReadDetails/id=105</a> )		
ICOLD Bulletin 170 Flood Evaluation and Dam Safety, 2018		
ANCOLD Guidelines for Design of Dams and Appurtenant Structures for Earthquake, 2019		
ANCOLD Guidelines on Tailings Dams – Planning, Design, Construction, Operation and Closure		
ICOLD Bulletin 170 – Flood Evaluation and Dam Safety		
CDA Dam Safety Review Guideline (2016)		

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THE APPENDICES WILL CONTAIN TECHNICAL NOTES THAT WILL ELABORATE ON ITEMS PRESENTED IN THE GUIDANCE DOCUMENT, SUCH AS: EDFs, THE FACTOR OF SAFETY GUIDANCE, ETC.

## 1 INTRODUCTION

### 1.1 Purpose

This Bulletin has been prepared by ICOLD to document technical practices for planning, design, construction, operation and closure of tailings dams. The bulletin draws on the experience and technical knowledge of the members of the ICOLD Sub-Committee on Tailings Dams, with reference to existing Bulletins produced by ICOLD and Guidelines produced by member countries including Australia (ANCOLD), Canada (CDA) and Industrial bodies, such as the Mining Association of Canada (MAC) and the International Council on Mining and Metals (ICMM), to document appropriate practices for design and safe management of tailings dams. Application of technical and governance principles described in this Bulletin are to be applied throughout the life phases of a tailings dam to achieve a level of safety to protect human lives, societal infrastructure and the environment.

The technical aspects of the Bulletin are expected to be used by tailings engineers and other professionals that are involved in all the phases of the tailings dam life cycle. The Bulletin also provides a framework for Owners for governance of tailings dams and informs Regulators of the broad range of governance and technical components of safe tailings dam management.

### 1.2 Bulletin Scope

The Guidelines cover tailings dams and associated infrastructure (known collectively as tailings storage facilities, TSFs). The scope of the Bulletin covers key technical components of tailings dam planning, design, construction, operation and closure. Supporting governance components highlight the importance of, and requirements for, good governance to achieve safe tailings dams. The Bulletin is structured as follows:

- Section 2 – Tailings planning and governance
- Section 3 – Dam classification.
- Section 4 – Site and tailings characterization
- Section 5 – Design
- Section 6 – Risk management
- Section 7 – Dam breach analysis
- Section 8 – Emergency preparedness and response management
- Section 9 – Construction requirements
- Section 10 – Operations
- Section 11 - Closure

Appendices have been included that contain technical notes expanding on various technical details identified in the main body of the Bulletin. This structure allows for ready inclusion of additional technical notes or updating the technical notes as new or improved information becomes available.

## 2 TAILINGS PLANNING AND GOVERNANCE

### 2.1.1 Tailings Management System

Tailings planning and governance is directed by the Owner of the TSF who oversees design, construction, operation and closure. The tailings management system (TMS) comprises the key components for management and design of the TSF throughout the life phases and is often referred to as the “framework” that manages these components. An example of the system components is presented in Figure 2-1. The following sections elaborate on each of the major headings: Planning, Implementation, and Review.

FIGURE IS TO BE MADE CLEARER (abbreviations explained, terms to align with this bulletin, and Closure included)

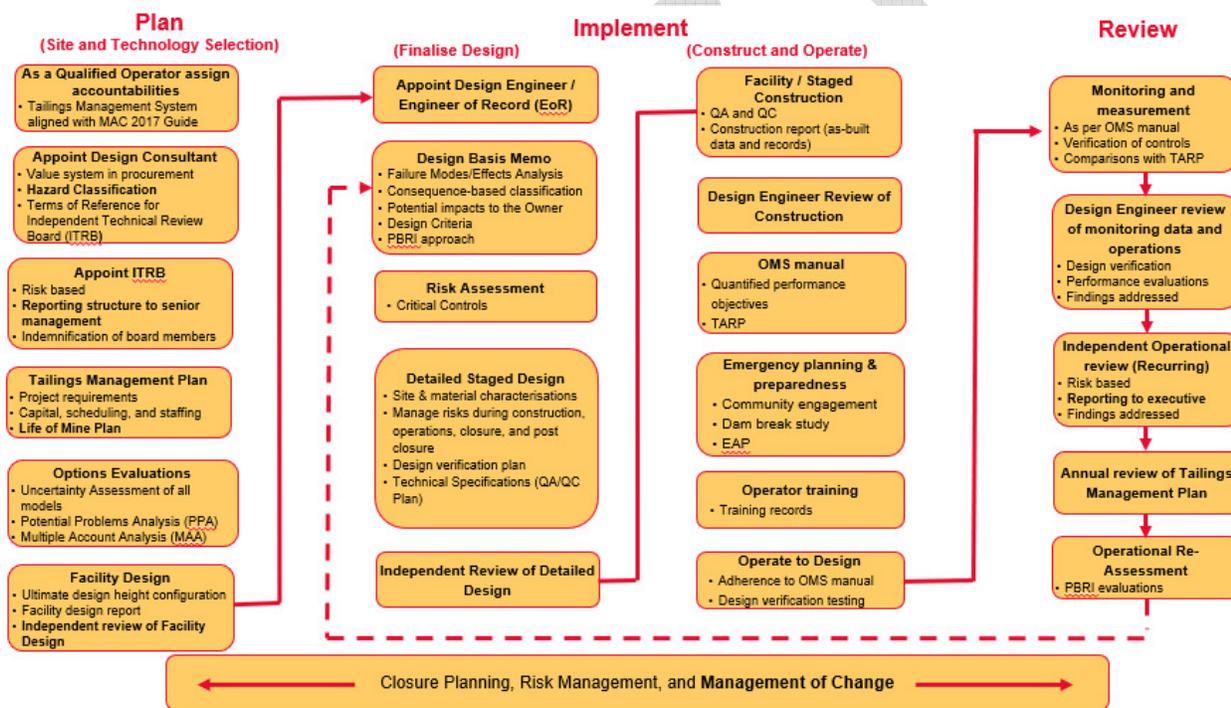


Figure 2-1 Example of a Tailings Management System Components

### 2.1.2 Planning

The objective of planning is to ensure a commitment to managing risk during all phases of the life cycle of a tailings dam, including concept development, design, construction, operation, decommissioning, rehabilitation, ongoing monitoring and the extended post-closure period.

Planning should integrate all the processes, systems, procedures and other activities required for a safe TSF. As noted in Figure 2-1, planning includes assigning appropriate accountabilities in support of the tailings management system, appointing a design consultant, developing a tailings management plan that includes an options evaluation, and undertaking the design of the TSF. Site Characterization and definition of the tailings properties commences at this stage of design (refer to Section 4 in this Technical Guideline).

Planning should consider the potential activities that will take place throughout the life of the TSF. This will include the initial “mine life” but also should consider potential extension of mining or changes in tailings properties that might affect the design and, ultimately, closure. It is important that the requirements and conditions necessary for the safe construction, operation and closure of the TSF are integrated in the wider project plan (Life-of-Mine plan) in both the early stage of the project development and throughout the life of mine.

Integrating the planning for tailings storage into Life of Mine planning should also consider impacts or synergies with other aspects of the mine operation. This can be particularly important to take advantage of other mine wastes for construction, water management impacts on mining and processing and particularly on closure methodology. Often cost and environmental benefits can be achieved in the overall project with minor extra effort or cost imposed on one aspect. Tailings storage considerations should be part of optimising mining and processing operations.

Additional considerations for planning include:

1. Full understanding of the setting, the operating environment and the potential risks including measures to prevent adverse impacts
2. Allowance for adequate margins of safety, with risks that place an exposure to hazards on third parties or the environment kept as low as reasonably practical
3. Development of a closure plan considering the potential final landform, land use and environmental safety
4. Adopting a management process that optimises and improves the TSF operations and reduces risks
5. Consideration of possible developments beyond the immediate economic mine life. Planning should provide a degree of flexibility that might allow significant strategic and economic benefits to be achieved in the future with minimal cost in the present.
6. Considering the performance of the tailings dam being potentially affected by other mining operations including blasting, dewatering, groundwater recharging, surface water redirection, mine pits development etc.

In the options evaluation for new TSFs or major changes to existing TSFs, the full cost of tailings production and disposal from conceptualisation to closure need to be considered. This includes long-term post-closure maintenance considerations as well as social, geochemical, and environmental aspects.

Planning should adapt to potential changes that could impact the TSF including, but not limited to, the following:

- Variations in tailings properties resulting from changed ore types or processing technologies to mined ore, ore types blending, processing technology etc.
- Quantities of tailings and water volumes reporting to the TSF, possibly due to increased production rates or changes in water management.
- Personnel changes both within the mine and with external consultants.
- Dam design changes and changes or awareness of unexpected geotechnical conditions.
- Climate change.
- Changes to tailings to other mine waste ratio, where the other mine waste is intended to be used for the tailings dam construction or closure.
- Changes in land use and population downstream of the dam that could affect the consequences of dam failure in the future.

Documentation from the planning phase should be comprehensive and able to stand alone in the event of changes in personnel that have been involved with the design (from the Owner's team or the designer's team). Details should be provided on key assumptions that were made, where information was lacking, the basis of key decisions that were made, and the potential risks so that future personnel do not lose track of these important aspects.

### 2.1.3 Implementation

As noted in Figure 2-1, implementation includes the preparation of the final design (detailed design to support construction), and the construction and operation of the TSF.

As part of final design, the Engineer of Record is identified, the Design Basis and risk assessment that was developed in the planning stage is updated, the detailed design of the dam and TSF is completed for the initial dam, or the planned raise, while also considering the ultimate configuration, and the design is reviewed by an independent party.

During construction/operation, there should be ongoing monitoring, design reviews, preparation or updates to the Operations, Maintenance, and Surveillance (OMS) Manual and the Emergency Preparedness and Response Plans, training of operators, and implementation of tailings disposal operations to meet the design requirements and intent.

As for the planning phase reports noted above, the final design reports, as-constructed reports, OMS Manual and Emergency Planning documents should be comprehensive to preserve the “corporate memory” as personnel change positions.

Sections 3 to 10 of this Technical Guideline provide details on these aspects.

#### **2.1.4 Audits, Verifications and Reviews**

Review of the TSF design, construction, and operation provides an important feed back loop to the tailings management system and design. As noted in Figure 2-1, the review stage includes the reviews undertaken by the design engineer and/or the EOR as well as independent reviews that may be done as peer reviews or by Independent Review Boards.

As part of the tailings governance program, the following should be undertaken:

- Dam Safety Verifications (DSVs) should be carried out by the Engineer of Record (EOR) , or their designate, and include, as a minimum: summary of construction/raise works, QA/QC results, instrumentation and monitoring results, stability of structure review, incident reporting, etc. Recommendations for “dam safety” requirements and recommendations for “improvement of practices” should be documented. The frequency of the DSV is normally annual and may depend on the dam classification as described in Section 3 of this Bulletin, and the changes that may be occurring with the TSF. The DSV is independent of other dam inspections that may be carried out during the year as described in Section 10.5 of this Bulletin.
- Comprehensive Dam Safety Reviews (DSR) should be carried out by an independent reviewer or independent review team (for very high or extreme consequence category dams), using a framework similar to the CDA Dam Safety Review Guideline (2016) at a frequency determined by the classification of the dam, the complexity of the dam and the potential changes to the dam. Recommendations for “dam safety” requirements and recommendations for “improvement of practices” should be documented. As a minimum, Action Plans should be developed to address “dam safety” recommendations in a timely manner.
- Independent technical review boards (ITRBs) should be established for dams with Very High and Extreme consequence classifications (see Section 3 of this Bulletin) and reviews should be carried out at least annually or more often depending on the complexity of the TSF and the changes that may be occurring. Peer review of design reports and technical review of dams with lower consequence classifications should be carried out considering the complexity of the TSF and the changes that may be occurring.
- Owner Audits should be carried out to verify that the tailings facility is being managed and constructed to meet requirements and that the ITRB, the EOR and the Tailings Responsible Person (TRP) are effective in meeting the objectives of a safe dam.

## 2.2 Dam Safety Roles and Responsibilities

The roles of the responsible persons involved in the governance, design and operations of the TSF should be developed to establish accountability and assurance that key activities associated with the TSF are appropriately carried out and managed. While management structures and capacity vary within different facilities, the minimum key roles should include:

### **Accountable Executive Officer (AEO)**

The Accountable Executive Officer (AEO) or equivalent, should be appointed for each TSF and should be a part of the Mine Owner's Management Team. The AEO should be appointed by senior management, taking into consideration the consequence rating, complexity and risk of the facility. The person should have decision-making ability and control through the business structure of the resources necessary to exercise this single point of accountability. The person should be accountable for maintaining effective governance and integrity of the TSFs throughout the life-cycle of the mine, so that risks associated with tailings facility design, construction, operations, maintenance and closure are effectively identified, controlled and managed to minimise impacts to health, safety, communities, the environment and the business. This includes ensuring that adequate resources, processes and systems are in place in consideration of the complexity of the TSF.

### **Tailings Responsible Person (TRP)**

A Responsible Person (RP) should be appointed for each tailings dam and should be a part of the Operations Team. The TRP would report to the AEO with respect to the TSF and would be the key point of contact with the Engineer of Record (EOR). The TRP should preferably be a qualified engineer and have a good understanding of the design, construction and operation of the facility. The RP should be informed and consulted on all matters related to the TSF and should ensure that key elements, such as design, documentation, deposition plans, surveillance, construction, are effectively implemented.

### **Engineer of Record (EOR)**

An Engineer of Record (EOR) should be a Professional Engineer responsible for confirming that the TSF is designed, constructed, operated and/or closed, with appropriate concern for health, safety and environment, and that it aligns with the current state of practice and meets applicable regulations, statutes, guidelines, codes and standards. The EOR is an individual, supported by a team of Subject-Matter Experts as applicable.

### **Independent Tailings Reviewer(s)**

At least one independent reviewer should be appointed for every TSF. If more than one reviewer is appointed, the reviewers may form an Independent Tailings Review Board (ITRB). The reviewers should be appropriately skilled and external to the Owner's company with relevant experience in key disciplines associated with the TSF. The reviewers report to the AEO and are responsible for judging the adequacy of the design and operations and governance of the TSF.

## 2.3 Management of Change and Incident Reporting

TSFs are typically built over extensive periods of time. Changes to the design, construction and operation of the facilities are often proposed due to changes in plant operation, regulatory requirements, availability of new data, changes or awareness of new site conditions, etc. and it is important that these changes are recognized and documented. Additionally, changes in ownership, personnel, consultants or contractors can introduce dam safety risks. A change management system that includes evaluation, review approval and documentation of all changes should be implemented.

Incident reporting is important to document incidents that occur with the TSF with respect to potential dam safety aspects such as cracks, unusual seepage, loss of freeboard, etc. The lessons learned from incidents is an important element of continual improvement and reduction of risks.

## 2.4 Documentation and Records

### TO BE WRITTEN

- Site and Technology Alternatives Selection report
- Dam Site Characterization report
- Design Basis Memorandum
- Design Record report
- Data Record report and/or database management system
- As-Constructed report(s) and representative cross-sections

### 3 DAM CLASSIFICATION

The purpose of assigning a dam failure consequence classification is to assist in communicating the potential consequence of a dam failure and to guide the design and governance requirements for the dam. A dam failure may have significant consequences to communities, environment and infrastructure beyond the mining company's property boundaries, as well as significant consequences to the Owner. The consequence classification is determined by assessing what happens when a failure mode causes the dam to fail, as discussed in Section 7 of this Bulletin.

Table 3-1 presents a dam classification based on potential effects to the environment, community, infrastructure and population at risk, which are considered impacts to society. The potential financial losses to the Owner are not directly considered in the dam classification. As noted in Section 5.9 of this Bulletin, the risks to the Owner of potential losses due to extreme events may be captured in setting the design criteria. Other dam classifications in the jurisdictions where the TSF is located may need to be considered depending on the applicable country regulatory requirements.

An initial qualitative or semi-quantitative dam breach analysis (refer to Section 7.4.2 of this Bulletin) may be completed without a detailed inundation mapping and may be applicable when the magnitude of the severity and loss is obvious, and the dam classification can be readily discerned. The initial consequence assessment, without a detailed flood mapping, may also be adequate for the selection of the preliminary consequence category in the early stages of a design of a new TSF facility.

A detailed consequence assessment supported with a detailed flood inundation and "mud flow" mapping should be undertaken for High, Very High and Extreme consequence dams as described in Section 7 of this Bulletin.

The following discussion provides details in support of Table 3-1.

#### **Population at Risk and Loss of Life:**

Life safety can be assessed in terms of Population at Risk (PAR) and potential Loss of Life (PLL). The PAR in an inundation area (due to the dam breach) provides an indication of the number of people that could be exposed to the hazard. The effects could range from inconvenience and economic losses to loss of life.

The PLL in the inundation area (due to the dam breach) depends on many factors such as depth of flow, velocity, time of day, advance warning, topography, transportation routes, mobility, etc.

#### **Environment:**

Environmental values include aquatic and terrestrial habitat, including rare and endangered species. Water quality effects include groundwater and groundwater use, as well as surface water quality effects on aquatic habitat and livestock and fauna use. The geochemistry of the tailings may influence surface water quality in cases where potentially acid generating tailings or tailings with neutral metal leaching are deposited within the inundation zone and have longer term effects on water quality and terrestrial habitat. The toxicity of the released process water may also have short term effects on the

environment. The scales of the impacts are assessed on short-term or long-term effects and on the ability for the environment to recover.

**Health, Social and Cultural:**

Health, social and cultural values include disruptions or losses to local businesses, services, or social dislocation of people and workers. Potential losses to local and regional recreational, heritage and cultural assets that may be affected by the dam failure or destroyed. Potential effects on human health may be influenced by the toxicity of the tailings process water and leaching of released tailings.

**Infrastructure and Economics:**

Infrastructure losses can include bridges, highways, power stations, commercial and residential/properties etc. Loss of infrastructure that may contain hazardous substances can exacerbate the consequence. Loss of employment and the economic requirements to compensate persons and property are considered. Economic assessment should also include the clean-up and rehabilitation costs potentially borne by the community in the event of bankruptcy of the Owner.

**Owner Losses**

Owner losses may not be directly related to the consequences outlined in Table 3-1 as a tailings dam failure may, in addition to the consequences described, lead to bankruptcy of the company, legal litigation uncertainty, or the loss of social licence to be able to operate the mine. These factors and risks should be considered in developing design criteria that is described in Section 5.9 of this Bulletin.

**Table 3-1 Tailings Dam Classification**

Dam Failure Consequence Classification	Incremental Losses				
	Potential Population at Risk	Potential Loss of Life	Environment	Health, Social & Cultural	Infrastructure and Economics
<b>Low</b>	None	None expected	Minimal short-term loss or deterioration of habitat or rare and endangered species.	Minimal effects and disruption of business and livelihoods. No measurable effect on human health. No disruption of heritage, recreation, community or cultural assets.	Low economic losses: area contains limited infrastructure or services. <US\$1M
<b>Significant</b>	1-10	Unspecified	No significant loss or deterioration of habitat. Potential contamination of livestock/fauna water supply with no health effects. Process water low potential toxicity. Tailings not potentially acid generating and have low neutral leaching potential. Restoration possible within 1 to 5 years.	Significant disruption of business, service or social dislocation. Low likelihood of loss of regional heritage, recreation, community, or cultural assets. Low likelihood of health effects.	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes. <US\$10M
<b>High</b>	10-100	possible (1 - 10)	Significant loss or deterioration of critical habitat or rare and endangered species. Potential contamination of livestock/fauna water supply with no health effects. Process water moderately toxic. Low potential for acid rock drainage or metal leaching effects of released tailings. Potential area of impact 10 km <sup>2</sup> – 20 km <sup>2</sup> . Restoration possible but difficult and could take > 5 years.	500-1,000 people affected by disruption of business, services or social dislocation. Disruption of regional heritage, recreation, community or cultural assets. Potential for short term human health effects.	High economic losses affecting infrastructure, public transportation, and commercial facilities, or employment. Moderate relocation/compensation to communities. <US\$100M
<b>Very High</b>	100-1000	likely ( 10 to 100)	Major loss or deterioration of critical habitat or rare and endangered species. Process water highly toxic. High potential for acid rock drainage or metal leaching effects from released tailings. Potential area of impact >20 km <sup>2</sup> . Restoration or compensation possible but very difficult and requires a long time (5 years to 20 years).	>1,000 people affected by disruption of business, services or social dislocation for more than one year. Significant loss of national heritage, community or cultural assets. Potential for significant long-term human health effects.	Very high economic losses affecting important infrastructure or services (e.g., highway, industrial facility, storage facilities, for dangerous substances), or employment. High relocation/compensation to communities. <US\$1B

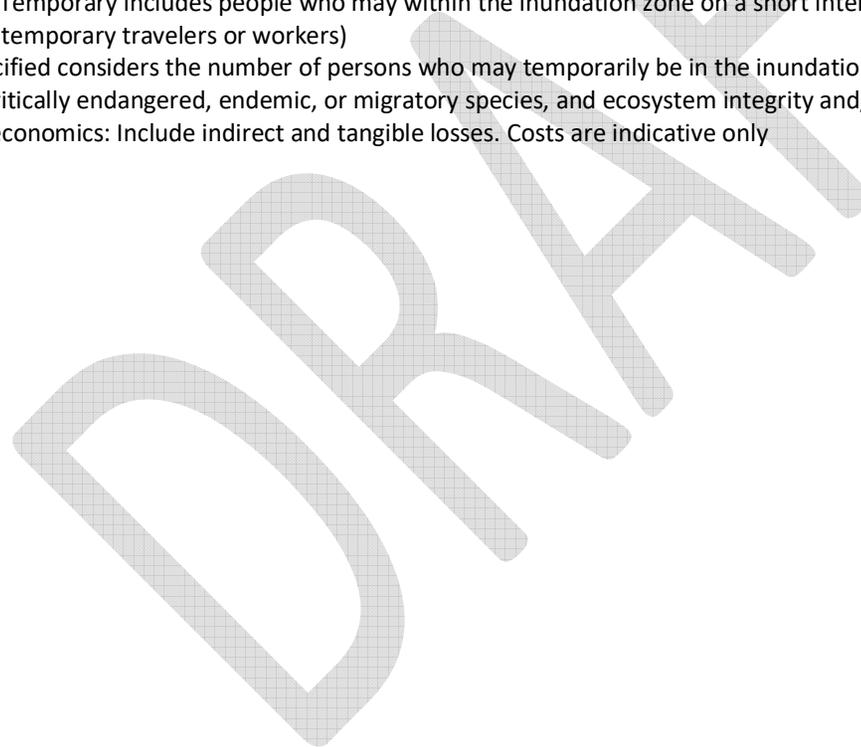
Dam Failure Consequence Classification	Incremental Losses				
	Potential Population at Risk	Potential Loss of Life	Environment	Health, Social & Cultural	Infrastructure and Economics
<b>Extreme</b>	> 1000	many (more than 100)	Catastrophic loss of critical habitat or rare and endangered species. Process water highly toxic. Very high potential for acid rock drainage or metal leaching effects from released tailings. Potential area of impact > 20 km <sup>2</sup> . Restoration or compensation in kind impossible or requires a very long time (>20 years).	>5,000 people affected by disruption of business, services or social dislocation for years. Significant National heritage or community facilities or cultural asset destroyed. Potential for severe and/or long-term human health effects.	Extreme economic losses affecting critical infrastructure or services, (e.g., hospital, major industrial complex, major storage facilities for dangerous substances) or employment. Very high relocation/compensation to communities and very high social readjustment costs. >US1B

Notes: Population at Risk: Temporary includes people who may within the inundation zone on a short intermittent basis (e.g. seasonal or recreational visitors, temporary travelers or workers)

Loss of Life: Unspecified considers the number of persons who may temporarily be in the inundation zone, their exposure time and other conditions.

