

Considerations for Preparing Design Criteria for Dewatered Tailings Facilities

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Abstract

Dewatered tailings facilities (thickened, paste, filtered) are generally considered safer alternatives to conventional tailings disposal, primarily due to the lower amounts of water stored as a pond or interstitially within the tailings mass. While it is acknowledged that a risk-based approach to TSF design should always be followed, the pressure to deliver projects quickly and often within limited budgets creates a tendency to rely on standards-based design criteria which may not always be directly applicable to dewatered tailings facilities.

Key design criteria commonly adopted from conventional TSF design are driven by the Population at Risk (PAR) and Dam Failure Consequence, slope stability Factors of Safety (FOS), Stormwater storage and Earthquake Loading. For dewatered tailings facilities it is important for stakeholders to recognise that prescriptive design elements, typically adopted from conventional TSFs, may not represent the most critical sources of risk, and therefore selection of design criteria should be case-specific.

There is arguably a void in international guidelines with respect to incorporating a design flowchart to streamline the design of dewatered tailings facilities. This paper discusses current practice for evaluating key TSF design criteria, taking as a base leading guidelines such as MAC (2019), ANCOLD (2012) and CDA (2007, 2014), and relates this to the context of dewatered tailings facilities. It identifies important elements to consider, issues likely to be encountered and areas of improvement, and provides a basis for continuing research and discussion.

Introduction

The devastating impact of catastrophic tailings dam failures has brought increased focus to risk-based design processes, especially for high-risk facilities. The implementation of risk-based criteria at the design stage is considered industry best practice. The aim of a risk based approach is to align the TSF design with the level of risk acceptable to the designer, the owner and the community impacted by the construction of the facility.

In the search for alternative tailings storage solutions that carry lower risk and less severe failure consequences, dewatered tailings management systems such as thickened/ paste and filtered tailings present as an attractive option because the reduced moisture content and smaller volumes of free water promote increased water efficiency and result in more stable landforms.

Despite being internationally recommended, risk-based design is not always practical to achieve, with some dam owners and designers choosing to implement prescriptive criteria defined by international standards and guidelines as a quick and convenient design methodology that is unlikely to be challenged by peers or by government agencies.

This paper discusses the prescriptive design criteria for TSFs, considering current tailings management guidelines from relevant mining jurisdictions, and relates this to the context of dewatered tailings facilities. It identifies important elements to consider, potential issues to be addressed and possible areas of improvement.

Methodology

This paper is based on a limited review of current leading design tailings guidelines and design codes from around the world, including the best practice guidelines from agencies across a range of jurisdictions where mining is a relevant industry listed below:

- Australian National Committee on Large Dams (ANCOLD)
- Canadian Dam Association (CDA)
- The Mining Association of Canada (MAC)
- Supreme Decree (DS) No. 248/2007 (Chile) – abbreviated DS248.

The following section provides a summary of the standards-based design criteria from each of the international agencies relating to:

- Population at Risk (PAR) and Dam Failure Consequence
- Factor of Safety (FOS)

- Stormwater Management
- Earthquake Loading.

Population at risk and dam failure consequence

Where a standards-based design approach is adopted, prescriptive design loads and contingencies are based on PAR and impacts/ losses resulting from a potential dam break. Of the guidelines reviewed, only ANCOLD and CDA present a framework to define PAR and dam failure consequences.

ANCOLD

Definition of the PAR involves considering a dam break situation under “sunny day” (no flooding) and extreme flood events (ANCOLD, 2012a). The dam break PAR is defined as the total PAR minus the PAR affected by a natural flood event immediately prior to the dam break (flood dam break scenario only). Specific criteria outline scenarios in which people can be discounted from the PAR, this includes scenarios where it can be proven that people within the breach flow zone can be evacuated by means of an effective and reliable Emergency Action Plan.

ANCOLD (2012a) suggests that for simple cases the dam break could follow empirical/ qualitative methods or make a general assumption that the tailings are replaced with water. Where a more complex dam break assessment is warranted, a 2D mudflow can be completed. However, the guidelines note that considerable judgement is needed to determine a realistic mudflow scenario.