Habitat: Includes critically endangered, endemic, or migratory species, and ecosystem integrity and/or ecosystem services

Infrastructure and economics: Include indirect and tangible losses. Costs are indicative only



## 4 SITE AND TAILINGS CHARACTERIZATION

### 4.1 Introduction

Site and tailings characterization are the building blocks of a good design and, as the understanding of their properties develops during the design stages and throughout operation, the appreciation of the site and tailings increases. The characterization activities are iterative with continual improvement of understanding.

This section covers characterization of the dam and impoundment foundations and the climate, seismicity and social/environmental setting of the TSF. Characterization of the tailings, considering both geotechnical and geochemical properties is also addressed.

### 4.2 Site Characterization of Dam and Impoundment Foundations

#### 4.2.1 Overview

The general approach to site characterization of the dam and impoundment area is to develop a broad appreciation of the site with respect to the overall landscape and geology in the region and then to progress to more site-specific information and details until a sufficient three-dimensional understanding of the foundation conditions has been developed commensurate with the nature of the dam envisioned be constructed. A thorough understanding of the site geology and the geotechnical conditions is crucial for the safety and structural integrity of the TSF as demonstrated by the Mt Polley (2014), Cadia (2019) and many other TSF failures.

During scoping level design (discussed in Section 5.2), the concept for the dam may be partially or completely developed, and some level of site characterization work is required. The concept for the dam could require changes as a result of the site characterization, and these developments are often iterative processes. The questions that are asked about the site's geological, geomorphological, geotechnical, hydrogeological, and environmental characteristics are a function of the concept for the dam and the anticipated foundation conditions.

The site geology and geotechnical conditions are determined from desktop studies, intrusive and non-intrusive investigations that should be carried out in phases to identify and progressively reduce risks and uncertainties and increase reliability of the information about the site.

A model of the regional and site bedrock/structural and surficial (geomorphic) geology and associated historic processes is a primary outcome of the site characterization. These are further assessed to determine the associated geotechnical and hydrogeological parameters for design. The overall model is referred to as a Site Geological Model (SGM). The SGM should focus not just on the dam and the impoundment but also on the surrounding area, and includes the following components:

- bedrock & structural geology
- surficial geology and geomorphology
- geotechnical conditions
- hydrogeological conditions

A preliminary SGM is developed based upon existing geological maps, reports, satellite imagery, LIDAR images and site reconnaissance. The preliminary SGM captures the general composition and assembly of the rock and soil types across the site and identifies major geological and geotechnical hazards such as discontinuities, weak or high permeability zones etc. The preliminary SGM is often used for the concept design of the TSF, which may then require changes as a result of the site characterization, and these developments are often iterative processes. The questions that are asked about the site's geological, geomorphological, geotechnical, hydrogeological, and environmental characteristics are a function of the concept for the dam and the anticipated foundation conditions.

The preliminary SGM informs the planning of the site investigation, purpose of which is to verify and further refine the preliminary SGM and provide inputs into the dam design. The site investigations should not commence without the preliminary SGM being completed. Site investigations include intrusive and non-intrusive methods. Typical activities that are undertaken during the site characterization include:

- Desktop studies: e.g. air photo/satellite/LIDAR, internet searches, Government reports, seismic data, regional reports, etc.
- Mapping and site visit: terrain and geologic mapping, test pits and field probes, etc.
- Geophysical surveys: seismic, radar, resistivity, etc.
- Drilling and in situ testing: sonic and rotary drilling, coring and sampling, seismic cone penetration testing (SCPT), standard penetration testing (SPT), field vanes, packer and permeability testing, etc.
- Laboratory testing: index tests, strength tests, permeability, consolidation, etc.
- Reporting: data reports, site characterization reports

The SGM forms the basis for the geotechnical design used for the purposes of analysis, design, and verification of design details (filters, drainage, pore pressure response, etc.).

The extent of the site investigations should be commensurate with the geotechnical complexity of the site and with consideration of the potential consequences of the TSF failure. As the dam develops through the design stages and into construction and operations, the site characterization will typically become more detailed. It is common to have ongoing site characterization works throughout the life phases of the dam. A general principal is to assume that site conditions could be complex and to apply the ongoing characterization works to confirm a good understanding of the SGM.

#### **4.2.2 Site Characterization Activities**

Characterization of the dam and impoundment foundations most commonly begins during the scoping-level site selection studies and expands during the development of the project. The extent of the site investigations at each stage should be commensurate with the complexity of the site geology with consideration of the potential consequences of failure of the TSF.

### 4.2.3 Geological and Geomorphological Conditions

Bedrock and surficial geology mapping should emphasize features that affect the geotechnical properties. Bedrock considerations include, for example: potential for weak bedding planes or structures, weathering, karst features, stress relief features, etc.

Assessment of the surficial geology should start with understanding the deposition or weathering history, for example glacial stratigraphy, physical and geochemical weathering of rock in situ and sediment transport mechanisms. The regional surficial geology history is important in understanding and determining the site-specific conditions.

### 4.2.4 Geotechnical and Hydrogeological Conditions

The objective of the geotechnical component of the site characterization program is to develop parameters that can be used in the dam design. The geotechnical component may include, for example, investigation related to stability, deformation, settlement, seismic response, seepage and piping potential. Geotechnical characterization of bedrock foundations should assess lithological rock units, as well as orientation and distribution of main joint sets within each lithological unit. Additionally, it is important to identify major faults and shear zones. The strength of the bedrock will be influenced by bedding orientation, weathering, and rock mass quality. The hydraulic conductivity of bedrock is typically controlled by the degree of fracturing and rock quality.

Geotechnical characterization of the foundation soils should delineate representative geotechnical units. The geotechnical units would consider, for example, the surficial geologic history and geotechnical properties. Index testing of soils is used for general characterization and generally includes, for example, moisture content, grain size, Atterberg limits, and density and shear strength indices. Undisturbed samples of cohesive soils are required for strength and consolidation testing. Strength tests should consider drained and undrained strength response and peak and residual/large strain strength as well as the stress state of the soils and the stress state that will be imposed by the dam. Determination of the critical state line should be considered for contractive soils.

The understanding of the bedrock and surficial geology and the geotechnical conditions is intimately related to, and complementary to, the development of the hydrogeological component of the SGM. The interpretation of site data defines the foundation conditions and associated groundwater regime. Prediction of seepage through the dam foundation and from the impoundment is used to support design of seepage and piping controls and predictions of pore pressure for stability assessment.

## 4.3 Other Site Characterization Components

The physiographic setting, for example: topography, vegetation and water courses, is an important element of both assessing site conditions, as well as influencing the siting and design of the TSF. The hydrological setting, climate, seismicity and the social and environmental context of the site are required to support design.

### 4.3.1 Hydrology and Climate

Both hydrology and climate influence the surficial geology, hydrogeology and the geotechnical conditions around the dam foundation. The amount of precipitation and the climate type influences rate of infiltration into the ground and, additionally, could introduce artesian pressures in both confined and unconfined pervious layers in the dam. Thermal effects can range from arid environments with high evaporation to arctic environments with permafrost. Global warming is influencing climate patterns, often with increases in the intensity of short duration precipitation and potentially wetter or drier than normal conditions. Understanding the potential for changes is required to support sizing of spillways, diversions and flood storage requirements.

The hydrologic setting is also a very important component in site selection as it will influence the requirements for management of flood waters both around the TSF as well as flood storage and spillways for the TSF. Assessment of the meteorological and climate conditions is required to assess and design water management facilities.

### 4.3.2 Seismicity

The objective of seismotectonic assessments is to develop an understanding of the regional tectonic conditions at the dam site and to carry out site characterization studies to develop parameters that can be used to support a seismic hazard assessment for the site. These parameters would include the design ground-motion event/parameters that will be used for the seismic response assessment for the dam and foundations and impoundment slopes. Seismic hazard analysis considers two approaches, the probabilistic seismic hazard assessment (PSHA), which determines events for various annual exceedance probabilities, and the deterministic seismic hazard which identifies potentially active faults and the response at the dam due to the fault. Both cases should be considered for dam design and the selection for design should be the most critical case.

### 4.3.3 Social and Environmental

The social and environmental setting of the TSF influences the design and the design and operation of the TSF should be integrated with these components in all life phases. Environmental components include water quality (both surface and groundwater) and water uses downstream (aquatic, livestock/fauna, drinking), and the potentially sensitive environmental receptors both within the TSF footprint, as well as the receiving environment.

Environmental design requirements can include, for example, very low seepage allowances requiring liners and low permeability zones in dam to protect sensitive downstream receivers, such as fish. Social components include incorporation of knowledge and concerns from relevant stakeholders. Other examples may include the presence of 'sacred sites' within the TSF. While these components are directed by the Owner of the facility, the designer for the TSF needs to incorporate these aspects into the design

## 4.4 Tailings Characterization

### 4.4.1 Classification of Tailings

ICOLD (2020) has classified tailings into five categories depending on their geotechnical properties and these five categories are summarized in Table 4-1.

**Table 4-1 Summary of Tailings Types and Geotechnical Classification**

Tailings Type	Symbol	Description (compare)	Example of mineral/ore
Coarse tailings	<b>CT</b>	Silty SAND, non-plastic	Salt, mineral sands, coarse coal rejects, iron ore sands
Hard Rock tailings	<b>HRT</b>	Sandy SILT, non to low plasticity	Copper, massive sulphide, nickel, gold
Altered Rock tailings	<b>ART</b>	Sandy SILT, trace of clay, low plasticity, bentonitic clay content	Porphyry copper with hydrothermal alteration, oxidized rock, bauxite. leaching processes
Fine tailings	<b>FT</b>	SILT, with trace to some clay, low to moderate plasticity	Iron ore fines, bauxite (red mud), fine coal rejects, leaching processes, metamorphosed/weathered polymetallic ores
Ultra Fine tailings	<b>UFT</b>	Silty CLAY, high plasticity, very low density and hydraulic conductivity	Oil sands (fluid fine tailings), phosphate fines; some kimberlite and coal fines

### 4.4.2 Laboratory Based Tailings Properties

Estimates of tailings properties for each tailings type have been developed based on historical data and a series of charts are presented in the ICOLD (2019) Bulletin. Examples of charts include: Plasticity chart shown on Figure 4-1 and a chart of void ratio versus effective stress (consolidation curves) shown on Figure 4-2. Additional charts and guidance are included in the ICOLD Bulletin.

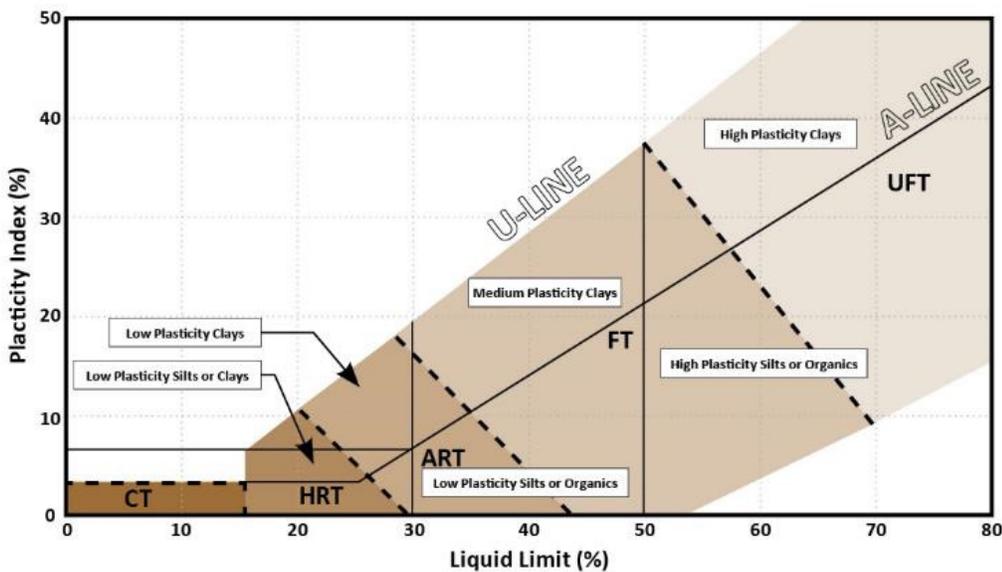


Figure 4-1 Plasticity Chart for Tailings Types

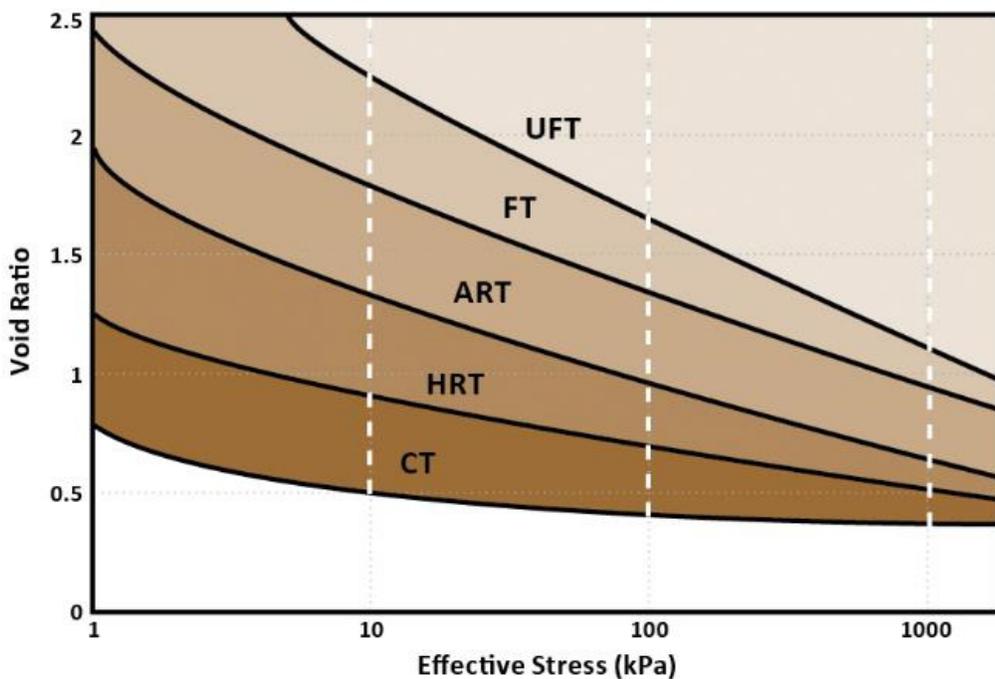
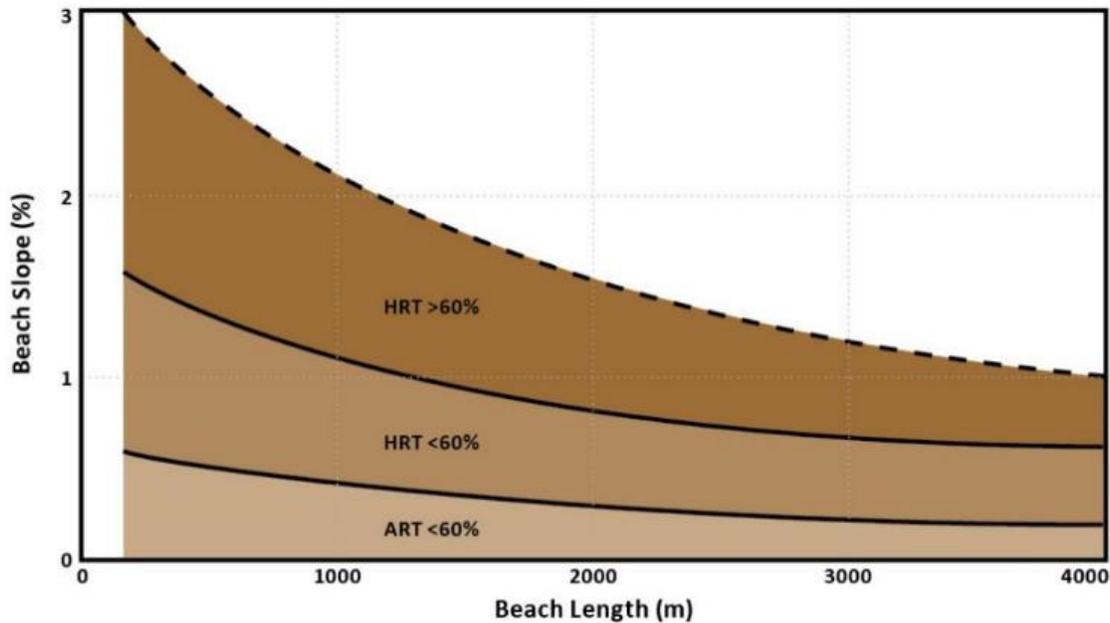


Figure 4-2 Void Ratio versus Effective Stress for Tailings Types

#### 4.4.3 In Situ Tailings Properties

In situ tailings properties are typically determined based upon field surveys: beach slopes measurements, seismic cone penetration testing with pore pressure measurements (SCPTu), standard penetration testing (SPT), and field shear vane tests. Figure 4-3 presents typical beach

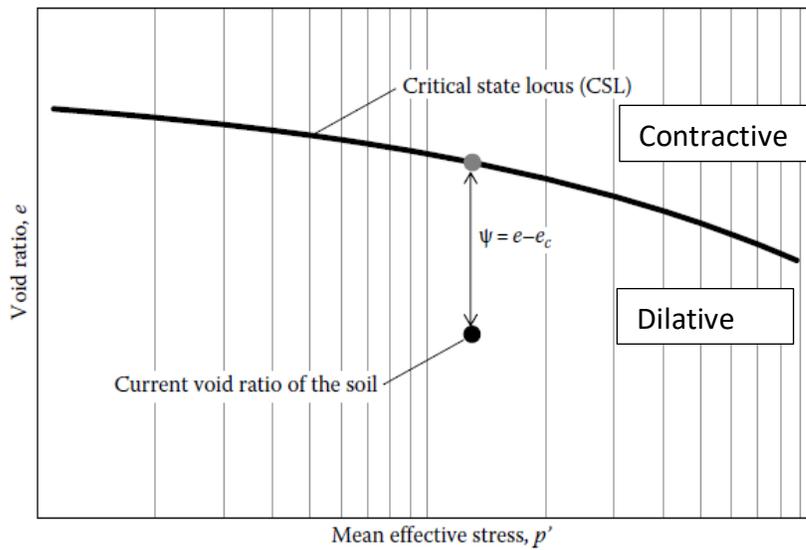
slopes for Hard Rock tailings with various slurry discharge percent solids by weight (assuming a S.G = 2.8).



**Figure 4-3 Beach Slope (%) and Tailings Discharge Distance Relationship for Tailings Types**

#### 4.4.4 In Situ Strength Parameters

The drained strength of most tailings is relatively high, as the tailings are usually a product of crushing rock, which commonly results in angular competent particles. Drained friction angles typically vary from 30° to 35° or higher, although the drained strengths of fine and ultrafine tailings are lower. However, drained strengths rarely control the strength of uncompacted tailings, because as failure is initiated the tailings behave in an undrained state, with generation of pore pressures. An understanding of the behaviour during undrained loading is best illustrated with critical state soil mechanics (Jeffries & Been, 2018). Critical state can be viewed as the ultimate condition that will be achieved after sufficient shear. Uncompacted tailings behaviour ranges from contractive (loose) to dilative (dense) states and the boundary between these is commonly referred to as the critical state line, as illustrated on Figure 2.16, which plots void ratio against mean stress. The further the tailings density is from the final critical state the faster dilation or contraction occurs. The state parameter  $\psi$  is defined as a measure of that deviation, as illustrated on Figure 4-4.

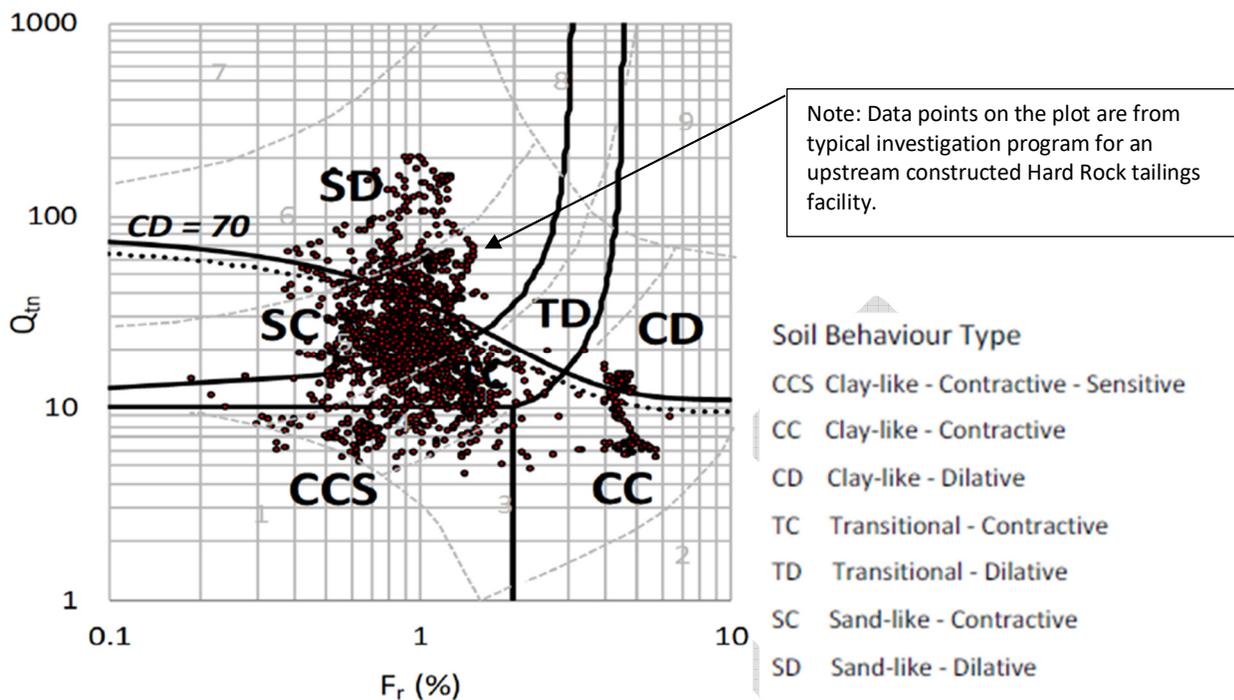


**Figure 4-4 State parameter ( $\psi$ ) and critical state line (after Jefferies & Been 2016)**

Determination of  $\psi$  has been advanced with the development of Cone Penetration Testing (CPT) technologies in which laboratory tests have been correlated with CPT testing to develop a relationship to determine  $\psi$ . A value of  $\psi > -0.05$ , is typically used to identify contractive soils, defined as losing volume on shearing. CPT has also been developed to determine peak and residual undrained shear strengths where the cone tip resistance and side friction have been calibrated with empirical and laboratory data (Robertson, 2010).

Laboratory determination of the peak undrained shear strength and residual shear strength of in situ tailings is challenged by the difficulties in collecting representative undisturbed samples, and often CPTu is the primary assessment tool. The critical state line and soil behaviour can be determined in the laboratory, however there are challenges with collecting representative samples and assuring undisturbed sampling and testing conditions.

An example of data plot of CPT testing (normalized tip resistance versus normalized sleeve friction) for a typical upstream Hard Rock tailings facility is shown on Figure 4-5. The plot demonstrates the extremely heterogeneous nature of the tailings deposit which further exacerbates the challenge of collecting and testing of representative samples in the laboratory.



Reference: Robertson, P.K., 2016. "Cone penetration test (CPT)-based soil behaviour type (SBT) classification system—an update." *Canadian Geotechnical Journal*, 53(12), 1910-1927.

**Figure 4-5 Example of Typical Soils Behaviour Classification for an upstream Hard Rock tailings facility (normalized tip resistance versus normalized sleeve friction)**

## 4.5 Geochemical Characterization

Geochemical characterization of tailings is required to determine the potential for metal leaching and acid rock drainage (ML/ARD) (also known as acid and metalliferous drainage, AMD) under both neutral and acidic conditions, respectively. Tailings geochemical characterization should be carried out in conjunction with process water quality testing, and the testing should recognize the potential for longer-term geochemical changes. Geochemical testing typically proceeds with static testing, followed by kinetic testing, to assess metal leaching. As with geotechnical characterization, sample selection and sample representativeness are important to allow extrapolation of the testing to the orebody and the deposited tailings over the life of the TSF.

ARD occurs when reactive sulphides contact with oxygen and water in the presence of iron/sulphur-oxidising bacteria, and there is insufficient or ineffective alkaline material to neutralise the products of oxidation and formation of acid. ARD is a dynamic and spatial phenomenon, and acid conditions occur if the acidity generated is greater than the neutralisation capacity of the system at any stage of the life cycle of sulphide oxidation, both during the deposition period and post closure. The term "ARD" is applied to the resulting leachate, seepage, or if drainage is acidic, typically defined as pH less than 6. Tailings can be classed as potentially acid generating when the acid potential exceeds the

neutralization capacity and can result in  $\text{pH} < 6$  in contact water. Additionally, neutral mine drainage (NMD) and saline drainage (SD) can occur at  $\text{pH} > 6$ . The range of tailings classification is described below and illustrated on Figure 4-6.

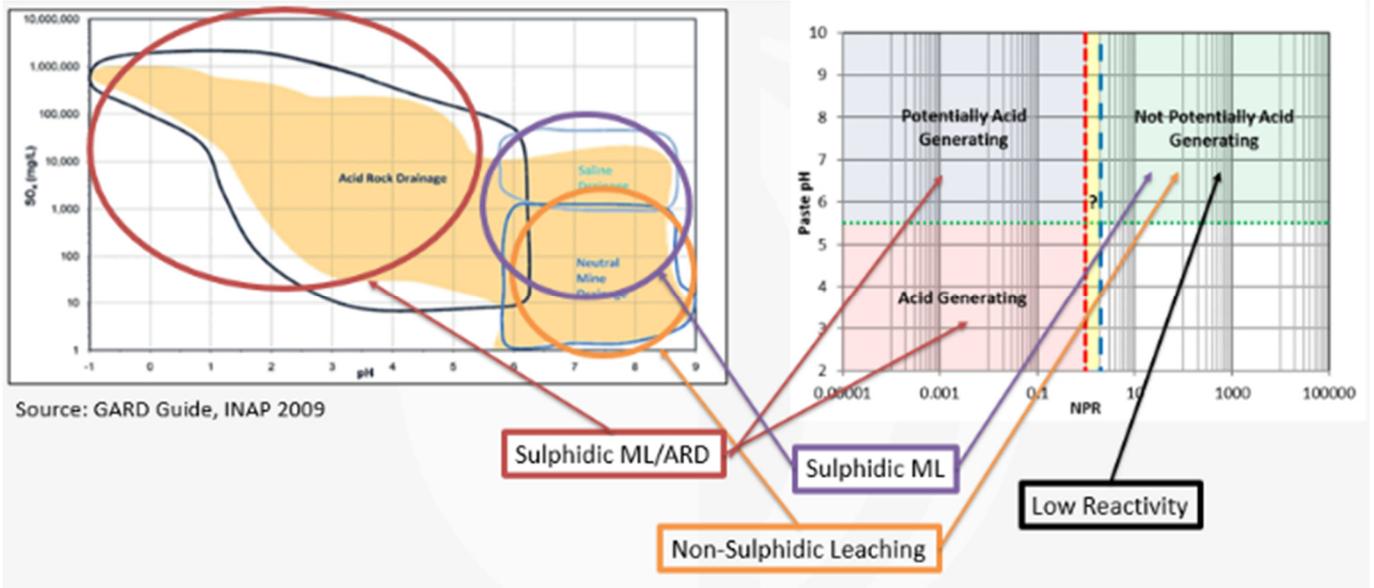


Figure 4-6 Ficklin-Style Diagram showing ARD, NMD and SD and relationship with paste pH and NPR (KCB 2017)

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## 5 DESIGN

### 5.1 Introduction

The design of a TSF starts when the need to store tailings is identified and typically ends when the closure has been implemented. In some cases, the design activities may continue after closure has been completed due to changes in the site conditions, regulatory requirements or other factors.

The goal of the design is to safely store the tailings during the operational life of the facility and to be able to create a physically and chemically sustainable structure after its closure - in perpetuity. With this objective, if the tailings have potential to generate ARD, there can be a conflict between the environmental objective to keep the tailings saturated to prevent acid rock drainage, as opposed to the geotechnical objective of transitioning to a drained pile for long term physical stability. There may also be a conflict with the desire to minimize the footprint of the TSF to limit loss of habitat, which requires a higher dam, as opposed to a lower height TSF with a larger surface area.

A TSF has many components and systems such as embankment(s), impoundment, reclaim water, tailings delivery, seepage collection, monitoring, water management, safety, communications, access roads and others. The design of the TSF considers these components to ensure they work together as an integrated system.

### 5.2 Life Phases and Design Stages of a Tailings Dam

A TSF typically involves the following life phases:

- Concept development— the general location, configuration, and type of dam is considered.
- Planning and site selection— involves a comprehensive review of potential sites, dam technologies and dam configurations.
- Design of the dam.
- Construction of the dam— initially the starter dam and then dam raises throughout operations.
- Operation— routine tailings deposition and water management which is integrated with progressive raising of the dam in stages.
- Closure— the TSF and associated dams likely need to last in perpetuity (transition, active care and passive care).

Design stages for a new tailings dams typically include:

- Scoping-level design – this design stage develops the initial concept for the dam, including site selection and possible options for the dam configuration, location, size, and so on. The study typically focuses on identifying major features that could have a bearing on the dam siting, configuration, and operation. The key objective of this stage is to determine whether the project should move forward.

- Pre-feasibility design – this stage typically considers multiple options and possibly multiple sites for the dam. The preferred site and location for the dam will typically be defined during this stage.
- Feasibility design – this stage advances the design to support financing, environmental assessments, and other regulatory requirements for approval of the project.
- Detailed design – this stage occurs just prior to construction and is when the scope of work, specifications, and construction drawings are prepared. Additional regulatory approvals may be required after the detailed design has been completed and prior to construction commencing.

Design stages during operations will include:

- Raises of the dam to suit the actual tailings deposition results and water management requirements.
- Design changes to adapt to developing understanding of the site conditions, the performance of the dam and risk reductions measures.
- Design changes due to changing regulatory or governance requirements.

### 5.3 Design for Closure

Closure design should be the final goal that informs the design throughout the life of the TSF and will influence design factors such as: site selection, tailings technologies, dam construction methods, tailings deposition plans, water quality and management, and other factors.

Design for long term physical and geochemical stability requires consideration of these processes on the stability of the dam and water management structures. Additionally, consideration of geochemical processes and the potential for adverse environmental effects over the long term need to be incorporated into the design. The long-term geochemical stability of the tailings and the potential for contaminated seepage or surface flows need to be predicted over the closure period and its mitigation incorporated into the design.

Potential physical influences on stability include physical and chemical weathering of materials, which may lead to a reduction in the strength or erosion resistance of the dam fills. Chemical precipitates associated with acid rock drainage can plug filters and drainage systems leading to elevated phreatic levels and reduced stability. Spillways may become blocked with debris or the flood attenuation capacity of the TSF impoundment may decrease over time with inflow of eroded sediment leading to higher peak flows. Surface erosion and potential effects of climate on soil covers, freeze thaw effects or desiccation need to be considered in the design.

Determination of the end land use and the incorporation of the closed TSF into the natural landscape is required. The ecological stability of the TSF with respect to sustainable land and water use includes assessment of potential reclamation alternatives and end land use alternatives. Social stability begins with the development of site-specific land and water use objectives that support the long-term sustainable use of the TSF. An important sustainable benefit of this approach is that if the community

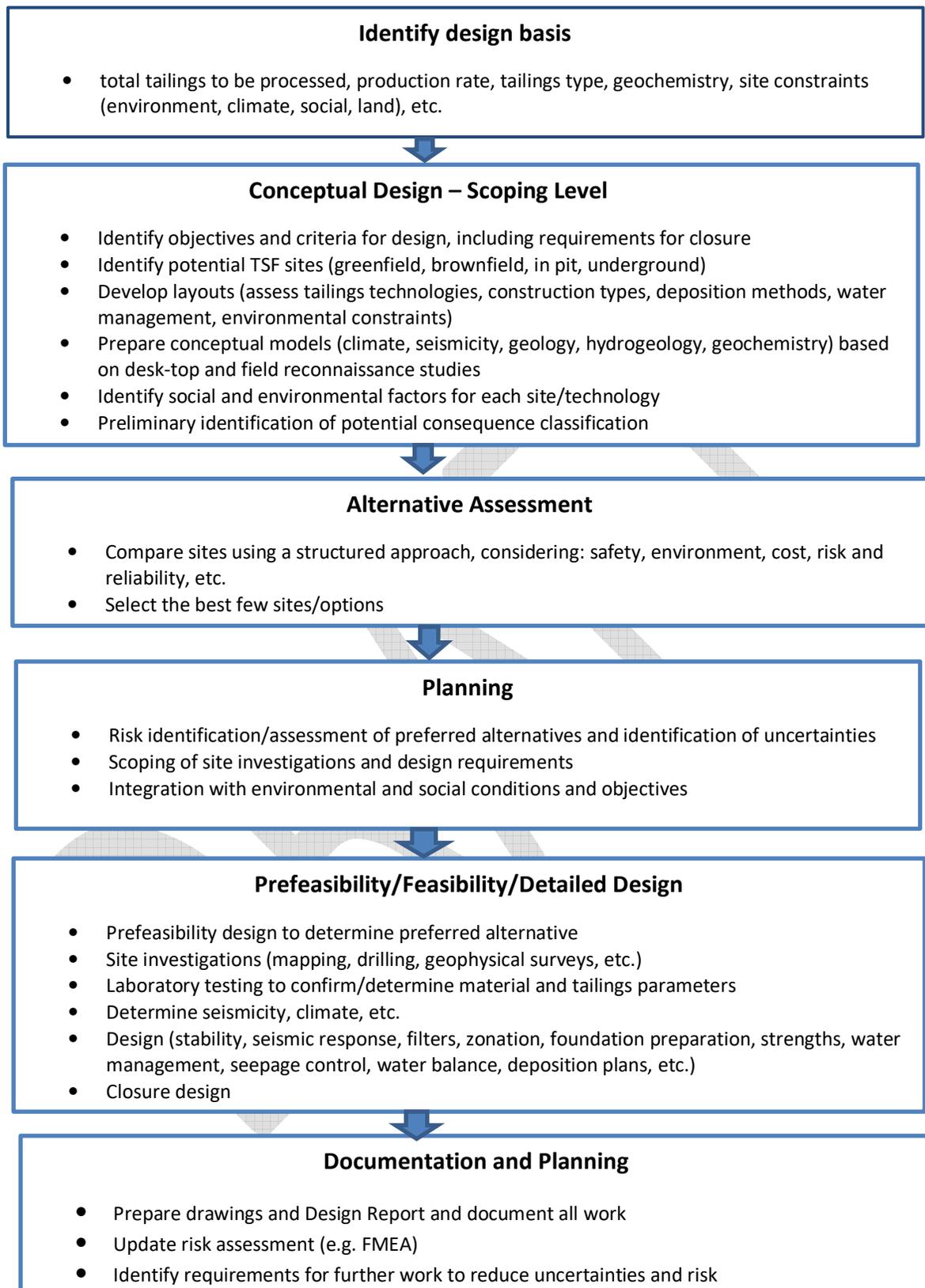
supports the land and water use, there is a much higher likelihood that the closed TSF will be maintained and that the value of the property can revert to the community (or State).

Section 11 provides further details on closure.

## 5.4 Design Steps for a New Tailings Dam

The design of a tailings facility is a progressive, and iterative process that starts with conceptual planning of requirements for storage and potential sites and technologies for dam construction. The design is part of the Tailings Management System (described in Section 2.1.1 of this Bulletin). Design progresses through stages from conceptual through to feasibility design, leading to detail design and construction. Figure 5-1 shows a schematic of the typical steps and studies involved during the process. A key over-riding tenet is to continue to reduce the risk and cost of the facility and to optimize the ability to transition to a long-term stable facility on closure.

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**Figure 5-1 Schematic of Typical Design Process for New Tailings Facilities**

## 5.5 Design of Raises and Ongoing Operations

The initial design of the dam typically considers the starter dam and the raises required to reach full dam capacity. However, subsequent detailed design of individual dam raises often need adjustments to the initial design to respond to such items as:

- ◆ Changes in production rates and actual settled densities that influence the storage requirements
- ◆ Ongoing site investigations and laboratory testing including classification of the tailings previously placed (particularly for upstream construction)
- ◆ Changing water balance conditions
- ◆ Response to dam performance monitoring (pore pressures, deformation, seepage, etc.)
- ◆ Contractor schedules and constructability of dam components
- ◆ Quality assurance observations with respect to such aspects as dam fills (gradation and compaction), abutment/foundation conditions
- ◆ Need to maintain effective tailings discharge during construction works

## 5.6 Risk-Informed Design

### 5.6.1 Overview

Throughout the design process, the designer and Owner need to consider the potential risks associated with the tailings facility and dam and design controls and measures to limit these risks. The potential dam failure modes are identified together with the associated causes or triggers of each of those modes. The design either renders some of these failure modes as physically inadmissible (non-credible) or reduces the risk as far as reasonably practical (AFARP). Risk management tools such as potential problem analysis (PPA) and semi-quantitative or quantitative risk assessments are commonly used to characterize likelihood and consequences for each failure mode. Risk assessments need to be comprehensive so that uncertainty is reduced.

A risk register should be prepared during the design stage and updated throughout the life of the TSF and into closure.

Other components of the risk-informed design is the use of the observational method and performance based design principles discussed in the following sections.

### 5.6.2 Observational Method

A key risk management tool is the Observational Method. The Observational Method can be used to manage uncertainty with material parameters, stability analyses, and safety evaluations. The Observational Method is not simply monitoring performance, but rather using it to inform design and reduce risk. Baecher and Christian (2003) provide a succinct summary of the essential aspects of the Observational Method as follows:

“The observational method grew out of the fact that it is not feasible in many geotechnical applications to assume very conservative values of the loads and material properties and design for those conditions. The resulting design is often physically or financially impossible to

build. Instead the engineer makes reasonable estimates of the parameters and the amounts by which they could deviate from the expected values. Then the design is based on expected values – or on some conservative but feasible extension of the expected values – but provision is made for action to deal with the occurrence of loads or resistances that fall outside the design range. During construction and operation of the facility, observations and measurements of its performance are made so that appropriate corrective action can be made. This is not simply a matter of designing for an expected set of conditions and doing something to fix any troubles that arise. It involves considering the effects of the possible range of values of the parameters and having in place a plan to deal with occurrences that fall outside of the expected range. It requires the ongoing involvement of the designers during the construction and operation of the facility.”

To properly utilize the Observational Method to manage uncertainty and reduce risk, the full method as described above must be adopted. Also, it is important to note that the Observational Method is not always applicable, particularly where:

- The nature of the project does not allow the dam design to be altered during construction and operation
- There are no contingency measures available
- The mode of failure occurs relatively rapidly (i.e. in a “brittle” manner where there is significant strength loss over small shear strains), and no or little instrumentation response can be expected prior to failure, or
- The critical failure mode is due to seismic loading where there would be not be time to respond

### 5.6.3 Performance Based Design

Morgenstern (2018) advocates for the performance-based risk-informed design (PBRID) process. The risk informed aspects of this process are discussed above. This sub-section focusses on the performance-based aspects, which are linked to the Observational Method.

The performance-based design approach involves informing the risk and design based on monitoring the performance of the dam. Tailings dams are often constructed over tens of years during which time significant changes and understanding of the site conditions, behaviour of the dam, design and operations will likely occur. The performance-based design approach includes:

- For the main failure modes, identify performance parameters (e.g. shear strength, density, pore pressures, deformation, freeboard, etc.) that should be monitored during operations, including dam construction.
- Predict the anticipated characteristics of each of the performance parameters or state the assumptions that were made.
- Monitor the actual characteristics of the performance parameters to check against the predictions/assumptions.

- If there are adverse deviations from the predictions/assumptions, take action to correct the situation by either improving the situation or modifying the design to account for these and reduce the risks.
- If the actual performance is better than expected, then possibly optimize the design to account for these favourable conditions.

The safety of the dam can be described in terms of how well the dam performs, rather than in terms of a Factor of Safety as described in Section 5.10.2.

For dams where the Observational Method is being employed, the performance-based approach and Observational Method are similar, except the performance-based approach extends the Observational Method to making a safety statement of the dam based on performance.

For dams where the Observational Method is not being employed (such as for dams with brittle elements), the performance-based approach is also useful to predict conditions under which strength loss could occur, design against that condition, and monitor to confirm the effectiveness of the design.

A performance-based approach utilizes engineering analysis and judgment (including the principle of defense-in-depth and the incorporation of safety margins), and performance history to:

- Focus attention on the most important activities
- Establish objective criteria for evaluating performance
- Develop measurable or calculable parameters for monitoring system and performance
- Provide flexibility to determine how to meet the established performance criteria in a way that will encourage and reward improved outcomes
- Focus on ongoing observations of the dam performance as the primary basis for decision-making.

## 5.7 Dam Failure Modes

This section provides an overview of the potential failure modes for a tailings dam and is provided to set context for the remainder of this section on design. Risk assessment methodologies to address the main failure modes are further discussed in Section 6 of this Bulletin.