In some scenarios, an assessment using an incremental Potential Loss of Life (PLL), defined as the PLL after an event that causes dam failure minus the PLL for the same event in the absence of a dam failure, is recommended. The dam break PAR/ PLL is assigned an order of magnitude grouping in a range from <1 (0) to >1000.

The ‘Severity of Damage and Loss’ is evaluated across a range of impact areas (business importance, public health, social dislocation and environmental consequences) and condensed to an overall severity level based on the impact area with the highest severity rating (minor, medium, major or catastrophic). The facility’s dam break PAR/ PLL grouping and overall severity level are then used to define the consequence category.

Population at Risk	Severity of Damage and Loss			
	Minor	Medium	Major	Catastrophic
<1	Very Low	Low	Significant	High C
>1 to 10	Significant	Significant	High C	High B
>10 to 100	High C	High C	High B	High A
>100 to 1,000		High B	High A	Extreme
>1,000			Extreme	Extreme

Replicated from ANCOLD 2012a (Table 2: Recommended consequence category); supplementary notes are not shown.

CDA

During the dam classification process, each of four hazard rating components – PAR, loss of life, environmental and cultural values, and infrastructure and economics – is considered independently. The overall dam hazard rating is defined by the component which suffers the highest incremental loss. Similar to ANCOLD (2012a, b), CDA (2007) defines the dam break PAR (based on the total flood PAR) as None, Temporary or Permanent. In dam break scenarios with a ‘Permanent’ PAR, the facility’s classification is based on the PLL. CDA (2007) stipulates that “the potential for flow of the impoundment contents beyond the perimeter containment is a determining factor on whether the containment needs to be considered as a dam”. Such terminology may provide potential for re-classification of dry stack facilities if it can be proven that flow failure is not a foreseeable consequence of an eventual slope failure.

Dam Class	Population at Risk	Incremental losses		
		Loss of Life	Environmental and Cultural values	Infrastructure and economics
Low	None	0	Minimal short-term loss No long-term loss	Low economic losses; area contains limited infrastructure or services
Significant	Temporary only	Unspecified	No significant loss or deterioration of fish or wildlife habitat Loss of marginal habitat only Restoration or compensation in kind highly possible	Losses to recreational facilities, seasonal workplaces, and used transportation routes
High	Permanent	10 or fewer	Significant loss or deterioration of important fish or wildlife habitat. Restoration or compensation in kind highly possible	High economic losses affecting infrastructure, public transportation, and commercial facilities
Very high	Permanent	100 or fewer	Significant loss or deterioration of critical fish or wildlife habitat Restoration or in kind possible but impractical	Very high economic losses affecting important infrastructure or services (e.g. facility, storage facilities for dangerous substances)
Extreme	Permanent	More than 100	Major loss of critical fish or wildlife habitat Restoration or compensation in kind impossible	Extreme losses affecting critical infrastructure or Services (e.g. hospital major industrial complex, major storage facilities for dangerous substances)

Replicated from CDA 2007 (Table 2-1: Dam Classification)

Factor of safety

The slope stability FOS is defined as the ratio of available shear resistance along a potential failure plane to the activating shear forces along the same plane. The FOS is commonly used to account for uncertainties in design and construction elements such as material properties, foundation variability and construction quality.

ANCOLD

ANCOLD notes that there are no rules for acceptable FOS as it is incumbent upon the design engineer to make considerations and judgements on the selection of the minimum FOS. While the suggested minimum FOS under static loading is 1.5, a lower value of 1.3 may be adopted for short-term undrained conditions (i.e. construction) where it is deemed the critical failure surface does not have potential to cause loss of containment, and the available strength will increase with time. ANCOLD (2012) no longer recommends the use of pseudo-static analysis as a screening tool for slope stability under seismic conditions, but instead recommends an assessment of liquefaction potential followed by deformation estimates using numerical models (Finite Element/ Finite Difference) or simplified methods. The designer should exercise discretion when defining the minimum FOS for post-seismic stability based on the reliability of residual/ liquefied shear strength estimates.