### 1. Instability Due to Foundation Failure

Instability of the dam foundation can occur possibly due to undetected weak materials, incorrect strength assumptions, and or incorrect seismic hazard/response analysis. Other failure mechanisms could include, for example, pore pressure generation and artesian water pressures.

Foundation failure is a common failure mode for tailings dams with the most recent examples of Cadia, Australia (2018), Mt. Polley, British Columbia, Canada (2016), Aznocolar (Los Frailes), Spain (1994). The potential for a foundation failure increases in complex geologic formations,

particularly in materials that could include weak clay layers (e.g. complex glacial history at Mt. Polley), or weak bedding planes (e.g. claystone layers within the mudstone, sandstone sequences at Aznocolar). Lightly consolidated clays and desiccated residual clay soils are sensitive to the height of the tailings dam and may become normally consolidated as the height of the tailing dam increases. Soil behaviour changes significantly once the pre-consolidation stress is exceeded. The soil becomes normally consolidated and, if saturated, can result in positive pore pressure generation during shearing. This can result in progressive failures that can occur rapidly. Loose, saturated, granular soils are sensitive to static liquefaction and cyclic liquefaction under seismic loading.

## **2. Instability Due to Failure of the Dam Slope**

Instability of the dam slope can occur due to inclusion of weak materials in the structural portion of the dam, lack of compaction and poor drainage, or incorrect seismic hazard/response analysis. Upstream tailings dams with thin structural shells are typically more vulnerable to slope failure as the tailings are normally placed in a heterogeneous manner and are contractive. This was observed with dam failure examples in Brazil in 2015 and 2019. Static liquefaction of upstream dams may become a concern as the dam height increases, and static stresses and stress concentrations increase. Cyclic liquefaction due to seismicity needs to be considered. Centerline and downstream dams are normally constructed with compacted fills with QA/QC procedures typical of conventional earth and rockfill dams. However, they can be prone to slope failures if the compaction is not met as planned and drainage measures in the dam shell can be compromised.

## **3. Overtopping**

Tailings dams can overtop during flood events possibly in concert with blocked spillways or improper water management. Baie Mare (2000) is an example of overtopping due to rain on snow event, common in cold temperate climates. Merriespruit (1994) is an example of inadequate freeboard. Facilities that store the flood (no spillway) may be more susceptible to overtopping as the ability to implement emergency controls, such as pumping, may be hindered during an extreme event.

## **4. Other Natural Hazards and Erosion**

In addition to flood events within the TSF, natural hazards could include rock, soil or snow avalanches into the TSF impoundment leading to overtopping or instability of the dam or natural landslides that may form part of the dam abutment or foundations. Other natural hazards include extreme floods in adjacent streams that could erode the toe of the dam or erosion of the dam due to high intensity rainfall on the downstream slope of the dam.

## **5. Piping**

Piping (internal erosion) occurs when the hydraulic gradients are high enough to move fine particles within the dam fill and there are not adequate filters to control movement of particles that can lead to failure of the dam. The Omai (1992) piping failure occurred when the water pond was against the face of the downstream constructed dam and the filter between

the clay core and the rockfill shell was not adequate to prevent piping of fines out of the core. As a result, the dam failed.

## 6. Failure Along Decant Towers, Pipes or Pipelines

Where used, decant towers or pipes through the dam or foundation can fail due to lack of structural integrity under static and dynamic loading, blockage with debris, piping of fines along/around the pipe extension through the dam. An uncontrolled rupture of a tailings slurry delivery or water reclaim pipeline could erode the dam crest potentially leading to release of tailings and water.

## 7. Environmental Effects

Tailings dams are typically constructed to limit surface and groundwater contamination. Potential failure modes include release of acidic waters or neutral metal leaching. Failure of seepage barriers to perform as per the design may be due to unidentified seepage paths, poor construction and other factors. Other environmental failure modes may include, for example, dust generation or fauna impacts with contaminated water.

## 5.8 Design Basis

The Design Basis establishes the key parameters and criteria needed to progress the design. Parameters include storage requirements for the tailings such as production rate, process type, tailings properties, life of mine, climate, seismicity, site conditions, and other key data. These parameters are established at the start of the TSF design and updated during design and operations to reflect changes.

Design Criteria are the key elements of a safe design. The criteria are typically related to the main failure modes and are often selected based on a consequences of failure classification (Section 3) and consideration of the potential losses to an Owner.

The Design Criteria are explicit goals and/or defined targets that the design needs to meet/achieve. The criteria are developed in accordance with the operational and regulatory requirements. The Design Criteria are developed in the beginning of a design process by the Owner of the facility in consultation with the EoR and/or Design Engineer. It is important for the Design Criteria to meet all applicable regulatory and permitting obligations as well as recognizing the potential losses to the Owner in the event of a failure. The overarching purpose of the structure and its objectives (not necessarily quantifiable, but some can be) are also stated with the Design Criteria.

The design basis parameters are developed by the Design Engineer to list the key characteristics, and assumptions that characterize the site and are adopted in the design to achieve the goals/targets listed in the Design Criteria. Key parameters include, but are not limited to, strengths, densities, seismic and flood loading requirements, climate, water quality, tailings geochemistry and other key data. These parameters are established at the start of the TSF design and updated during operations to reflect improved knowledge.

Design Basis could also include items such as scheduling, interaction with other structures, constraints or limitations, borrow sources, etc. The Design Basis may be updated during the design as additional information is discovered or made available.

Updating the Design Basis is also linked with the Performance-Based Risk-Informed approach. During design of TSFs for new mine developments, there is limited access to representative tailings samples for laboratory testing and there is no performance data available. In these and similar situations, conservative estimates of tailings characteristics, such as in situ density, geochemistry, strength and permeability are made and adopted in the design. During operations, these design parameters continue to be assessed as additional information arises and are compared against design assumptions and used to update the design and operations. The same approach also applies to potential uncertainty with the dam foundation characteristics or environmental conditions.

The Design Basis must be presented by the designer and accepted by the Owner prior to commencement of the design. The Design Basis is usually presented at the start of the initial design process as a Design Basis Memorandum (DBM) and may be progressively updated as the design progresses. An example of a DBM is included in Appendix A.

The final Design Basis must be clearly set out in the Design Report. Changes in the Design Basis must be subject to a management of change process.

## 5.9 Design Criteria

### 5.9.1 Design Criteria Selection

The design criteria selection is based upon consideration of the following:

- The Consequence Classification of the TSF based upon a dam breach analysis (Section 7 of this Bulletin) and Table 3-1.
- The complexity of the site with respect to such aspects as the foundation conditions, soil behavior (e.g. brittle, strain dependent), constructability and other challenges, complexity of the dam design, sensitivity to operations, and others
- Generally, higher consequence dams also require a higher standard of care with design, construction/operations, and governance

The design criteria for flood and earthquake for water dams has been developed for many jurisdictions around the world and some jurisdictions have specific requirements for tailings dams, which are commonly aligned with water dam criteria. The criteria are expressed as an annual exceedance probability, developed principally on societal acceptance for the probability of loss of life. In some cases, it may be warranted to carry out a quantitative risk-based approach that seeks to quantify the events and probabilities of events that could lead to failure of the dam. However it is important to consider that the accuracy of prediction of probabilities and combinations of events leading to a failure is often subjective and largely based on the professional opinions of the persons carrying out the analyses.

The criteria presented in the following sections should be considered as guidance for minimum criteria. The AEO and the EOR should assess each facility for the potential to increase the design criteria as far as reasonably practical. In some cases, the EOR may be able to make design changes that can meet higher criteria without significantly increasing the cost or risk. Equally, the AEO may require higher criteria to reduce the risk of temporary or permanent closure of the mine even in the event of a small-scale failure. Local jurisdictional requirements should be met or exceeded.

The design criteria for closure should consider a higher criterion than for operations to reflect the long-term performance requirement. One approach is to adopt an increase to at least the next highest consequence category, another would be to assess the worst-case scenario for change to the consequence category over the expected post-closure life of the TSF. The selection of the design criteria for closure should consider the potential changes to the facility over the long term. Changes may be positive or negative. For example, tailings consolidation and drainage may reduce the risk of liquefaction and “flowability” and removal of the ability to store water reduces the risk of dam breach outflow. However, increased population in the area could increase the population at risk and the potential for loss of life or impacts to communities and infrastructure.

Design criteria for geotechnical Factors of Safety are complex and these are discussed in Section 5.10 of this Bulletin.

Design criteria for seepage and surface water components are discussed in Section 5.11 and Section 5.12 of this Bulletin, respectively.

Design criteria for permissible seepage rates to limit potential environmental effects, are discussed in Section 5.13 of this Bulletin.

### 5.9.2 Flood Design Criteria

Most countries have defined criteria and methods to select the inflow design flood (IDF) for dams to protect their population based on the flood estimation methods available. These fall generally into three methods as follows:

- Empirical – based on size of dam and storage without reference to downstream consequences of failure.
- Consequence Based – depending on the assessment of the consequence classification of the dam in the event of failure.
- Risk Based – the selection of the design flood based on risk and the findings of a risk analysis.

ICOLD consider the Consequence Based methods are adequate given the current state of understanding of dam safety and hydrology, although risk-based approaches may be appropriate in some cases. The inflow design flood (IDF) is the flood used to design and/or modify a specific dam and its appurtenant works; particularly for sizing the spillway and outlet works, and for determining extreme flood storage and height of dam requirements. The tailings facility must be capable of withstanding the flood conditions, accepting some damage and a reduction in safety factors but without causing dam failure.

Table 5-1 provides the minimum IDF criteria corresponding to the consequence classification. The criteria presented is guidance for recommended minimum criteria. The AEO and the EOR should assess each facility for the potential to increase the design criteria as far as reasonably practical.

**Table 5-1 Suggested Minimum Flood Design Criteria**

Consequence Classification	Flood Criteria -- Annual Exceedance Probability (AEP) <sup>1</sup>
	Operations and Active Care Closure
Low	1/100
Significant	1/1,000
High	1/3 <sup>rd</sup> between 1/1,000 and PMF
Very High	2/3 <sup>rd</sup> between 1/1,000 and PMF
Extreme	PMF

Note: 1) The criteria presented is guidance for suggested minimum criteria. The AEO and the EOR should assess each facility for the potential to increase the design criteria as far as reasonably practical.

2) The probable maximum flood (PMF) has no associated AEP

The other criteria which needs to be defined as part of the mitigation against uncertainty is minimum freeboard. Minimum freeboard is defined as the difference in elevation between the dam crest and the maximum flood elevation. Minimum freeboard determination considers the potential for wind and wave run-up, embankment settlement or irregularities in the dam crest elevation. The freeboard should be assessed using a realistic design wind with an AEP of at least 1:10, but should not be less than the values provided in Table 5-2.

**Table 5-2 Minimum Freeboard Design Criteria**

Consequence Classification	Flood Freeboard Criteria – Above IDF Level (m)
	Operations and Active Care Closure
Low	0.3
Significant	0.5
High	1.0
Very High	1.0
Extreme	1.0

Where the design flood is to be passed through a spillway, the critical duration will be determined by flood routing through the impoundment.

Where the design flood is to be temporally stored the critical duration will be determined in consideration of:

- Potential duration of extreme storms or multiple extreme storms considering the emergency response capability to release water under the likely conditions of the extreme event. A minimum duration of 3 days, or longer, should be considered.

- The ability to construct an emergency spillway in a location that would not jeopardize the safety of the dam.
- The storage available within the freeboard allowance and the erodibility of the dam fills

ICOLD recommend that, as far as practical, an emergency spillway be provided and/or be included in the emergency response plan, as discussed in Section 8.2.1 of this Bulletin.

### 5.9.3 Seismic Design Criteria

As with floods, the estimation of earthquake loadings is a complex matter and includes significant uncertainty (ICOLD, 2016). A seismic hazard assessment is required to determine the earthquake loading characteristics, as described in Section 4.3.2 of this Bulletin.

**Table 5-3 Suggested Minimum Seismic Design Criteria**

Consequence Classification	Seismic Criteria <sup>1</sup> Annual Exceedance Probability <sup>2</sup>
	Operations and Active Care Closure
Low	1/100
Significant	1/1,000
High	1/1,2475
Very High	1/5,000
Extreme	1/10,000 or MCE <sup>1</sup>

Notes: 1) The selection of the probabilistic or deterministic design earthquake should consider the seismic setting and the reliability and applicability of each method.  
2) The criteria presented is guidance for suggested minimum criteria. The AEO and the EOR should assess each facility for the potential to increase the design criteria as far as reasonably practical.

The key seismic design criteria include determination of the moment magnitude ( $M_m$ ) of the earthquake, the peak ground acceleration, and the earthquake characteristics (acceleration variation during the duration of the earthquake). Seismic hazard assessments include due consideration of epistemic and aleatory uncertainty.

## 5.10 Geotechnical Design

**THIS SECTION IS BEING REVIEWED**

### 5.10.1 Slope Stability

Assessment of slope stability is a key element of the safety evaluation of tailings dams and is normally based upon limit equilibrium analyses and Factors of Safety. Alternatively, more complex analyses can be carried out using deformation models that can more accurately model stress, strains and deformations as described in Section 5.10.3

### 5.10.2 Stability Evaluation with Limit Equilibrium

Table 5-4 provides target Factors of Safety for static loading conditions and post-peak/residual conditions, based on limit equilibrium analyses.

For the limit equilibrium safety evaluations, equilibrium conditions are considered for the failing soil mass that assumes that the failure criterion holds everywhere along the failure surface. The analysis assesses multiple potential failure surfaces and typically the critical failure surface, which passes through the crest of the dam and could lead to a potential release of tailings is selected. Other failure surfaces, particularly if they could lead to progressive failure of the dam, are also assessed. The targets in Table 5-4 apply to slip surface that could release the materials (tailings and water) that are contained by the dam.

The solution obtained by the limit equilibrium method does not account for strain compatibility and displacement boundary conditions. In addition, material behavior is assumed to be rigid-perfectly plastic and is typically considered in a two-dimensional plane. Yet, because of its simplicity and its proven track record when input parameters are appropriately selected, the limit equilibrium method is used in most design situations, particularly where the availability of input parameters or the complexity of the soil behavior(s) does not warrant the use of more sophisticated approaches as described in Section 5.10.3.

**Table 5-4 Target Factors of Safety**

Condition	Factor of Safety
Static	1.5
Post- Peak/Residual Strengths	1.1

The selection of a Factor of Safety requires consideration of the potential variability in materials and site conditions and is largely based on accumulated experience with various soils. If the targets in Table 5-4 are met, this can be generally viewed as acceptable practice. However, if they are not met, further investigation and analyses, supplemented by comprehensive use of the “observational method”, may be used to reduce uncertainty and support lower targets. Conversely, higher Factors of Safety may be required to account for uncertainties in: material properties, sensitive strain-weakening soil behavior, complex geological conditions that may not, or cannot, be fully defined for design, or potential changes to soil properties or loading conditions with time.

The selection of the methodology for the stability assessment and the appropriate Factor of Safety is influenced by the reliability of the data and the analyses and its selection should consider key factors, such as:

- The consequences of failure
- The uncertainty in material properties and subsurface conditions
- Variable construction and operating conditions
- Comprehensiveness of site investigations and geotechnical monitoring

- Soil response (contractive/dilative) and its variation with confining stress and stress level, including the potential for brittle failure mechanisms
- Time-dependent, deformation-dependent and stress-path-dependent processes that may affect the critical material properties such as the operational pore pressures and shear strengths
- Strain-incompatibility of the different materials forming the dam and its foundation, and,
- Implementation of an effective risk management system to reduce or mitigate the residual risks associated with the uncertainties of these factors over the lifecycle of the dam

Further discussion is included in Appendix III.

The target Factors of Safety described in Table 5-4 are based on the assumption that a typical standard of care has been adopted with respect to the site characterization, selection of parameters, and design.

### **Static Loading Condition**

The static loading condition in Table 5-4 refers to the condition where the tailings dam is operating and impounding tailings and/or water.

Stability analyses need to consider both drained and undrained behaviour and select the appropriate material properties. Fine grained contractive soils and normally consolidated soils, when strained, tend to contract and generate pore pressures, hence the peak undrained shear strength applies for the stability assessment of the static condition.

Dilative and coarse-grained soils tend to dilate when strained and, for practical purposes, the effective strength with no change in pore pressures during shearing (i.e., the drained shear strength) can be used for the stability assessment. Care must be taken with over-consolidated soils that are dilative but can become normally consolidated when loaded beyond the pre-consolidation pressures.

When dealing with dams with contractive elements in them, typical triggering mechanisms for undrained failure include:

- Added soil loads to the dam (dam raising, tailings placement, etc.)
- Reduced soil loads at the downstream slope or toe (by erosion or excavation)
- Increase in stress concentrations associated with higher dam heights
- Deformation and shear straining in contractive materials at the base of a dam that causes a change in stress state for the materials in the upper portions of the dam, resulting in static liquefaction
- Development of significant erosion features on the downstream slope of a dam due to precipitation that can change the stress and deformation conditions in the dam (more so a closure concern)
- Increase in pore pressure conditions due to water level rises or failure of a diversion system
- Loss of soil suction or creep

- Changes in the pore pressure conditions in a dam or foundation due to dewatering that cause the effective stresses to increase and result in deformations that trigger the undrained event
- Progressive failure (over-stressing of a local zone in the soil or rock, leading to stress transfer and failure of adjacent zones)
- Earthquake, blasting, and construction traffic
- Combinations of the above.

Analyses can be done to assess the likelihood of triggering an undrained instability. Even if a trigger for undrained instability cannot be identified, it must be recognized that if the dam was to fail, it would likely still fail undrained and, hence, an undrained analysis still provides the correct Factor of Safety. A “drained analysis” could provide misleading (and unconservative) results since it is unlikely that a dam with contractive elements will fail in a drained manner, even if the excess pore pressures from construction have dissipated.

There is a potential for the peak undrained shear strength to decrease under static conditions and modifications may need to be made to the Factor of Safety or the strength. Examples include:

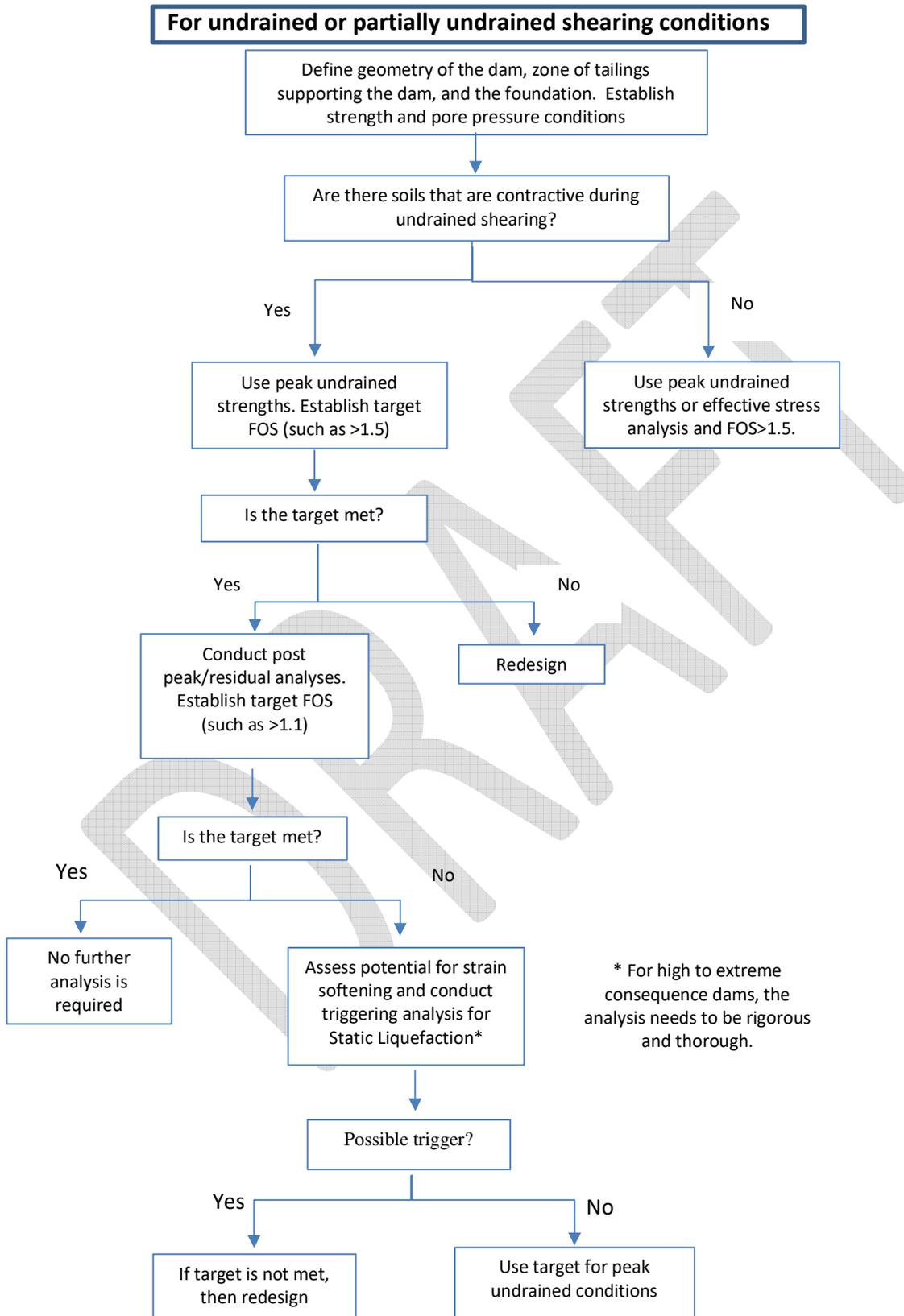
- Potential for brittle behavior whereby a soil may lose its strength at small strains resulting in significant deformation. This issue may potentially be addressed either by increasing the target Factor of Safety or reducing the strength.
- Potential for strain incompatibility whereby some soils in the dam or foundation might reach and exceed their peak strength at much smaller strains than others. An example of this situation is where there is an over-consolidated clay crust over a normally consolidated clay and the strength used to represent the crust needs to account for the strain incompatibility. This is typically addressed by discounting the strength in the over-consolidated clay crust from what is measured.

The target Factor of Safety may also have to be increased to help control deformation. If a soil in the dam or foundation may not reach the peak strength until there is substantial straining, the Factor of Safety may have to be increased to prevent unacceptable deformation.

Figure 5-2 shows a flow chart for the static loading condition, that includes consideration of static liquefaction.

There are cases where soil in the foundation of a dam is already at residual strength due to prior geological processes, or there is a high potential that such zones exist in the dam foundation. In this case, the strength that would be used in the stability analysis is the residual strength. This would be considered the “peak strength” that would be operational in the foundation of the dam, and the target Factor of Safety might be reduced below 1.5 to account for this. This is not to be confused with the post-peak/residual strength condition described below that deals with the case where the strengths start at a higher strength and then reach a minimum condition as a result of liquefaction or significant movement.

**Figure 5-2 Schematic of Static Factor of Safety Logic for Static Loading Conditions**



### **Post-Peak/Residual Strength Condition**

As noted above, the post-peak/residual strength condition in Table 5-4 refers to the condition where the strength of the soil in the dam or foundation has reached a minimum condition as a result of liquefaction or significant movement.

A liquefaction analysis is required to determine if the design earthquake can liquefy the soils. Seismic hazard assessments should be carried out in a detail commensurate with the consequence classification of the dam and the sensitivity of the stability to seismic loading conditions. Liquefaction analysis should consider amplification associated with the spectral period of the dam and static bias due to the dam slope. If liquefaction of the soil due to a seismic event is determined, then the post liquefaction residual shear strength of the soil is applied and the Factor of Safety checked against Table 5-4.

Liquefaction can also occur due to static triggering and deformations. To rule out this trigger requires a deformation analysis with a comprehensive understanding of the stress-strain behaviour of the soil. For dams that have consequences of high to extreme, it is prudent to assume that a liquefaction trigger can exist and, hence, the post liquefaction analyses should be undertaken, unless a thorough and rigorous analysis can be done to disprove the potential trigger.

The post-liquefaction residual shear strength is dependent on factors such as density, gradation, grain shape, and plasticity. Some tailings can lose a significant amount of strength during liquefaction, while others do not.

Residual shear strengths of contractive materials should not be arbitrarily selected but should be based upon an understanding of the soil behaviour. Residual shear strengths, by definition, develop after material undergoes very large strains typically following failure.

Contractive clay soils that have not reached residual can still strain soften due to cyclic loading and/or deformations and reduce in strength, moving toward the residual strength. The applicable shear strength is influenced by the brittleness of the soil, e.g. how much strain is required to go from peak to residual strength, and therefore the extent of potential deformation required to achieve a residual shear strength condition.

The analyses of strain to achieve residual strength can be complex, hence the post-peak strength will typically be the residual strength. For some strain softening materials, there still could be significant strength loss over a possible range of shear strains that could be expected in the dam fill or foundation. In this case, the target Factor of Safety for post-peak in Table 5-4 might be modified.

### **Other Loading Conditions**

Table 5-4 does not reference other typical loading conditions such as:

- End of construction
- Maximum operating level of the pond
- Post seismic for well- built dams on dense foundations.

If these loading conditions are applicable to the tailings dam being designed, then the designer should select targets that are appropriate for their dam.

A Factor of Safety for end of construction has typically been set at 1.3 there is no water or tailings impounded and the consequences of a failure of the dam would be low. However, this may not be the case for a tailings starter dam that may be large and will commence impounding water behind the dam before tailings are deposited.

It is important to note that when a tailings dam is being raised, the dam is being constructed, but the end of the raise does is not the same as the “end of construction case” that is commonly referred to in other guidance. During raising of a tailings dam, the targets in Table 5-4 apply.

For the case with the maximum operating water level in the pond, an analysis needs to be done that considers the frequency and duration of the pond being operated at the maximum level; and, The seepage conditions in the dam and foundation and how they may respond to the maximum operating level. If the frequency and duration of the pond being operated at the maximum level is low, such that this is an exception rather than the norm and the seepage in the dam would not change significantly if the maximum operating water level was reached, then the designer might specify a lower target Factor of Safety for this condition. However, if the converse is true, then that condition should represent the design condition and Table 5-4 should be used.

Rapid draw down could be an issue for a tailings dam, especially in the initial stages of operations before beaches are well established. Reclaim and water treatment requirements may draw the pond down quickly. If this condition could occur, then the designer should specify a suitable target Factor of Safety that accounts for the frequency and magnitude of the drawdown and the consequences of failure of the upstream slope due to rapid drawdown.

For compacted fill dams on competent foundations with dilative soils, the post seismic condition could involve an assessment of pore water pressures as a result of the seismic activity and checking the Factor of Safety. The designer should specify a suitable target Factor of Safety. The analysis of post seismic pore pressures can be complex since dilative soils can generate negative pore pressures in response to the shearing induced by the earthquake that off sets the positive pore pressures generated by the earthquake. As a result, a limit equilibrium analysis for this class of dams for post seismic conditions may be challenging. Hence, seismic deformation analyses should be done to estimate the amount of deformation that could occur as a result of an earthquake and the results compared to a deformation criteria.

For compacted fill dams on competent foundations, the pseudo-static analysis by Hynes-Griffin and Franklin (1984) is often used, but the results of this analysis are not an indication of whether the dam is safe during a seismic event. It provides an indication of potential deformation and this is discussed further in 5.10.3.

### **Special Considerations for Upstream Dams**

Upstream constructed dams present a unique challenge for application of undrained shear strengths due to the highly non-homogenous nature of deposition. Deposition typically results in random

interlayering of sands, silts and clays of various densities. An example of the wide variation of soils types within an upstream dam are shown on Figure 4-5. Collection of representative samples for advanced soil testing present challenges with sample disturbance and test procedures, but more importantly with assuring that the range of soils within the upstream dam can be adequately represented. Cone penetration testing (CPTu) is typically relied upon to provide the spatial variability, soil type, strength parameters and pore pressure characterization. Consequently, the selections of the strengths, particularly for static and seismic liquefaction assessments, need to be considered carefully.

### **Limit Equilibrium Evaluation and Performance-Based Stability Evaluation**

Section 5.6.3 described the performance-based approach for evaluating dam safety. As noted in this section, there are several limitations to the limit equilibrium approach for assessing the stability of a dam. The limit equilibrium analyses are appropriate for new dams that are being designed without performance data available.

A performance-based stability evaluation can be undertaken for dams that are being built and raised over several years. In such an approach, the initial Factor of Safety targets should be evaluated and modified based on the behaviour of the materials involved and recognizing the level of risk and uncertainty.

Limit equilibrium factor of safety calculations should be supplemented by deformation analyses where deformations, stress states, pore water pressures and other measured behaviours can be used to provide a better indication of performance and safety of the dam.

### **5.10.3 Safety Evaluation with Deformation Models**

The use of deformation models with appropriate constitutive relationships (stress/strain models) can simulate the stress-strain conditions in the dam. These are valuable for understanding the time-dependent, deformation-dependent and stress-path-dependent processes that may affect the critical material properties such as the operational pore pressures, shear stresses/strength and deformations. The soil response (contractive/dilative) and its variation with confining stress and stress level, including the potential for brittle failure mechanisms can be modeled.

Other applications include modeling of strain-incompatibility of different materials forming the dam and its foundation. The constitutive models that are used in the deformation modelling rely upon adequate site investigations with high quality sampling and testing to understand the material parameters variability and complexity of the dam foundation and dam fills.

Deformation models can be a very valuable tool for a tailings dam that is being raised and where there are stress-strain dependent soils that influence the strengths. Monitoring of deformations and pore pressures can be used to calibrate the model over time, leading to an improved understanding of the soil behavior. Application of the “observational method” with the associated constitutive models may support the use of lower Factors of Safety than conventional limit equilibrium analyses.

Deformation criteria should be established that considers aspects such as crest settlement that can lead to overtopping and damage narrow zones of fill, such as filters.

Simplified deformation analyses should be carried out empirically (Newmark etc.) or with advanced models that include constitutive relationships. Dynamic deformation models are used to simulate the potential earthquake loadings and determine deformations within the dam components.

Although not recommended, a surrogate for a screening evaluation of potentially allowable deformation has been developed empirically using the pseudo-static method as a screening tool to indicate if there could be deformations of potential concern. For the method recommended by Hynes-Griffin and Franklin (1984), if the pseudo-static Factor of Safety is less than 1.0, this could indicate that the crest could deform more than 1.0 m and, if this is a potential concern, then a deformation analysis is required to assess the response of the dam to seismic loading. Note that the Hynes-Griffin and Franklin method is not to be used for dams that have soils in the dam or foundation that could liquefy or experience significant strain softening.

## 5.11 Groundwater Design

### 5.11.1 Pore Pressures, Filters and Drainage

An understanding of the seepage that develops through the embankments, abutments, foundations and impoundment footprint is required for design. For slope stability analyses, normal loading consolidation and shear induced pore pressure are important mechanisms and these are considered in Section 5.10.2. This section deals with the seepage and groundwater conditions that develop due to flow of water through the dam and foundation.

A 2-D seepage analyses is typically required to define pore pressures/phreatic surfaces, gradients and seepage rates for use in stability analysis and to design drainage and filter components. The phreatic surface within the tailings is controlled by the rate of tailings deposition and whether adequate time between deposition cycles and climatic (arid) conditions are present to result in lowering of the phreatic surface near the dam.

The results of seepage modelling guides selection of instrumentation locations to monitor performance of the dam during construction and operation. It is also necessary to understand the difference between the phreatic surface and pore pressure as they may or may not coincide, depending on the soil properties.

Drains and/or drainage layers in the dam are used to maintain a lower phreatic surface to improve stability and to reduce the risk of piping on the downstream slope of the dam. The design of drainage is described in ICOLD Bulletin No 97, "Tailings Dams Design of Drainage". Drainage components may also be required to control uplift pressures due to artesian conditions. Design of dam zonation and filters should maximize the benefit of the tailings to reduce the hydraulic gradients by limiting the use of high permeability fill zones adjacent to the tailings.

Filter requirements for closure should consider that the potential changes to the hydraulic gradients and the potential for geochemical clogging of filters due to precipitates associated with the geochemistry of the tailings.

Impoundment liners and low permeability elements in the dam and impoundment may also be required to limit environmental effects associated with the geochemistry of the tailings pore water as described in Section 5.13 of this Bulletin.

### 5.11.2 Design Measures to Minimise Seepage

Minimization of seepage may be: 1) an engineering control to reduce hydraulic gradients and seepage flow rates; and/or 2) an environmental control to minimize potential seepage of contaminated water to the receiving environment (refer to Section 5.13 of this Bulletin). Seepage controls in a dam typically include low permeability soil zones and, in some cases, geosynthetic liners. Geomembrane lined dams should consider a bedding that is filter compatible with the tailings, in case there are defects in the liner.

Methods to minimize foundation seepage include cut-offs (e.g. slurry trenches and grouting) interception trenches or wells, and collection sumps/dams below points of seepage. Cut-offs are useful in areas where preferential seepage zones of higher permeability exist within the foundations. In situ soils (clays) may have relatively high permeability due to fissure, root holes etc. and permeability may be reduced by re-working and compaction. Low permeability liners include many options, such as: compacted clay, bentonite mixed soils, geomembranes (high density and linear low-density polyethylene (HDPE or LLDPE) and poly, geosynthetic clay liners (GCL). Geomembrane/tailings liner systems have been shown to have extremely low leakage rates, on the order of  $0.001 \text{ L/s/km}^2$  (Rowe et al. 2016). Synthetic liner systems may have limited life expectancy although well designed and specified liners can have a design life in terms of hundreds or thousands of years. However, the long-term effect of liner degradation and potential future release of contaminants needs to be considered. When considering the potential need for an engineered lining system, such as a geomembrane or a composite liner, it is necessary to quantify the benefit of such a solution. The tailings material itself may have a very low permeability, particularly the tailings at the base of the TSF where consolidation has reduced void ratios and thus hydraulic conductivities.

Consideration of an engineered lining system should consider the risks associated with underdrainage, as seepage through the tailings would need to be collected and managed, otherwise there is the risk of rapid build-up of excess pore water pressures as downward drainage into the sub-surface is limited. The higher pressures could increase seepage loss and reduce the consolidation of the tailings.

## 5.12 Hydrotechnical Design

### 5.12.1 General

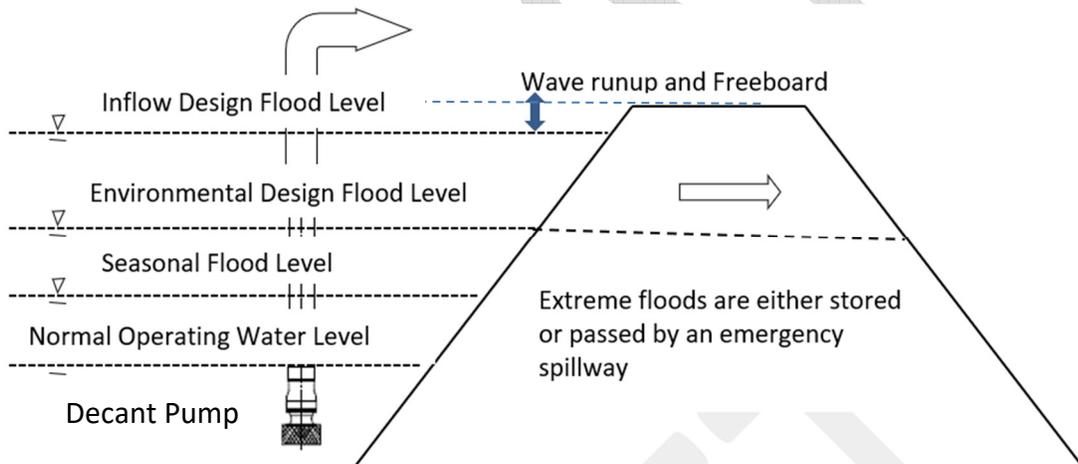
Water management for the TSF needs to allow for both dam safety and environmental safety in an operational situation where the water storage capacity is continually being modified by the deposited tailings solids and dam raises and water quality is often unsuitable for release to the environment.

Allowance needs to be made in design and operations for storage of solids that leaves adequate room for water storage allowances, which includes consideration of:

- A minimum water pond to allow settling of fines and for geochemical attenuation of reclaim water
- Temporary storage of normal seasonal flows and decant water for processing
- In cold climates, storage of water to account for ice formation and to allow deposition below the ice
- Temporary storage of the Environmental Design Flood (EDF, discussed below)
- Storage and/or safe passage of the Inflow Design Flood (IDF) to ensure the integrity of the containment dams.

Figure 5-3 shows a section through a generic tailings dam and the operating and flood water levels. Excess surface water can be conveyed by a decant pipe or pump system or through a spillway. The invert elevation of the spillway is set to contain the EDF. The crest of the dam is established to prevent overtopping during the IDF. For some dams, there is no spillway and the EDF and IDF are stored with the water removed by the decant pipe or pump system.

**Figure 5-3 Schematic Showing Operating and Flood Levels**



Water inflow to a TSF is typically recycled or treated and released over time following a storm event to draw down the reservoir from a level at or below the Environmental Design Flood (EDF level) to the Normal Operating Water Level (NOWL). In many cases, discharge from a pond can be subject to seasonal and environmental constraints, resulting in periods when water accumulates in the impoundment and these inflows must be managed between the normal operating level and the seasonal operating level. The design of the dam must be based on an appropriately detailed water balance, which can change over the life cycle.

Wave-freeboard, between the maximum flood water level and the dam crest, should be provided to prevent wave action overtopping the crest. It may be appropriate to add additional freeboard to allow for wind set-up in larger storages and for uncertainties of calculation, particularly if erosion has potential for embankment breaching.

There will normally be some minimum level of decant storage required to allow settlement of decant water or chemical equilibrium development prior to water removal from the TSF. Normally it is desirable to minimize the pond size and maximize the extent of tailings beach development.

### 5.12.2 Environmental Design Flood (EDF)

The Environmental Design Flood (EDF) is the flood that is to be managed without release of untreated water to the environment. Retention of water during the EDF requires storage capacity above the NOWL.

The selection of the return period and duration of the EDF must consider factors such as the water quality that is being stored and could be released, regulatory requirements, frequency of overflow events, the rate and duration of overflows, the environmental sensitivity of the receiving environment, downstream flow in the receiver, downstream mixing characteristics, and public perception on the matter. The selection of an appropriate EDF is therefore site specific and should be derived through:

- consultation with regulatory agencies
- consideration of environmental effects associated with the frequency, magnitude and duration of an infrequent release
- consideration of dilution that may be available from flood flows in the receiving water
- consideration of the costs associated with varying degrees of environmental control.

Typical EDF return periods range from 1 in 50 years to 1 in 200 years, but more stringent criteria may be required depending on the site conditions. The appropriate EDF duration is site specific and typically ranges from weeks to months depending on the assimilative capacity of the receiving stream and the capacity of the water treatment system to process the stored volume. An example of a method for assessing the EDF is contained in Appendix A.

If storm water is to be temporarily stored in the TSF without a spillway, then the dam design must be suitable for safe water storage. Upstream constructed dams may not be suitable for storage of water against the perimeter dam and may have a minimum beach width specified.

The maximum operating water level should be identified for each TSF. If the water in that dam reaches the maximum operating level, the deposition of tailings (and all process water streams), the relevant sections of the Trigger Action and Response Plan (TARP as described in Section 6.4) should be initiated.

### 5.12.3 Inflow Design Flood (IDF) and Freeboard

The inflow design flood is the most severe inflow flood (peak, volume, shape, duration, timing) for which the tailings dam and associated facilities (spillway) are designed to protect the dam from overtopping. The IDF return period is selected depending of the Consequence Category of the dam as described in Section 5.9.2 of this Bulletin and any additional owner requirements. An example of the selection of the IDF is presented in Appendix II. The IDF is typically conveyed from the pond via a spillway or equivalent overflow structure, however in some cases the IDF may be stored in the dam.

The IDF needs to consider the critical duration of the flood. It is also necessary to recognize that ground conditions during the extended rain events typically result in a runoff coefficient of 1.0. Where appropriate, water inflows due to snowmelt need to be included. Additional considerations include the functionality of the diversions during extreme events as they may be subject to erosion, landslides, ice jamming or other similar events.

For design of a spillway to cater for the IDF, it is normal to assume that the water level in the pond is at the invert elevation of the spillway prior to the design storm event. The functionality of water diversions around the TSF need to be assessed for extreme events which may exceed their design capacity. Functionality of diversions could also be reduced with snow/ice plugging or with erosion/landslide events. Typically, it is assumed that diversions are ineffective, especially during passive care closure.

If the IDF is stored in the TSF, then the design must allow for removal of the stored water over a realistic time period with the time period established by considering the draw down rate and the hydrology of the area (the likelihood of successive large storms).

As described for EDF storage, if the IDF is to be temporarily stored in a tailings dam then the dam design must be suitable for safe water storage and for upstream constructed dams, a minimum beach width is usually specified.

### 5.12.4 Water Balance and Water Recovery

A water balance model for the TSF is required to track the ongoing water losses and gains during the life of the facility and for optimizing the use of water. Tailings transport water is one of the larger components of the water balance with water loss to tailings voids often being the largest water loss and much of the remainder being recycled to the process plant or discharged to the environment, if appropriate. Water will also be lost through evaporation and/or seepage. Water gains may include runoff from the TSF catchment areas, groundwater inflow and precipitation. The TSF is also often used to attenuate water flows from other disturbed areas associated with the mine and these inflows need to be accounted for in the water balance.

Components of Water Balance to be considered include:

- Stream Management - The tailings area is often separated from the surrounding storm water streams to minimise flood design requirements, to maximise settling of tailings and to minimise the volume of water which may need special management due to water quality issues. Catchment areas above the tailings dam should be diverted as far as practical. The

design flow capacity of diversion works should relate to the relevant predicted flood flows and the need to protect the tailings dam from flood inflow. However, if the diversion works have limited capacity, then the consequences of overtopping need to be considered in the capacity of the tailings dam and its outlets. The potential failure of a diversion system is likely during extreme flooding and the added inflow to the tailings dam should be considered.

- **Precipitation** – Precipitation can be a major component of water inflow, with catchment runoff mixing with process water in the TSF. Run-off calculations should be made in accordance with normal hydrological methods. Run-off from the contributing land surfaces, either as direct or indirect (pumped) catchments, any tailings beaches and from the pond area itself, will need to be considered. In regions with highly seasonal precipitation, runoff coefficients need to take account of pre-existing soil moisture conditions. In regions with snow, runoff needs to consider rain on snow events and frozen conditions in the subsoil.
- **Tailings Decant Water** - Tailings consolidate as they are deposited with a significant portion reporting directly to the decant pond. It is commonly found that the increase in initial settled density is greater in sub-aerial deposition than in sub-aqueous deposition. As tailings dry, the capillary tension in the pores may cause major consolidation forces.
- **Evaporation** - Evaporation from tailings beaches and ponds can lead to significant water losses. Losses from ponds can be evaluated from pan-evaporation data using appropriate adjustment factors. A common assumption for wet beaches is to assume beach evaporation is equal to lake evaporation. Salinities above that of sea water may reduce evaporation significantly. More importantly, the formation of a salt crust on the tailings surface will create a barrier which slows further drying of the beach and impedes release of consolidation water.
- **Seepage** - Seepage will occur through the embankments, foundations and impoundment footprint. Seepage losses may not be significant in the overall water balance, but the environmental impact of contaminated seepage may be a significant factor.