Loading Condition	Recommended Minimum for Tailings Dams	Shear strength to be used for evaluation
Long-term drained	1.5	Effective strength
Short-term undrained (potential loss of containment)	1.5	Consolidate undrained strength
Short-term undrained (no potential loss of containment)	1.3	Consolidate undrained strength
Post Seismic	1.0 – 1.2	Post seismic shear strength

Replicated from ANCOLD 2012a (Table 8: Recommended factors of safety); supplementary notes are not shown.

CDA

Prescriptive TSF slope stability criteria summarised in CDA (2014) have been derived from CDA (2007) criteria for water dams. Similar to ANCOLD, an FOS of 1.3 is proposed as a lower limit for safe slopes during construction/ operation where the failure consequence is minor and mitigation measures can be readily implemented. A minimum FOS of 1.5 is stipulated for downstream slopes where long-term, steady-state seepage conditions are expected to prevail. A pseudo-static FOS of >1 is used to indicate that the performance of the dam under earthquake conditions is acceptable; CDA (2007) notes that the prescriptive FOS criteria are applicable to both limit equilibrium and numerical finite element shear strength reduction factors (SSRs). Full or partial drawdown scenarios may not be directly applicable to all TSFs.

Loading Condition	Recommended Minimum for Tailings Dams	Shear strength to be used for evaluation
During or at end of construction	> 1.3 depending on risk assessment during construction 1.5	Effective strength
Long term (steady state seepage, normal reservoir level)	1.5	Consolidate undrained strength
Full or partial rapid drawdown	1.2 to 1.3	Consolidate undrained strength

Replicated from CDA 2014 (Table 3-4: Target Factors of Safety for Slope Stability in Construction, Operation, and Transition Phases - Static Assessment)

Loading Condition	Minimum Factor of Safety
Pseudo-static	1.0
Post-earthquake	1.2

Replicated from CDA 2014 (Table 3-5: Target Factors of Safety for Slope Stability in Construction, Operation, and Transition Phases - Seismic Assessment)

MAC

The intent of the MAC guidelines is to address the specific needs of facility owners and tailings facilities by using critical risk control. The MAC guidelines therefore avoid defining generic FOS criteria, but make reference to the 'Detailed technical guidance' provided in CDA (2007, 2013). ANCOLD and ICOLD are also referenced as recommended resources.

Chilean Tailings Practice and Regulations

The DS248 guidelines outlines a phased stability assessment, with each phase introducing increased complexity in the stability analyses, dependent on the TSF's business importance, risk profile and the level of the study. No guidance is provided with respect to assignment of categories to each of these aspects.

Static and pseudo-static methods are recommended for Phase I and Phase II analyses, with Phase I including pseudo-static analysis and assuming all tailings liquefy following a seismic event. Phase II incorporates simulation of pore water pressures. For both phases, the recommended minimum FOS is 1.2; compliance with Phase I and II is sufficient for low embankments (less than 15 m high); further analyses are required for the remaining phases. Phase III applies to embankments higher than 15 m and should incorporate stress-strain dynamic analyses. In Phase IV, closure criteria are applied to the analyses, where loads correspond to maximum credible events. There is no minimum recommended FOS for static analyses, the reason for this may be related to Chile falling in a zone of high seismicity, which requires the static FOS to be high enough to ensure that the FOS for pseudo-static analyses exceeds 1.2. The FOS values for Phases III and IV are not stipulated, and there is no a definition of allowable deformations.

Stormwater management

Water management is a fundamental contributor to the overall success of tailings management and therefore receives good coverage in design and operations guidelines.