## Water Recovery

Recovery of water may be achieved by a fixed or floating pump system or a gravity system. Floating pump stations allow flexibility of operation with water level changes being easily accommodated. Pump sizing may need to cope with volumes accumulated in severe flood events. Floating gravity decants or siphon decants can also be developed if adequate head is available.

Fixed decant structures are often used and typically comprise concrete or steel tower structures with controllable outlets at various levels. The structural design of tower decants should consider the potential down-drag forces applied to the structure by consolidation settlement of the tailings, seismic loading and other risks during operation. The design should address how the structure will be decommissioned on dam closure. Pipes through the embankment have been the cause of internal erosion failures under tailings dam embankments. If this type of outlet pipe is provided, particular care is needed in design and construction to reduce the risk of this type of failure.

### 5.13 Environmental Design

Environmental design of the TSF considers the potential effects of the TSF on the receiving surface and ground water quality, the potential for dust emissions and potential effects on fauna associated with the TSF impoundment water or beach. The Environmental Design Flood discussed in 5.12.2 of this Bulletin is established to protect the receiving surface water during operations. The groundwater aspects are discussed in Section 5.11.

Environmental design is an important component of closure to provide long term geochemical and ecological stability of the TSF (see Section 5.3 of this Bulletin). As discussed in Section 4.5, geochemical characterization of the tailings and process water is required to inform the design with respect to potentially permissible seepage rates and the closure plan.

Contaminants of potential concern that may be associated with the tailings pore water, with respect to the environment, should be identified. As a minimum, the process water quality should be compared against potential receiving environment water quality objectives. E.g. drinking water, aquatic life, etc.

Contaminants in groundwater may be subject to attenuation by various natural processes including decay, biological and/or chemical breakdown, retardation/absorption, dispersion, and dilution. Flow through unsaturated zones, particularly if the soils or weathered rocks have high clay content, is particularly important in this regard. Estimates of cyanide and metals absorption characteristics in soils may be augmented with laboratory scale tests.

A seepage analysis and an understanding of what rate of seepage may be acceptable for environmental purposes should be integrated into design of the dam and impoundment. The “allowable” seepage rate to the receiving environment should be estimated to support engineering design of seepage control measures. In some cases, it may be possible to base estimates of quality solely on the measured quality of decant water; however, it is becoming increasingly necessary to predict the fate of contaminants (contained within the tailings seepage water) in the surrounding environment. Input from specialists such as geochemists and hydrogeologists may be required.

A monitoring program for surface and ground water quality should be in place. Where water treatment for discharge is required, it is important to determine the quality of process influent and discharge water, criteria for discharge (quality and flow), design meteorological events, etc.

Air quality can also be a concern with respect to dust generation from a tailings facility and this must be considered in the design.

## 6 RISK MANAGEMENT

### 6.1 Overview

It is important that dam Owners and regulators recognise the potential losses and risks associated with each dam and that appropriate risk reduction measures are undertaken to limit them. Risk assessment methods should be used to evaluate specific tailings design and operational risks (individual or combined). The type of assessment that is chosen depends on the complexity of the risk, the criticality of the element under consideration (related to safety, health, environment, business continuity), the potential consequence of a failure, and the quantity and quality of available data. A risk assessment of a tailings dam should clearly identify the indicators of potential failures, either of individual elements, or in combination where several individual issues combine to result in a failure.

Risk assessment is the overall process of risk identification, risk analysis and risk evaluation. ISO/IEC 31010 provides guidance on risk assessment techniques.

Risk assessment is used in varying forms to evaluate specific tailings design and operational risks (individual or combined). The type of assessment chosen depends on the complexity of the risk, the criticality of the element under consideration (related to safety, health, environment, business continuity), the potential consequence of a failure, and the quantity and quality of available data. A risk assessment of a tailings dam should clearly identify the leading indicators of potential failures, either of individual elements, or in combination of individual issues result in a failure.

Quantitative risk assessment is frequently used by designers of high and extreme consequence category dams to quantify and evaluate the risk tolerability of specific elements or features of a tailings dam such as spillway capacity (ANCOLD, 2003).

Qualitative or semi-quantitative assessments are often used to rank and prioritise risk controls and risk action plans, or to demonstrate the risk associated with a combination of events e.g. fault event tree.

### 6.2 Risk Assessments

Qualitative or semi-quantitative assessments are used to identify and characterize the risks and control to reduce the risk. Combinations of events also need to be considered. The risk assessment should consider, as a minimum, the key potential modes of failure as outlined in Section 5.7 of this Bulletin.

A risk assessment/risk register that describes the failure modes, triggers, controls, and consequences should be developed in the early stages of design and be routinely updated during the design stages, operations and closure. The Risk Register should describe the likelihood of occurrence of a failure mode, the consequence of the event, and the effect of mitigating measures that might be implemented after the failure. The Risk Register can then be used to rank risks and identify critical controls needed.

### 6.3 Preventative Controls and Monitoring Options

Preventative controls are developed for potential failure modes and these are developed during the design of the facility and then updated during the construction and operation. If the failure, or unwanted material event, occurs there will be a consequence and mitigative controls are implemented to reduce the risk or consequence of the event. These controls need to be reviewed and monitored throughout the life of the TSF.

Monitoring of tailings dams is not limited to visual observations and instrumentation, but also includes ongoing design reviews as described in Section 2.1.4. The main categories of preventative controls for the main failure modes as described in Section 5.7 are summarized in Table 6-1, along with the key monitoring methods.

**Table 6-1 Tailings Storage Facilities –Example of Key Preventative Controls**

Main Failure Conditions	Key Preventative Controls	Examples of Typical Monitoring Methods
Foundation failure	Site Investigation	Peer review, External review boards, Dam Safety Reviews (DSR)
	Dam design	
	Pore Pressure monitoring/responding	Piezometers, seepage weirs, Dam Safety Inspections (DSI)
	Deformation monitoring/responding	Inclinometers, DSIs
	Design – static stability	Peer review, External review boards, DSR
	Design – seismic stability	
Dam slope failure	Material characterization	As-constructed records, Data records, DSI
	QA/QC	
	Design – static stability	Peer review, External review boards, DSR
	Design – seismic stability	
	Monitoring/responding to – pore pressure	Piezometers, DSI
	Monitoring/responding to - deformations	Slope surveys, Lidar, inclinometers, drones, satellite, DSI
Piping	Design - limiting hydraulic gradients	Peer review, External review boards, DSR, As constructed records
	Design - filter compatibility	
	QA/QC of filters	As constructed records, DSI
Overtopping	Design criteria	Peer review, External review boards, DSR
	Design -flood storage capacity	
	Design - spillway capacity	
	Monitoring/controlling water levels	Level recorders, cameras, DSI
	Monitoring width of beaches	Survey and visual assessment
	Monitoring/controlling flows	Flow meters, cameras, DSI
Decant	Design decant structure	Peer review, External review boards, DSR
	Operations and maintenance procedures	DSI, Camera surveys and deformation monitoring
	Monitoring/controlling flows,	Flow meters, DSI
	Design erosion controls	Peer review, External review boards, DSR

Main Failure Conditions	Key Preventative Controls	Examples of Typical Monitoring Methods
Geohazards and Erosion	Inspection and maintenance	DSI
	Design geohazard controls	Peer review, External review boards, DSR
	Monitoring slopes, snowpack, deformations	Satellite, Lidar, inclinometers, snow gauges
Water Contamination	Waste and water chemical characterization	Peer review, External review boards, DSR
	Design of seepage controls	
	Design of filters for ARD precipitates	
	Monitoring water quality	Peer Review, Real time sensors, e.g. pH, EC, Neutron probes, Lysimeters, Sampling and testing
	Monitoring water flows	Stream gauges, seepage collection weirs

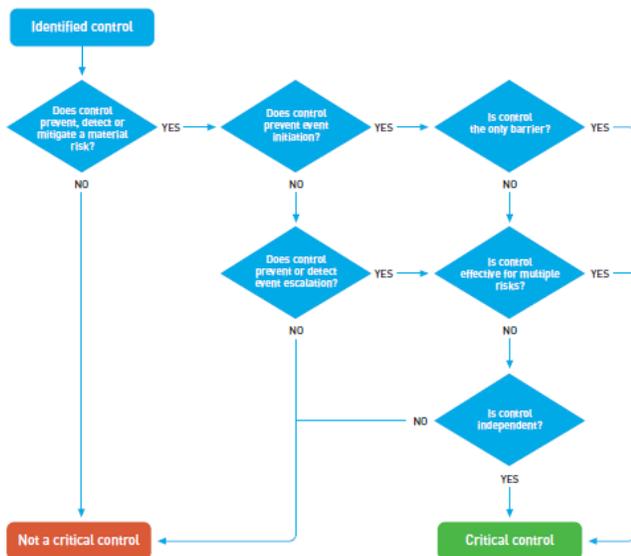
### Critical Controls

The key preventative controls indicated in Table 6-1 and other identified preventative controls should be assessed to determine if they are critical controls. A critical control is crucial to preventing an event or minimizing the consequence of the event. Key indicators for a critical control also include, for example:

- would the absence or failure of the control significantly increase the risk despite the existence of other controls? and,
- does it address multiple causes or mitigate multiple consequences?

A decision tree framework for selection of critical controls is shown Figure 6-1.

**Figure 6-1 Critical Control Framework (ICMM XX)**



Source: Adapted from BHP Billiton.

## Mitigative Controls

Mitigative controls are measures that may be implemented if a dam failure occurs. These measures could be implemented prior to failure, which could, for example, include:

- construction of deflector berms to direct inundation flows around critical facilities
- maintenance of a large beach width to minimize the potential for release of water in the event of a slump of the dam

Mitigative measures to be implemented prior to, or during failure could include, for example:

- construction of emergency spillways
- installation of emergency pumping systems to reduce stored water volumes
- placement of fill materials in the dam breach

## 6.4 Trigger Action Response Plans

NEEDS A DESCRIPTION

- Identify instrumentation/surveillance required for critical controls
- Quantify performance indicators, e.g. pore pressure levels with respect to factor of safety, allowable deformations, beach width, pond water levels, freeboard, etc.
- Identify response levels that escalate with decreasing performance of the TSF
- Identify responsible persons
- Link to EPRP

## 6.5 Monitoring Technologies

Monitoring technologies continue to develop and adapt to ongoing technological developments and improvements in application of the technologies to monitoring of dams. Not all technologies are applicable, and care should be taken to ensure that selected technologies are effective in monitoring critical controls and in providing information on the performance of the dam. For example, stress and strain monitoring in a dam may be of benefit in assessing how a dam has responded during earthquake loading. Table 6-2 provides a summary of some of the current monitoring technologies, and one should recognize that this is a continually evolving and improving field.

**Table 6-2 Summary of Monitoring Technology Examples**

Equipment Measuring Device and Methods	Parameters Measured	Application	Research / Experience
<b>Monitoring of Pore Pressures or Moisture Changes</b>			
Electric piezometers with telemetry to process plant or phone	Pore pressure and temperature	Monitor pore pressure changes due to loading and changes in hydrogeological conditions	Standard practice at many mines. Strings at multiple depths is preferred
TDR, Neutron Probes	Saturations levels and temperature		
Self Potential	Passive electrical method which is sensitive to the flow of seepage water	Electrodes are placed on the dam surface both for investigation and monitoring	Research and long-term field measurements have been performed especially in US, Canada, France and Sweden.
Distributed Fiber Optic sensing	Temperature and strain are measured in optical fibers using laser light.	Cables are installed in new or old dams for seepage evaluation using temperature and strain analyses to assess movements	Basic research since 1996 in Germany and Sweden. Further research especially in France, Austria, the Netherlands, UK and US. Challenges are calibrating measurements to site conditions.
<b>Monitoring of Deformations</b>			
Vibration Measurements	Dynamic response (modes and frequencies)	Long term monitoring of the integrity of concrete structures	Either forced or natural ambient loads are used for excitation. Change in dynamic response under the same loading conditions indicate changes in the integrity of the structure
Borehole Instruments (inclinometers)	Electro-Mechanical devices used to measure deformation	Devices are placed where movements/tilts may occur	Recent developments allow continuous monitoring both in vertical boreholes as well as longitudinally within the dam.
Settlement plates	Change in elevation	Monitoring of dam settlement	Common practice at dams sensitive to settlement and to understand the deformation and stress state of the dam.
Global Navigation Satellite System (GNSS)	Accurate distance measurements between orbits and sensor.	Local monitoring of movements.	Extensive research with improved accuracy for different applications.
Laser scanning and digital imagery	Accurate distance measurements using laser with high spatial resolution over surfaces	Provide a three dimensional geometric model of dam. Deformations can be detected by regular measurements	Technology continuously improving by lasers, sensors and digital image processing. Method is used in several countries as a normal procedure.
Satellite Synthetic Aperture Radar (Satellite SAR)	Photogrammetry method using Satellite images	Surveying of dams and impoundment and monitoring of	High resolution surface

Equipment Measuring Device and Methods	Parameters Measured	Application	Research / Experience
		movements at regular intervals	surveying method producing a digital 3-D representation of the surfaces
Ground survey Aperture Radar (GBInSAR)	Photogrammetry method using ground station images	Surveying of dams and impoundments and monitoring of short-term movements	High resolution surface surveying method producing a digital 3-D representation of the surfaces
<b>Monitoring of Stresses</b>			
Load cells	Stress	Monitor stresses at different locations in the dam	Applicable for high dams sensitive to stress and strain changes.
<b>Other Monitoring Technologies</b>			
Multi-beam bathymetry	Echo-sounding	Bathymetric survey of ponded water	High resolution underwater surveying producing a digital 3-D representation of the surfaces. Used on tailings ponds with a miniature submarine.
Drones and cameras	Visual record	Monitoring of spillways, beach lengths	Allows visual reconnaissance on a continual or periodic basis.
Seismographs (accelerometer)	Earthquake acceleration	Monitoring attenuation of earthquakes and the seismic response of the dam.	Common in high seismic setting.
Resistivity	Active electrical method that can detect changed material properties	Electrodes are placed on the crest or at the dam toe.	Research and long-term field measurements have been performed especially in US, Canada, France and Sweden.
Ground Penetrating Radar (GPR)	Detect changes in properties of near surface soil layers, localization of defects or voids in concrete structures	Non-destructive and rapid method based on measuring transmission time for radar signals reflected from or transmitted through a media	Localization of seepage zones, sinkholes and deterioration of cores in embankment dams. Monitor remedial grouting of dams. Limited survey depth
Water quality sensors	Electrical conductivity and pH	Monitoring water quality to optimize attenuation/mixing with receiving waters	

Note: Table adapted from: ICOLD Bulletin 158, Dam Surveillance Guide, circa 2007, Table 8.1 *General comments on the application of some methods for dam monitoring and investigations*

## 7 DAM BREACH ANALYSIS

### THIS SECTION IS BEING REVIEWED

A key purpose of Dam Breach analysis is to determine the consequence of failure of the dam, which is used to support the Consequence Classification (Table 3-1) and emergency planning (Section 8 of this Bulletin). The process starts with identification of credible failure modes and development of breach and runout inundation models that can support estimates of runout inundation and the flow behaviour of the tailings during the dam breach.

The consequence assessment may be developed to various level of details depending on the purpose of the consequence assessment (TSF classification, Emergency Panning, Risk Assessment), the stage of the TSF project and the magnitude of the potential losses.

- TO REFER TO CDA TECHNICAL GUIDANCE ON DAM BREACH THAT IS IN PROGRESS
- TO ADD IN DISCUSSION ON HOW TO CONSIDER CREDIBILITY OF THE FAILURE MODE FOR DAM CLASSIFICATION AND EMERGENCY PLANNINGS

### 7.1 Credible Failure Mode Assessment

The dam breach assessment should be based on credible failure mechanisms that even though the likelihood of such an event is extremely low it is conceivable that it could happen. A credible failure mode assessment identifies conceivable (credible) events and failure modes that could result in a breach of the dam. The modes are typically related to floods, earthquakes, site and operating conditions.

Dam failure modes need to consider technical aspects such as the dam materials, foundations, abutments and the impoundment footprint and catchment area, as well as human aspects that could compromise the structural integrity of the dam. Such human aspect can, for example, range from mismanagement of the decant pond level and freeboard to a civil unrest that prevents access for maintenance and safe management of the TSF.

### 7.2 Dam Breach Assessment

The main objective of the tailings dam breach analysis is to map the extent of the flooding and tailings transport downstream of the dam. A key input to this mapping is estimating the amount of water and tailings that can be released and the rate of the release.

Dam breach analyses for tailings dams were traditionally based on the methodologies developed for water dams. However, different types of tailings have different properties that influence their behaviour. Dam breach analyses is an evolving science that continues to advance with our understanding of the mechanisms of water/tailings flow and static and seismic liquefaction. The principles outlined in this section of the bulletin should be used to guide the dam breach assessment for application today recognizing that ongoing developments will continue to improve the technology and allow updates to the assessments in the future.

## 7.3 Determination of the Consequence Classification of the Dam

The consequence classification is used to inform the seismic and flood criteria and, therefore, the dam needs to be tested against extreme events to assess what could happen under such events. Two conditions are typically considered.

A “Sunny Day” or “Fair Weather” event that would typically consider a failure triggered by a slope/foundation instability, piping or an extreme earthquake, and is used to determine the seismic design criteria. The potential extent of deformation or liquefaction of tailings or foundation soils should be incorporated into the consequence of failure. The normal operating pond water volume should be used unless it can be demonstrated that the dam breach would not reach the pond level, then it may not be necessary to assume that the pond is released during this analysis.

A “Flood Induced” or “Rainy Day” failure that could be triggered either by an extreme flood or by a series of smaller events and is used to inform the flood classification and the inflow flood design criteria. The failure mode triggered by the flood could be combinations of overtopping, piping, or slope instability. The volume of water accumulated varies between TSFs that store the flood or TSFs that have operating spillways. For TSFs that store the flood, the volume of water considered for the dam breach should be the total volume that could be expected to be stored during the extreme flood event. For TSFs that have spillways the water volume could be determined by the maximum water level during the extreme flood event.

The “Flood Induced” analysis is also done to determine the incremental effects of a failure on the downstream environment when there is a flood already occurring in the downstream environment. In some cases, the flood can already cause significant damage in the downstream environment and lead to evacuation of people to higher ground, without the dam failure. For this reason, the dam breach analysis should consider several flood events (from average conditions to PMF conditions) to arrive at the most significant incremental losses due to the dam breach, which would set the dam classification. The determination of the concurrent flooding for the flood-induced failure needs to be undertaken by a suitable qualified hydrologist who is familiar with the local climatic conditions.

It is important to note that once the consequence classification is completed additional dam breach analysis is required, based on the corresponding design criteria, to determine the inundation zones for purposes of assessing the impact of a potential failure and to prepare emergency response plans.

## 7.4 Dam Breach Methodology

### 7.4.1 Dam Breach Mechanisms

Dam breach analyses for tailings dams can include three main mechanisms of flow, and combinations of them, that consider:

#### Water transported tailings:

Tailings will be transported by the release of stored water until the density of flow increases and tailings will then flow as a “mud-flow”, similar to a landslide flow, which can limit its mobility. For example, a back-analysis of the recent Mt. Polley (2014) failure indicated that approximately 1 m<sup>3</sup> of

tailings was transported for each 1 m<sup>3</sup> of stored water. Additionally, there was a limited mud flow runout near the dam breach and the residual tailings slopes in the TSF were up to 2H:1V.

The volume of water/sediment flow is also influenced by lower density tailings which occur in the top few meters of many impoundments.

#### Static liquefaction and mudflow:

The state of practice for estimating if static liquefaction will occur during a dam breach is evolving. Case histories of dam failures show a broad range of potential “mud-flow” behaviour. The susceptibility to liquefaction and the runout flow behaviour are determined by the properties of the tailings, such as the liquidity index, viscosity and brittleness index, with the recent Brazilian iron ore tailings failures (Fundao, 2015) and Brumadinho (2019) as examples of extreme sensitivity to static liquefaction.

#### Seismic liquefaction

Saturated tailings can liquefy under seismic loading. Case histories from seismic failures suggests that the tailings flow out to slope on the order of 3% to 10%. However, the actual geometry will be influenced by the seismic loading and the tailings properties.

### **7.4.2 Dam Breach Modeling and Inundation Mapping**

Dam breach modeling should be carried out for both the *dam failure* and *overtopping* scenarios. Overtopping scenarios can consider different flood conditions in the receiving environment to assist in comparison of the overtopping failure with natural flood events.

Numerical models that can model the full range of water/sediment runout and mudflow runout are evolving and often the dam breach mechanisms are modeled separately, resulting in assessment that involve a minimum two-step process which includes:

- Use of a water/sediment transport flow model which treats the water/sediment as a Newtonian fluid. The extent of water/sediment release however is constrained by the volume of water that can transport the tailings as discussed in Section 7.4.1.
- Assess the potential for static and (or) seismic liquefaction during the dam breach and use non-Newtonian landslide models to assess the runout based upon the potential viscosity, brittleness and residual shear strengths of the tailings. Use numerical models or empirical methods for predicting runout slopes.,

Quantitative dam breach models for the water and sediment flow typically use numerical models. The breach formation is a function of the available water volume, the tailings beach parameters and the dam fill parameters. The turbulent flow of tailings and water with a dynamic and directionally dependent viscosity, interacting with and changing the flow boundaries (i.e. erosion of downstream channel) is a very complex process. Although the theoretical basis of these complex interactions is understood, the numerical complexity of the problem exceeded the computational limits at the time of writing this bulletin.