ANCOLD

As outlined in ANCOLD (2012), the definition of stormwater storage criteria is based on the facility's spill consequence category, which considers the consequence of the release of stored water from the dam, as opposed to the consequence category which considers failure of the embankment. Fall-back methods for 'non-spill' facilities where water quality is unsuitable for release define allowances for extreme storm storage in terms of Annual Exceedance Probability (AEP), contingency freeboards and in some cases, wet season water storage. Even where a facility is classified as a 'non-spill' facility, implementation of an emergency spillways is recommended. The magnitude of the design flood adopted for spillway design of 'spill' facilities is based on the dam failure consequence category. Additional spillway freeboard allowances are required to account for wave action and wind set-up conditions. The estimation of closure spillways and freeboard allowances should always be based on the Probable Maximum Flood (PMF).

Dam Spill Consequence Category	Minimum Wet Season Water Storage Allowance	Extreme Storm Storage Allowance	Recommended Contingency Freeboard	
Low	1:5 notional AEP wet season runoff	Determine by risk assessment	nil	nil
Significant	1:10 notional AEP wet season runoff	1:100 AEP, 72 hr flood	1:10 AEP wind	0.3
High C	1:100 notional AEP wet season runoff	1:100 AEP, 72 hr flood	1:10 AEP wind	0.5
High B		1:1000 AEP, 72 hr flood	1:50 AEP wind	0.5
High A / Extreme	1:1000 notional AEP wet season runoff	1:10000 AEP, 72 hr flood	1:50 AEP wind	0.5

Replicated from ANCOLD 2012a (Table 4: Minimum Extreme Storm Storage – Fall-back method and Table 5: Recommended Contingency Freeboards)

Dam Failure Consequence Category	Design Flood AEP	Wave Freeboard Allowance
Low	1:100	Wave run-up for 1:10 AEP wind
Significant	1:1000	Wave run-up for 1:10 AEP wind
High or	1;100,000	Wave run-up for 1:10 AEP wind
	PMF	None
Extreme	PMF	To be determined by risk assessment

Replicated from ANCOLD 2012a (Table 6: Recommended minimum design floods for spillway design and wave-freeboard allowance during operation phase); supplementary notes are not shown.

CDA

CDA defines three functions of the TSF in relation to water management:

- Temporary storage of water during operations
- Temporary storage of the Environmental Design Flood (EDF)
- Storage and/ or passage of the Inflow Design Flood (IDF) runoff to ensure the integrity of the facility.

Management of the TSF pond under normal conditions requires definition of a safe range within which the pond should be maintained. This range is defined by the Low Operating Water Level (LOWL) and the Normal Operating Water Level (NOWL), which are based on site-specific constraints, such as beach development, required decant depth and critical phreatic conditions, and does not include a storm allowance.

The EDF is a water storage allowance above NOWL when a 'no spilling' condition is prescribed. While the CDA recommends estimating the EDF based on a storm event with a return period between 1:50 years and 1:200 years, it is also suggested that site conditions and the quality of the stored water be considered in consultation with the facility owner and regulators, which may require a more severe storm to be adopted.

The IDF is the most severe flood condition that a TSF design must be able to accommodate. The designer should indicate in its water management strategy whether the IDF volumes are to be safely contained above the EDF volumes, or will be passed through a spillway. It is recommended by CDA that even when IDF volumes are to be stored within the TSF, the design should always include an emergency spillway. The CDA recommends IDF target levels be increased in line with the Dam Classification.

Dam Classification	Annual Exceedance Probability – Floods	Annual Exceedance Probability – Wind setup - Freeboard
Low	1/100	1/100
Significant	Between 1/100 and 1/1,000	1/10
High	1/3 between 1/1,000 and PMF	1/2
Very High	2/3 between 1/1,000 and PMF	1/2
Extreme	PMF	1/2

Replicated from Technical Bulletin Application of Safety Guidelines to Mining Dams, CDA (Table 3-2: Target Levels for Flood Hazards, Standards-Based Assessments, for Construction, Operations, and Transition Phases)

MAC

The MAC guidelines consider water management as an inherent component of tailings disposal. It is implied that a High consequence category is typically assigned to facilities that hold a significant amount of water, and the category is lowered as the amount of water decreases. A site-specific water management plan should include common elements such as design floods (assigned considering requirements of Best Available Technology), dynamic water balance models, life of mine surface water management plans, and effluent criteria. No specific criteria or exceptions are indicated for water management in the case of dewatered tailings facilities.

Chilean Tailings Practice and Regulations

The DS248 mainly defines basic documents and design elements that should be presented for regulatory approval purposes. While the estimated should align with local hydrological conditions, a minimum freeboard allowance of 1 m is stipulated.

DS50 typically regulates the preparation of water management plans, but explicitly excludes dewatered tailings facilities. DS50 indicates that in cases where dewatered facilities are placed on existing basin drainage, diversions should be constructed using a return period of 50 years and the freeboard must be able to accommodate a 100-year return period.

Earthquake loading

Design guidelines and codes provide recommendations for estimating applicable seismic loads; some are more focused on technical aspects, while others discuss failure mechanisms and allowances that should be included in the analyses. These are discussed as follows.

ANCOLD

ANCOLD recommends implementing a flowsheet for conducting seismic stability analyses for tailings dams. The earthquake severity is determined from the dam failure consequence category that applies. The liquefaction potential is evaluated using semi-empirical methods based on tailings properties, and depending on the outcome, appropriate post-seismic strengths should be used to run static limit equilibrium stability analyses. Pseudo-static stability methods to estimate the FOS due to dynamic loads are no longer recommended. The tailings liquefaction potential is a critical element when tailings is part of the embankment or where portions of the tailings beach raise above the embankment's maximum level.

Dam Consequence Category	Operations phase		Post Closure
	OBE	MDE	
Low	1:50	1:100	MCE
Significant	1:100	1:1000	MCE
High / Extreme	1:1000	1:10000	MCE

Replicated from ANCOLD 2012a (Table 7: Recommended Design Earthquake Loadings (AEP))

CDA

Definition of seismic criteria should consider the Dam Classification. While CDA (2007) provides recommendations with respect to target earthquake levels, the facility owner may adopt more stringent criteria commensurate with its risk tolerance.

The CDA indicates that criteria for post-seismic crest deformation should be established in accordance with the type of facility. For tailings stacks without a pond (dry stack scenario or facility with external ponds), CDA (2014) stipulates that the seismic analysis should include a review of the liquefaction potential of the materials as part of the design of the facility, and that this should be confirmed through Dam Safety Reviews undertaken during operations.

Dam Classification	Annual Exceedance Earthquakes	Probability –
Low	1/100	
Significant	Between 1/100 and 1/1,000	
High	1/2,475	
Very High	½ between 1/2,475 and 1/10,000 or MCE	
Extreme	1/10,000 or MCE	

Replicated from Technical Bulletin Application of Safety Guidelines to Mining Dams, CDA (Table 3-3: Target Levels for Earthquake Hazards, Standards-Based Assessments, for Construction, Operations, and Transition Phases)

MAC

There is no specific guide for defining seismic conditions; where applicable, MAC makes reference to ANCOLD, ICOLD or CDA guidelines.

Chilean Tailings Practice and Regulations

DS248 indicates the use of pseudo-static stability analysis as part of the engineering analyses required for project approval. The design earthquake corresponds to the maximum credible earthquake and must be estimated using a region-specific database. The minimum allowable FOS is 1.2. Although there is no specific TSF failure consequence categorisation, it is indicated that depending on the severity or consequence of TSF failure, additional analyses are required – including dynamic analyses based on stress-strain techniques using dynamic properties of the tailings in which case potential deformations should be estimated.

Results

PAR and Dam Failure Consequence

When considering dewatered tailings facilities, modelling of dam breaks using water flows may produce unrealistically large breaches which do not provide an adequate evaluation of actual risk and potential impacts in the event of a dam break. The use of strength-based modelling approaches, such as those proposed by Seddon (2010) and Martin and Fontaine (2015), is considered a more appropriate dam break modelling method for thickened tailings facilities where appropriate rheological and/or strength parameters are adopted.