The flow of water and sediment flow can be modelled with commercially available software that continues to improve and tries to also better capture the sediment component of flow and potentially, with time, should capture the breach formation and mud flow components more effectively. The inundation outflow is overlaid on a digital ground surface model and estimates of flow rates, velocity and spatial distribution of the runout are developed.

When this bulletin was being prepared, there was no accurate and generally accepted numerical model for estimating the full behavior of TSF dam breach outflows. A sensitivity assessment should be included in the dam breach analyses to verify the magnitude of the breach flow depending on the key input parameters and to verify the credibility and reasonable conservatism of the dam breach model.

Mud flow models have been used extensively for landslide assessments and there are some commercially available programs. However, the application of these models and their interaction with the water/sediment flow model and modeling of complex systems that include liquefied layers continues to evolve.

A semi-quantitative assessment may also be appropriate for preliminary assessment of the consequence classification recognizing, for example, that dams classified as Low or Significant may not warrant a detailed numerical assessment. The assessment of an overtopping failure could determine the potential volume of water/tailings transport and assume a breach time to determine an average flood flow for the downstream inundation zone. The assessment of a dam slope failure could consider empirical correlations and estimates of maximum deformations and or slumping during different failure modes.

## 8 EMERGENCY PREPAREDNESS AND RESPONSE PLANNING

### 8.1 Summary

An emergency on a tailings dam is any event or situation that could compromise dam safety or the safety of individuals in the vicinity or compromise the ability of the TSF to fulfil the function for which it was intended. Frequently, an emergency is the result of a combination of circumstances that require intervention either by management or external resources.

An emergency could be initiated either by natural causes beyond the control of the operator (e.g. extreme flood or earthquake), or by operational issues (pump failure, pipe burst, etc.). In either event, intervention is required. Depending on the severity of the event and risk associated with it, reporting and intervention will need to be escalated to the appropriate level.

Every TSF dam must have an Emergency Preparedness and Response Plan (EPRP) which documents the potential failure modes of the dam and the measures required to address various levels of severity. Communication plans should be prepared for each level of severity.

Levels of severity of an incident on a tailings dam can be prioritised into the following risk categories:

- Risk level 1: Everything is normal and under control.
- Risk level 2: A non-conformance exists but the normal operating resources can manage the situation, commonly addressed with TARPS.
- Risk level 3: A non-conformance exists and appears manageable, but requires external resources to be engaged to manage the situation
- Risk level 4: A non-conformance exists which may not be readily manageable and may pose immediate risk to the integrity of the TSF and community. Response activities are initiated. Emergency notification to employees and community may be initiated.
- Risk level 5: Situation is out of control. Full emergency evacuation to be initiated

All employees engaged on the operation of a tailings dam should be trained to recognize unusual situations, and to understand that any deviation from normal operation could result in an emergency requiring that appropriate action be taken. Actions to be adopted for Risk levels 1 and 2 are covered under normal Operating, Maintenance and Surveillance (OMS) procedures, while incidents of Risk Level 4 and 5 should be covered in the EPRP. Risk Level 3 activities overlap both the OMS and the EPRP.

The EPRP should detail the hierarchy of reporting and should delegate responsibility for actions to be implemented to specific individuals or entities. The EPRP should include contact details of all persons or organisations affected or required to take actions and should identify specific assembly areas to be used in the case of evacuation. All assembly areas must be easily accessible and clearly demarcated.

As a minimum the EPRP should document the following steps to be taken as appropriate for each level of risk:

- Provide a summary of the dam (height, volumes) and plan of the TSF and the downstream inundation area in the event of a dam failure for sunny-day and rainy-day conditions.
- Provide procedures for engagement with local authorities, emergency services, the affected community and other stakeholders on dam safety, procedures and EPRP plans.

In the case of extreme events, the EPRP should document the establishment of a crisis control center (location, personnel involved and their roles, communication, emergency power source, food, water, rescue equipment and transport, media releases, family notification, etc.).

## 8.2 Emergency Preparedness Activities

### 8.2.1 Engineering

- Perform Failure Modes and Effects Analysis and evaluate plausible failure modes.
- Identify potential failure modes and features that could be a precursor to or an indication of a potential incident e.g. cracking, slumping, seepage, inadequate freeboard, abnormal weather etc.
- Determine appropriate responses to non-conformances at each risk level.
- Look for ways to minimize the extent of the flow and impacted area (should be a part of the critical mitigating controls).
- Prepare a mitigation plan (e.g. removal of released tailings and stabilization of the existing failed facility, stockpiling of construction materials, resourcing pumps, raising the dam, etc. Where the design flood is stored, assess potential locations for construction of an emergency spillway and identify the resources and time required to construct the spillway
- Develop dam breach and flood inundation studies for the plausible large-scale failures. Develop maps of the inundated area, time for the flow to reach key areas and depth of the flow.

### 8.2.2 Operations and Management

- Identify an emergency plan owner, who is responsible for preparing, maintaining the plan current and for performing the training and drills.
- Identify roles and responsibilities and command/decision-making structure.
- Identify safe higher ground locations for the people to evacuate to in an emergency. Place signs to guide the people to these locations. Perform training to simulate evacuation and adjust the plans as appropriate. Consider day and night scenarios.
- Establish warning/alert system (sirens, cell phones, etc.). Test the system.

- Identify trigger mechanisms that require that emergency services or community should be notified, with procedures for disseminating information and/or communicating warnings.
- Identify a location to set up an emergency command centre. List the required items and where they will come from (e.g. speaker phones, generator, portable printers, fuel, paper maps, light, water for drinking, food, etc.).
- Identify other equipment that may be required (vehicles, drones, helicopters, lighting, blankets, first aid, etc.). Prepare necessary permits (e.g. for flying the drones).
- Prepare a list of agencies and people (internal and external) to call, including experts in emergency situations, grief counsellors, people to answer calls from the communities, hospitals/doctors, suppliers of food and water, etc. Also, who will provide updates to the press and how.
- Identify accommodation where evacuated people can be taken to.
- In a case of hazardous tailings, prepare a list of instructions for safe handling and treatment of injuries.
- Implement a system for tracking the people who could be impacted by a potential failure (usually the workers), how they can be contacted and what to do if they are not responding.
- Identify roads for access to potentially impacted areas, locations where road closures may be required and road detours.
- Review the existing monitoring network and identify what additional monitoring could be required in an event of a failure. This should include environmental monitoring of the impacted area and monitoring of the physical stability of the failed facility and other facilities that could be impacted by the failure (e.g. bridges, roads, pump stations, pipelines, etc.).
- Complete training for key personnel at least on an annual basis to make sure they are familiar with the above. Adjust the plans based on the learnings from drills and training.

### 8.2.3 Emergency Response Plan (ERP)

The ERP should be prepared based on the outcome of the emergency response activities described above. It should list the steps to be followed during an emergency (large scale failure of the dam is eminent or is in progress) and contain the necessary information to allow quick reaction.

ALSO NEED TO ADD TESTING

## 9 CONSTRUCTION

### 9.1 Introduction

The objective of construction is to construct the facility to meet the project specification and the design intent. Construction management, technical supervision and quality assurance/quality control (QA/QC) are essential to ensure that this objective is met. The requirements for successful construction management apply equally to initial construction and any subsequent stages or raises. Construction must also meet all regulatory requirements.

For upstream dams, the management of tailings discharge may need to achieve various targets for beach development, including, layer thickness, surface profile and shape in relation to the decant pond. In this case, it is important that construction is planned and managed to ensure that the tailings discharge plan and the required parameters are not compromised.

The responsibilities for technical direction and documentation of the works need to be fully defined prior to the commencement of construction as discussed in the following sections.

### 9.2 Supervision and Documentation

#### 9.2.1 Engineer of Record (EoR)

The EoR is responsible for the design, documentation and specification of the tailings dam construction works and needs to be involved in construction. The specification should include definition of the QA/QC requirements for construction and the appropriate means of dealing with non-conformance. It is preferable that the Designer should also be the Engineer of Record (EOR), but where this is not the case, the EOR should have a defined relationship to the Designer to allow ongoing interaction to ensure the design intent is achieved and that any potential changes to site conditions and/or potential design considerations are communicated to and acted upon.

The EOR is responsible for the technical direction of the work and should certify that the tailings dam has been constructed in conformance with the design and specifications. The usual regulatory requirement for construction certification is that the works have been executed in accordance with the design intent. It follows that all design changes required during construction must be approved by the Designer and documented either by notes or revisions to construction drawings.

If not personally on site during all the construction period, the EOR should be represented by an Engineer's Representative or Resident Engineer who will carry out the technical direction of the work under the direction of the EOR. Technical direction comprises interpretation of the design and specifications and review of site conditions and materials to ensure that the intent of the design is implemented. Site conditions often vary from those assumed during the design and it is important that these variations are recognised, accommodated and documented during construction. Construction inspector(s), reporting to the EOR or Resident Engineer should be used when the complexity or importance of the work warrants it.

Visual inspection of works can be significantly more effective than random sampling and testing in maintaining the quality of workmanship and supervision by experienced personnel is recommended practice.

### 9.2.2 Quality Control/Quality Assurance

Quality Control (QC) comprises inspection of the work and testing of materials to verify compliance with the specifications. This work comprises testing of potential borrow areas, filter materials, concrete aggregates etc., inspection of membrane liners, pumps, pipelines etc. during or soon after manufacture and prior to installation or incorporation into the works. The QC work may be done by the EOR or an independent testing company who reports to the EOR. Irrespective of the size of the project, as a minimum, earthworks should be subject to geotechnical testing and test methods should be in accordance with the methods set out in relevant National or International Standards.

Quality Assurance (QA) comprises management of the design, construction and operation process to ensure that the systems in place deliver the quality objectives of a project that meet the specifications and design requirements. QA should be carried out by the EOR or his/her designate and should also include assessing the overall site conditions and construction to assure that the design intent is being achieved.

A Site Inspection Manual that presents QA methodology and the types and frequency of QA/QC test work, inspection, recording and reporting requirements, in accordance to the construction specification, should be prepared, maintained and amended when required. The Manual should include a site organisation chart showing lines of communication and responsibilities for the construction management team. The manual should include protocols for acceptance and rejection of components of the work, and re-work and re-testing requirements.

### 9.2.3 Construction Site Management

There are several ways in which the construction of a tailings dam can be carried out. These include:

- Tailings dam constructed by owner using mine equipment or by direct hire
- Tailings dam constructed by contractor, and
- Tailings dam constructed by combination of contractor and owner.

There will be subtle differences in the construction management structure in each case, but it is critical that the EOR has a role in each of them.

The size of this management team depends on the size and level of complexity of the construction project. A large tailings dam development may require a significant team comprising a Resident Engineer, project engineers and inspectors, and a site laboratory for materials testing. A separate construction management team may be required comprising an owner's representative, contract manager, quantity surveyors and cost control personnel. The lines of authority to ensure that the technical requirements of the tailings dam construction are met, need to be established and recorded in the Site Inspection Manual.

### 9.2.4 Construction Verification and Records

The EOR should be responsible for signing off on the final completion of the construction phase. This could be undertaken in several steps with a thorough review of construction records and issue of a Certificate of Practical Completion and “punch-list” of outstanding items produced when construction is substantially completed. Final Certification will occur once the punch-list items are completed.

Recording of comprehensive construction records is vital to ensure that data is available for future designers, operators or construction personnel. The documentation normally takes the form of a Construction or As-Built Report. This report should describe the construction in detail and present the results of inspections, testing, survey and certification of achieving the design intent. An example of a typical Construction or As-Built report is show on

**Figure 9-1 Example of Table of Contents for a Construction or As-Built Report**

CONSTRUCTION REPORT TABLE OF CONTENTS	
1. Introduction	5. Health & Safety
2. Contract Overview	6. Environment
2.1 Tendering Process	6.1 Water Quality
2.2 Award of Contract	6.2 Rehabilitation Works
2.3 Contract Administration	7. Financial Performance
2.4 Construction Programme	7.1 Lump Sum
2.5 Practical Completion	7.2 Security Money
3. Contractor’s Plant and Personnel	7.3 Progress Payments
4. QA/QC Documentation, As-Constructed v’s Design	7.4 Variations
4.1 Foundation Preparations/mapping	7.5 Extra Works
4.2 Embankment Geometry	
4.3 Zone 1 Earthfill placement and testing	<b>Appendices</b>
4.4 Filter Layers - placement and testing	A Survey Data
4.5 Zone 3 Rockfill. - placement and testing	B Photographic Record
4.6 Zone 4 Rockfill - placement and testing	C QC data records
4.7 Crest Road - placement and testing	D As-Constructed drawings
4.8 Spillway & Spillway Channel description and summary of QC tests	E Certification Documents
4.9 Infrastructure - decant/pipelines/pumps	
4.11 Instrumentation	

## 10 OPERATIONS

### 10.1 Overview

Operation of tailings dams should be in accordance with approved procedures, documented in an Operations, Maintenance and Surveillance Manual (OMS Manual). The manual should outline all designer requirements for operation, maintenance and dam safety surveillance that must be met to ensure the ongoing safety and effective operation of the TSF. The OMS Manual should also reference or include an Emergency Preparedness and Response Plan (EPRP) to assist sites prepare for and deal with an emergency incident if one occurred.

The Owner should ensure that the tailings dam is operated by an appropriately experienced team. For EXTREME, VERY HIGH and HIGH Consequence Category dams, the team should include a professionally qualified civil or geotechnical engineer. Operators should be appropriately trained for their roles with regular refresher training.

It is most important that the Owner is aware of the consequences of failure of the dam, and their legal responsibilities to ensure that proper and adequate attention is given to the management of risks. It is the owner's responsibility to ensure that adequate funds and resources are provided to allow staff to establish and maintain the required level of rigor in operating and maintaining the TSF.

### 10.2 Operations Plan

The objective of the operational phase of a tailings dam is to develop the storage in such a manner as to ensure that the tailings facility is:

- maintained in a safe and stable state and in accordance with prescribed risk management specifications
- operated in accordance with the requirements of the Design Basis Report and OMS Manual
- operated in accordance with legal requirements
- operated to achieve prescribed environmental objectives, and
- operated in accordance with the closure plan and intended use after closure.

The operation of the TSF should achieve the following objectives:

- control distribution of the tailings to achieve the required geometric shape of the deposit, to maintain ponded water within the specified position and to manage beach development
- control the level and position of the stored water to maintain freeboard
- control the flow and discharge of storm water to prevent damage
- control access so that only those persons authorised to gain access for the purposes of operation and supervisory management can do so
- optimise the recycle of water from the TSF
- keep uncontaminated water separate from contaminated water, and
- control dust during windy conditions by more frequent deposition to create maximum area of wet beaches and by control of traffic in the area.

### 10.3 Operations, Maintenance and Surveillance Manual

An Operation, Maintenance and Surveillance (OMS) Manual should be completed normally prior to commissioning of a tailings dam and updated throughout the life phases. Operational Management Plans within the OMS Manual should specifically highlight all designer requirements for operation and response actions that must be met to ensure the ongoing safety of the dam.

The Operation Plan should include, as a minimum:

- Description of the TSF, expected nature of the tailings, production rate, life of mine plan, dam type, dam raising schedule, etc.
- Roles and responsibilities of key personnel and organization chart
- Dam consequence classification and key design criteria (geotechnical, water management, environment);
- Deposition plan: spigot discharge locations, beach management, etc.
- Water management: requirements for managing diversions, pond size/location, reclaim and discharges, freeboard management, decant systems, pump barges, etc.
- Environmental controls: e.g. seepage collection, water discharges, dust control, etc.
- Surveillance requirements for dam inspections
- Risk assessment register
- Summary of preventative controls
- List of Critical Controls and trigger action response plans
- Maintenance requirements for pumps, pipelines, channels, etc.
- Training requirements for key staff
- Summary of the emergency preparedness and response plan (EPRP) and links to the document.
- Document management plan

The OMS Manual should specify all requirements for operators and the minimum level of operator training. The Manual should include a section dedicated to information specifically required by field operators, with the operators themselves preferably involved in preparation of this section. The operator's section should be able to be printed as a stand-alone document and used by the operators for guidance to their daily work.

OMS Manuals for tailings dams should be updated at least every two years with the whole tailings facility management strategy reviewed to see if there are better ways of achieving the facility's objectives. More frequent updating may be required if there are changes to personnel, operating methods or storage arrangements. A typical table of contents for an OMS manual is shown on Figure 10-1.

**Figure 10-1 Typical Table of Contents for an OMS Manual**

<p><b>1 TSF Description</b> Overview Summary of design, site description, life of mine, infrastructure Design criteria summary and consequence classification</p> <p><b>2 Governance</b> Roles and responsibilities Change management Incident management Documentation and tracking Training</p> <p><b>3 OMS Activities</b> Summary table of key activities covered in the Manual</p> <p><b>4 Operations</b> Deposition requirements (beaches, spigotting, cycloning) Freeboard, water levels and water balance procedures Construction schedule and controls Environmental controls Unusual operations</p>	<p><b>5 Maintenance</b> Maintenance programs Tailings pipelines Water reclaim system Water diversions and ponds Dam(s) Testing of control equipment</p> <p><b>6 Surveillance</b> Risk register Preventative controls Critical controls Dam instrumentation Visual inspections TARPS</p> <p><b>7 Emergency Preparedness</b> Escalation procedure and response to TARPS Link to Emergency Response Plan</p>
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## 10.4 Engineering Aspects of Operations

### 10.4.1 Tailings Deposition and Water Management Plan

The tailings deposition plan should document the tailings discharge procedures, such as numbers of spigot discharge points and timing, and the requirements for managing the shape of the beaches to manage the decant water pond and to meet beach width requirements for the dam. The deposition plan should be integrated with the requirements for water management, freeboard and construction raising of the dams. Where saturated beaches are required for dust control or mitigation of potential oxidation of sulphidic tailings, procedures should be documented.

The water management plan described in the OMS manual must clearly identify the critical water levels, particularly where stormwater needs to be contained within the storage and minimum beach widths are required.

TSFs must not be operated with water levels that are outside the limits defined in the facility water balance and the OMS manual. Where TSFs have a volume of water stored outside the limits defined in the facility water balance or OMM (such as due to storm surges and/or upset conditions), a risk assessment must be completed with participation from the EOR to identify the additional risks

resulting from excess water storage. In such cases, actions would need to be taken immediately to remove the excess water.

In some cases additional water storage may be required to limit sulphide oxidation. In such cases, attempt must be made to limit the volume of stored water and the facility must be designed to safely accommodate the additional water.

Water management infrastructure is required to safely manage the predicted variability in water flows and volumes, and to control the risk of catastrophic failure or release of contaminated water.

#### 10.4.2 Dam Raising

Tailings dams are often progressively raised during operation. Such raising should not increase the risk of operating the dam and needs to consider prevailing weather conditions during raising (flood risks, wet weather, cold weather) and geotechnical parameters. The interaction of construction work with tailings discharge needs to be coordinated to ensure there is no conflict, which may increase the risk of tailings spill or interrupt the schedule of discharge required to achieve the required density of tailings and other specified properties.

Upstream and centre line tailings dams require the highest level of design input, operator skill and owner diligence in order to maintain their stability. They also need to be subject to strict design and operational constraints to ensure their ongoing safety with the following critical operational issues highlighted for the consideration of dam owners and their designers. Section 6.4 describes the process for TARPs and how they should be utilized. The TARPs are a key component of an OMS Manual.

### 10.5 Monitoring and Surveillance

The operational procedures for the TSF should include provisions for surveillance (i.e. regular inspection, monitoring and evaluation) and documentation thereof. Conditions can develop during operations, which, if not detected early, could lead to loss of containment or unsuitable conditions for undertaking plans for extension or closure of the facility. Requirements for dam inspections and reviews are summarized in Table 10-1 and Table 10-2. Guidance on reviews is also included in Section 2.1.4 of this Bulletin.

**Table 10-1 Dam Safety Inspection/Review Levels**

Type of Inspection and Reviews	Personnel	Purpose
Comprehensive Dam Safety Review	Independent Engineer and Specialists (where relevant)	Independent dam safety review. The identification of deficiencies by through onsite inspection; by evaluating surveillance data; and by applying current criteria and prevailing knowledge. Equipment should be test operated to identify deficiencies.
Dam Safety Verification	EoR	The identification of deficiencies by visual examination of the dam and review of surveillance data against prevailing knowledge. Equipment is not necessarily operated.

Type of Inspection and Reviews	Personnel	Purpose
Routine	Operations personnel / inspector	The identification and reporting of deficiencies by field and operating personnel as part of their duties at the dam.
Special	EoR and Specialist	The examination of a particular feature of a dam for some special reason (e.g. after earthquakes, heavy floods, rapid draw down).
Emergency	EoR and Specialists	The examination of a particular feature of a dam which has been identified as having a possible deficiency or which has been subject to abnormal conditions.

**Table 10-2 Typical Frequency of Inspections and Reviews**

Dam Failure Consequence Category	Inspection Type			
	Comprehensive Dam Safety Review	Dam Safety Verification	Routine Inspection	Special
EXTREME, VERY HIGH and HIGH	After first year of operation, then 2-3 yearly	Annual	Daily high-level, weekly detailed	As required
SIGNIFICANT	After first year of operation, then 5 yearly	Annual	Twice Weekly high-level and fortnightly detailed	As required
LOW		On first filling then 5 yearly	Monthly	As required

In ensuring effective surveillance of tailings dams, the Owner should select suitable operational staff and arrange for their training in the areas of dam safety management with regular refresher courses to keep operators up to date with current practices. As part of that training, operators should be capable of recognising abnormal conditions and circumstances that could affect the safety of their dams and be able to institute appropriate actions including when to call for more expert assistance.

Inspection and monitoring of the dam by trained staff should be carried on a frequency commensurate with the complexity of the operations, the consequence classification of the dam and in accordance with the EOR’s requirements. The items that need to be monitored and the relevant associated instrumentation should be designated by the EOR to enable a suitable coverage of the aspects that affect the ongoing safety and operational performance of the facility.

Ongoing recording of inspection findings, monitoring instrument readings, and any incidents is essential for TSFs. Attention is drawn to ICOLD (1996) “Monitoring on Tailings Dams” which deals with the monitoring of tailings dams during construction and operation.

Records should be kept in an accessible, secure repository and in an organised form covering:

- Groundwater monitoring with special emphasis on the environmental impacts of the tailings dam on groundwater (e.g. geochemical processes)
- Surface drainage and seepage monitoring, both visual observations and seepage measurement are required as a minimum, with chemical analysis also of value (e.g. acid drainage generation)
- Capacity monitoring (tailings, process water, water recovery, evaporation)
- Tailings monitoring (e.g. beach development, drainage, density, desiccation)
- Monitoring of instrumentation and instrumentation readings
- Monitoring of equipment and pipework
- Monitoring of dam movements, stresses, cracking and seepage
- Inspection reports (i.e. times, dates, observations)
- Incident reports (i.e. time date, nature, actions), and
- Annual audit.

The monitoring reports must be reviewed by the EOR, or his/her designate who should provide written confirmation that the facility is operating within the design constraints. Unusual or unexpected monitoring data must be immediately shared with the EoR and appropriate actions implemented.

## 10.6 Governance Aspects of Operations

### Independent Operational Reviews

Formal technical reviews/audits should take place at regular intervals as discussed in Section 2.1.4 of this Bulletin. The reviews and audits should be undertaken by appropriately skilled personnel and documented. Effective management procedures are required to ensure that the outcome of the inspections, monitoring and audits are reported to the EoR and the relevant constructors, operators and regulator. Any necessary changes should be confirmed as having been carried out.

### Incident Management

An Incident Management Procedure should be in place. All significant incidents and/or non-conformances in the operations of the facilities must be investigated and recorded along with actions, accountabilities and schedule for mitigation. A significant incident or non-conformance is one that would have a material impact on the operation, cost or risk level of the facility.

Significant incidents and non-conformances identified in the monitoring, observations or reviews of the TSF must be reported to the EOR.

### Management of Change

A formal Management of Change (MoC) process must be carried out where significant changes are proposed to the design during construction and/or operation of the facility including change of consultant. The process must consider potential change in risk due to increased likelihood of impacts

on production, long term costs, safety, and/or regulatory non-compliance. Changes must be reviewed by the Design Engineer and changes accepted must be incorporated in the OMS manual.

### **Emergency Action Plan or Dam Safety Emergency Plan**

The OMS should provide a link to the Emergency Response and Action Plan (EPRP) discussed in Section 8 of this bulletin. The transition from escalation of TARPs from operational aspects to emergency response should be clearly described and key aspects of the EPRP should be summarized in the OMS manual. Operations should run simulations on emergency scenarios to confirm EPRP provisions and train staff at regular intervals.

## **10.7 Maintenance**

Appropriate maintenance must be carried out to ensure ongoing dam safety. In addition to normal maintenance of plant and equipment, it may be necessary to maintain the structure of the tailings dam with repair of cracks and/or erosion rills, grading of roads and various other matters. The principle in determining maintenance priorities is to attend to all items that affect the structural integrity first, followed by environmental items and then by conventional maintenance.

DRAFT

## 11 CLOSURE

Closure of a TSF (ICOLD, 2013) is defined as *the planned final cessation of tailings disposal and the modification/engineering of the tailings dam with the objective of achieving long-term physical, chemical, ecological and social stability and a sustainable, environmentally appropriate after-use*. This includes transferring the tailings dam from the operating phase to closure and ultimately through post-closure into the long-term phase that is sustainable and with minimal risks and requirements for supervision.

Physical stability refers to the suitable long-term integrity of the water management works, dam slopes and impoundment areas. Geochemical stability relates to the effective containment of environmental contaminants and minimization of potential effects on surface and groundwater quality. Ecological stability refers to the establishment of sustainable flora and fauna habitat and/or transition to productive land use that is acceptable to the local communities. Social stability means the minimization of risk to society and transition to productive land/water use and a facility that is societally acceptable.

As the tailings dam is developed over time, the construction and operation of the facility should progress towards the final closure conditions. Closure may occur over an extended period of time and can be characterized by three stages, each with a different time frame depending on the tailings facility characteristics:

- Transition: Following cessation of mining, closure works are constructed and monitoring of the performance of the closure works is carried out to inform the transition to Passive Care closure.
- Active care: During this period, the TSF is being maintained, ongoing water treatment may be required to assure environmental protection.
- Passive care: At this stage the TSF requires minimal or no maintenance and could be described as a 'land-form' with similar characteristics as other natural features. At this stage the dam could be described as "not a dam"

At the end of mine life, conservative closure spillways should be provided to account for the timeframe of the expected closure period. Plugging of closure spillways by debris, trees, ice, or animal activity (such as beavers) must be addressed. Ideally, closed facilities should have minimal capacity to store water, which greatly reduces the risk of overtopping and catastrophic failures (both likelihood and consequences).

The freeboard at closure should consider potential settlement of the embankment due to long term settlement and earthquake induced deformation. For the post-closure design period, the impact of multiple events should be considered. This could include cumulative settlements from several earthquakes smaller than the design earthquake.

It may be possible to convert a tailings dam to a structure that no longer needs to be considered as a dam. If there is no water on the surface and the tailings cannot "flow" if the perimeter containment is eroded, then the perimeter containment no longer needs to be considered as a dam.

## REFERENCES (INCOMPLETE)

ANCOLD, 20XX.

ICOLD, 2013. ICOLD Bulletin 153. SUSTAINABLE DESIGN AND POST-CLOSURE PERFORMANCE OF TAILINGS DAMS. International Commission on Large Dams, <http://www.icold-cigb.org/>. ISSN 0534-8293

ICOLD, 2019. ICOLD Bulletin 1XX. TECHNOLOGY UPDATE xxxx International Commission on Large Dams, <http://www.icold-cigb.org/>. ISSN XXXX-XXX

ICMM, 2019. ICMM 10 Principles xxxxxxxxx

World Bank & IFC (INTERNATIONAL FINANCE CORPORATION), 2002. It's Not Over When It's Over: Mine Closure Around The World, Mining and Development Series. Washington, USA.

- Australian National Commission on Large Dams (ANCOLD, 2012a), Guidelines on Tailings Dams: Planning, Design, Construction, Operation and Closure
- Canadian Dam Association, Dam Safety Guidelines (CDA, 2013) and their Technical Bulletin: Application of Dam Safety Guidelines to Mining Dams (CDA, 2014). I
- Recent documents issued by the Mining Association of Canada, "A Guide to the Management of Tailings Facilities (MAC, 2017), and the International Council on Mining and Metals (ICMM, 2016) "Position Statement on Preventing Catastrophic Failure of Tailings Storage Facilities" offer relevant up to-date guidance.
- The 2016 revisions to Part 10 of the Health, Safety and Reclamation Code for Mines in British Columbia is a useful example of legislative documentation prepared following the Mount Polley tailings dam failure in 2015.

Recent handbooks provided by the Australian Federal Government including "Tailings Management" (DITR, 2016a)", "Preventing Acid and Metalliferous Drainage" (DITR, 2016b), and "Mine Closure" (DITR, 2016c) expand on the issue of managing the geochemical stability of the sulfidic wastes within a physically stable dam, or within tailings released as a result of dam failure. The GARD Guide (<http://www.gardguide.com>) produced by the International Network for Acid Prevention (INAP), also provides leading practice guidance on the geochemical management of sulfidic mine wastes, including tailings.

## DEFINITIONS AND ACRONYMS (INCOMPLETE)

### ***Tailings***

Residue produced from ore or metallurgical processes that typically comprise sand/silt/clay particles in slurry form.

### ***Tailings Storage Facility (TSF)***

A facility used to store tailings, typically comprising one or more dams. The TSF refers to the dams, tailings discharge systems, water management and reclaim systems, and associated works. In this document TSFs also include dams that may store water, process residues, sediment or filtered tailings.

### ***Failure***

The occurrence of an event outside the expectation of performance or facility licence conditions that could range from the uncontrolled release of water including seepage, to a major instability of an embankment leading to loss of tailings and/or water.

### ***Designer***

Person with appropriate qualifications and experience responsible for the design of the tailings dam.

### ***Incident Management***

A system to document incidents at the TSF, with corrective actions identified and completed.

### ***Dam Safety Verification***

A verification of the safety of a Tailings Dam, including as a minimum, a physical inspection of the dam, review of monitoring and surveillance results, and review of stability. A dam safety assessment should be carried out at least annually by the EoR.

### ***Consequence Category***

The ranking of the severity of the consequences of dam failure.

### ***Comprehensive Dam Safety Review (DSR)***

A comprehensive dam safety review is carried out by an independent engineer and includes an assessment of site conditions, dam stability, TSF operations, etc. The framework for such a review should align with the Canadian Dam Association Guideline (reference)

### ***ICMM***

International Council of Mining and Metals

### ***Relevant International Standards and Guidelines***

ICOLD, ANCOLD, CDA AND ICMM.

### ***Risk Management Process***

Systematic application of management policies, procedures and practices to identifying, analysing, evaluating, treating, monitoring and reviewing risk.

### ***Design Basis Memorandum (DBM)***

A record of the important design related parameters for the TSF, which typically cover: site conditions, geotechnical properties, design criteria, water management and environmental components.

### ***Dam Breach Assessment***

An assessment of the potential consequence of failure of the dam which includes considerations of water transported tailings release and the potential for additional tailings for all potential failure modes. The operating case (sunny day) and the extreme flood case (flood induced) are considered.

### ***Probable Maximum Precipitation (PMP)***

The greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular time of year, with no allowance made for long-term climatic trends.

### ***Probable Maximum Flood (PMF)***

The PMF is the largest flood that could conceivably occur, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions.

### ***Environmental Design Flood (EDF)***

The maximum flood inflow that could occur before release to the environment has been determined to be acceptable.

### ***Maximum Credible Earthquake (MCE)***

The MCE is the largest conceivable earthquake magnitude that is possible along a recognised fault or within a geographically defined tectonic zone, under the presently known or presumed tectonic framework.

### ***Probabilistic Seismic Hazard Assessment (PSHA)***

PSHA is an evaluation of the ground motion level that will be exceeded at a specific frequency or annual probability.

### ***Factor of Safety***

With respect to slope stability of the dam the Factor of Safety is the ratio of the resisting forces and driving forces.

### ***Undrained Response***

Condition under which pore water pressure changes (increases or reduced) in a mass of soil as a result of a change in stress or strain.

### ***Contractive behaviour***

Reduction of soil volume during shearing. If the sheared materials are saturated or have a high moisture content, the material contraction is accompanied by an increase of pore water pressures in the shear zone.

### ***Dilative behaviour***

Increase of soil volume during shearing. If the sheared materials are saturated or have a high moisture content, the material dilation is accompanied by a reduction of pore water pressures in the shear zone.

### ***Liquefaction***

Loss of soil stiffness and strength due to undrained loading or unloading.

### ***Static Liquefaction***

Liquefaction caused by a rapid increase of pore water pressures resulting from an undrained response of contractive soils subject to monotonic shearing.

### ***Post Seismic Condition***

During a seismic event strength loss and liquefaction may occur. The soil strength after the liquefaction is used for the post seismic condition. This case would not include the horizontal driving forces of the earthquake.

### ***Residual Shear Strength***

The strength of soil after significant shearing (deformation), which may be caused by seismic, static or historical movements.

### ***Landform***

A closed facility that has a low risk of a catastrophic consequence with limited or no water/tailings release and limited capacity for stored tailings to flow and can be considered to have a risk profile similar to the surrounding

### ***Subject Matter Expert***

SME is a person who is by a reason of special qualifications able to express informed opinions on some subjects requiring special knowledge or understanding.

***Dam***

A barrier on the surface preventing uncontrolled release of either water, slurry or solids.

***Dam Engineer***

An engineer experienced in investigation, planning, design, construction or management of dams and qualified to undertake work in the field of dams. Some aspects of tailings dam engineering may require specialist input. A Specialist would be a person with special skills such as geochemistry, hydrogeology, etc.

***Decant Pond***

A pond within a tailings dam to allow collection and clarification of stormwater and tailings water released on settling and consolidation of tailings.

***Dry Density***

The mass of solids (by weight) per unit volume of a soil.

***Impoundment***

A body of water, slurry or solids that is confined by natural barriers or constructed dams and includes those barriers, dams and related items.

***Moisture Content***

The mass of water (by weight) per mass of solids (by weight) in a unit volume of soil.

***Slurry Density (or Bulk Density or Pulp Density)***

The mass of slurry (by weight) per unit volume of slurry.

***Solids Content (or concentration)***

Mass of solids (by weight) as a percentage of the total mass of slurry (by weight).

***Acid and Metalliferous Drainage (AMD)***

Also known as acid mine drainage, or acid rock drainage (ARD), refers to the outflow of polluted water to the environment. Usually the water is acidic but can be neutral and metalliferous (see below), or potentially just highly saline. AMD occurs naturally within some environments as part of the rock weathering process but is exacerbated and accelerated by large-scale earth disturbances characteristic of mining and other large construction activities, within rocks containing an abundance of reactive sulfide minerals.

***Annual Exceedance Probability (AEP)***

The probability that a particular event will be exceeded in any year. For example, a 1 in 1000 AEP Storm is a storm event which produces a rainfall that is statistically likely to occur once in 1000 years at the site under study.

***Best Available Technology (BAT)***

The site-specific combination of technologies and techniques that most effectively reduce the physical, geochemical, ecological and social risks associated with tailings storage during all stages of operation and closure.

***OMS Manual, Operations Plan***

Operations, maintenance and surveillance manual (may be called Management Plan, Operations Plan or equivalent). Documents responsibilities

***Failure Modes Effects Analysis (FMEA)***

A methodology for identifying potential failure modes and consequences. The risks are assessed with respect to the likelihood of occurring and the consequences. A standardized framework is typically used for likelihood (5 levels) and consequences (typically 5 levels with respect to: environment, financial, health & safety)

***Preventative Controls***

Design and operational controls which prevent a dam failure from occurring

***Critical Controls***

Preventative controls, which if not implemented, could lead to failure of the dam

***Mitigating Controls***

Design and operational controls that are implemented to reduce the consequence of a dam failure. These may also include active controls with equipment and emergency response teams

***Emergency Preparedness and Response Plans (EPRP)***

A plan which documents the potential failure modes of the dam and the preparedness and response plans required to address various levels of severity. Communication plans are developed for each level of severity. May be called Emergency Response Plan (ERP), Emergency Management Plan (EMP) or Dam Safety Emergency Plan (DSEP)

***Quality Assurance and Quality Control QA/QC***

Quality Assurance/Quality Control process for monitoring and confirming the quality of construction. Quality Assurance refers to the processes used to measure the quality of construction and that construction meets the design intent. Quality Control refers to the processes that ensure that dam construction meets the specifications for design.

### ***Trigger Action Response Plan (TARP)***

A plan which, with respect to dam safety monitoring & surveillance, identify “trigger” levels along with identified actions.

### ***Design Storage Allowance***

The remaining safe storage capacity that needs to be provided to accommodate tailings (solids and water), rainfall and wave action with a sufficient safety factor against overtopping and spillage of contaminated water.

### ***Freeboard***

A vertical distance between a water level within a dam and another point on the dam as defined below. For tailings dams there are various freeboards provided for different purposes as follows:

- **Total Freeboard** – The vertical distance between the Maximum Operational Pond Level and the crest of the dam. This represents the capacity of the dam to pass an extreme storm by combination of extreme storm storage, spillway discharge depth, wave freeboard and contingency freeboards to prevent overtopping of the dam.
- **Tailings Storage Allowance** – The volume of tailings allowed for at the design period of tailings dam operation stage, prior to closure or raising, calculated as the expected dry tonnage of tailings produced at the expected dry density to be achieved within the storage.
- **Minimum Decant Storage Allowance** – The expected minimum volume of water to be held on a tailings dam to achieve the desired water quality for discharge conditions either to the environment if appropriate or to return to the process plant for treatment and recycle.
- **Wet Season Storage Allowance** – The volume allowed for wet season water storage which could conservatively be required to be held in a tailings dam by a combination of excess wet season rainfall run-off from the tailings dam catchment and decant water from process inputs that cannot be progressively be extracted from the dam.
- **Extreme Storm Storage Allowance** – The volume allowed for storage of an extreme storm event to prevent spill from the dam.
- **Contingency Storage Allowance** – The additional freeboard allowed on top of the tailings, decant pond, wet season storage and extreme storm allowance to cater for wave run-up and uncertainty in the values adopted for the defined items.
- **Operational Freeboard** – The vertical distance between the top of the tailings and the adjacent embankment crest. A minimum operational freeboard is normally specified to minimise the potential for backflow and overtopping because of tailings mounding at discharge points.
- **Maximum Operating Level** – The maximum extent of a decant pond under normal operating conditions. During heavy rainfall it would be expected that this limit would be exceeded, and

procedures and facilities should be available that will allow recovery of the pond level, back to the Maximum Operational Level within a specified period.

- **Flood Spill Depth** – The depth of water flow over the spillway for the design flood event.
- **Wave Freeboard** – An allowance for wave run up over and above the maximum calculated flood level.
- **Beach Freeboard** – For upstream and centreline tailings dams without internal filters, it is crucial to control the phreatic surface level against the upstream face to minimise piping risks and maximise stability. This is achieved by placing tailings against the upstream face and maximising the distance between the decant pond and the embankment. A minimum beach freeboard is specified for these dams, defined as the vertical distance between the top of the tailings, abutting the upstream face of the dam, and the tailings pond level after an appropriate extreme storm event.
- **Maximum Operating Level** – The maximum level to which the water level can rise at which point the deposition of process tailings and water must cease, and the Emergency Response Plan (ERP) activated.

### ***Long Term***

For these Guidelines the term long-term has been assigned a nominal period of 1,000 years. This applies to the consideration of the potential design life of the post-closure landform.

### ***Mine Closure***

A process being undertaken between the time when the operating stage of a mine is ending or has ended and the final decommissioning or rehabilitation is completed. Closure may only be temporary or may lead to a period of care and maintenance.

### ***Mine Completion***

The goal of mine closure where mining lease ownership can be released and responsibility accepted by the next land user.

### ***Post-Closure***

For this Guideline, Post-Closure refers to the period after Mine Closure and rehabilitation works are completed and the tailings dam enters a period of long-term monitoring to confirm that the Tailings Dam is likely to perform safely into the long-term.

### ***Storage Capacity***

The potential containment capacity of the facility, usually referred to in units of dry tonnes. This requires knowledge of the in situ dry density of the tailings likely to be achieved in the storage.

# APPENDICES

# Appendix A

## **Example of a Design Basis Memorandum**

DESIGN BASIS MEMORANDUM										
Date										
								Basis/Source Reports		
SETTING	TSF Name									
	Location - GPS									
	Location town/country									
	Climate									
	Physiography									
	Seismicity									
	Social Environment									
TSF PLAN	Stage	Current	Ultimate							
	Dates (year)									
	Tailings production (tpd)									
	Tailings density (% by weight)									
	Stored tonnage (Million tonnes)									
	Estimated stored volume (Mm3)									
	Dam height TSF area (ha)									
GEO TECHNICAL	Geometry (u/s, CL, d/s)									
	Piping controls									
	Drainage controls									
	Seepage controls									
	Static factors of safety									
	Undrained factor of safety									
	Post seismic factor of safety Foundation challenges									
Water Balance	Annual surplus/deficit									
	Net water use									
	Water treatment for discharge									
	"Allowable" seepage rate									
DESIGN CRITERIA BASIS	Consequence classification									
	Classification reference									
	Sunny day water volume									
	Rainy day water volume									
	Sunny day dam break volume									
	Rainy day dam break volume									
	Mud flow (Liquefaction) release volume									
CLOSURE	Wet with water pond									
	Dry with saturated tailings									
	Drained landform									
	Water treatment required?									
TAILING PROPERTIES	Tailings	Total Tailings	Coarse Tailings	Fine Tailings						
	ICOLD tailings type									
	Specific gravity									
	% Fines									
	% Clay									
	Liquid Limit									
	Plastic Limit									
	Liquidity Index									
	% Sulphide									
	Neutralization potential ratio									
	Neutral metal leaching potential									
	Potential contaminants of concern									
	GEO TECHNICAL PARAMETERS	Material	Total tailings	Tailings Coarse Tailings	Fine Tailings	Foundation s Soil 1	Soil 2	Dam Fills Fill 1	Fill 2	
Bulk density										
Dry density										
Void ratio										
Peak friction angle										
Peak undrained shear strength ratio										
Post peak strength ratio										
Permeability (m/s)										
Coefficient of consolidation										
FLOOD		Return Period	Annual	1 day	3 day	7 day	Snowmelt included? Y or N			
		1								
	100									
	500									
	2500									
	5000									
	10000									
	PMP									
CLIMATE	Month	Rain	Snow Equivalent	Total	Avg. Temp.	Evap.				
	January									
	February									
	March									
	April									
	May									
	June									
	July									
	August									
	September									
	October									
	November									
	December									
SEISMICITY	Return Period	475	1,000	2,475	5,000	10,000	MCE			
	Peak ground acceleration									
	Magnitude									

## Appendix B

### **Technical Note 1**

#### **Determination of Spillway Sizing and Environmental Design Flood Storage**

This Technical Note describes the methodology used to determine the Environmental Design Flood in Australia. The method can be adapted to suit other regions depending of the tolerable risk profile adopted.

## Appendix C

# **CDA Guideline on Factors of Safety**