Where there is no potential for liquefaction and no pond, tailings are theoretically non-flowable and the dam break runout can therefore be modelled based on a slope failure (Small et al., 2017 as referenced by Orman, M, 2017). This scenario is considered most relevant to filtered tailings dry stacks where unsaturated, dilative material conditions are often achieved in peripheral structural zones through mechanical compaction effort. In circumstances where forecast of the failure mode of a TSF resembles a 'non-dam' facility, such as in the case of slumping on an unsaturated facility with no pond, there may be scope to consider the facility a 'non-dam' landform. Potential for dam break outflow increases where filter under-performance causes an unexpected build-up of pore pressures in contractive, saturated areas at the base of the landform. For this reason, it is imperative that the variability of the tailings mineralogy and gradation is considered at the design stage so that appropriate engineering and operational contingencies can be implemented and monitoring of the facility focuses on meeting key performance indicators related to those parameters.

The tailings flow behaviour resulting from a basal liquefaction failure is more difficult to predict due to the complex relationship between liquified strength and kinetics; at the onset of liquefaction, the driving shear stress exceeds the tailings peak shear strength and is considerably larger than the liquefied shear strength. Acceleration of the tailings mass starts mobilising the tailings down the slope and as the driving shear stress reduces, reaching a point lower than the liquefied tailings shear strength, the flow velocity would approach zero (Olson and Stark, 2002).

Regardless of the dam break impact, given the importance of tailings facilities in mining operations, dewatered tailings dams are still likely to be assigned a High Consequence Category, driven by the suspension of operations and financial/ reputational impact on the owner's business.

Factor of Safety

Unlike earthquake loading and hydrological criteria, fall-back FOS criteria are based on a set of universal loading conditions, independent of the dam failure consequence and the reliability of stability parameters. By comparison, stability criteria adopted for unsaturated waste dumps and stockpiles (CSIRO, 2017) are based on the failure consequence as well as level of confidence in stability parameters. As outlined by Herza et al. (2017), the use of prescriptive FOS criteria does not necessarily ensure a lower probability of failure, as the stability analysis depends on the reliability of the input parameters.

ANCOLD (2012) states that increasing the shear strength of unsaturated materials to account for suction effects should generally be avoided. In semi-arid climates where dewatered tailings technologies are implemented for water conservation, the influence of suction can be considerable and can result in significant increases in shear strength (Herramen, 2016). The practical benefits of steepening the landform slopes by accounting for unsaturated strengths need to be considered against increased regulator scrutiny and perception as well as the facility's closure requirements.

Crystal et al. (2018) have shown that where compacted tailings are placed in a peripheral 'structural zone' of the dry stack, it is possible for the tailings to behave as a saturated material, especially in areas of high rainfall. It is therefore imperative that the design includes appropriate contingencies to mitigate the development of a phreatic surface.

Stormwater Management

References to specific water management requirements for dewatered tailings are generally limited in the guidelines reviewed for this paper. Given that conventional tailings facilities carry high risks due to maintaining a pond on the facility, the stringency applicable to the design criteria for water management is related to the dam failure consequence category. When designing dewatered tailings facilities, there are essentially two ways to manage runoff – store runoff in the facility or divert it to an external pond.

Dry stacks are typically built up in levels, where the lowest point would vary according to the development of the stack. For facilities developed in arid regions, runoff may be accumulated in low spots, preferably away from the TSF perimeter. In this case, design criteria would be based on the dam failure consequence category of the TSF similar to a conventional facility; the storm storage capacity and the freeboard allowances would be used to define the gradient towards the centre of the facility that should be considered in the stacking operation. A water balance would be required to estimate the capacity of the stack to absorb and evaporate the transient pond formed after seasonal and extreme storm events.

For some dewatered facilities, it may be impractical to maintain a reclaim pond on the TSF and runoff would often be diverted to an external pond. In these cases, criteria for the design of the external pond may be dictated by the dam failure consequence category of the stormwater pond; the effect of this is that design criteria for water management would be less onerous.

While the authors recognise that water management is a site-specific design element, given the reduced amounts of water available in dewatered facilities, water management strategies to achieve a cost-effective solution should be explored rather than using prescribed solutions that predominantly apply to conventional tailings facilities. MAC (2019) provides a comprehensive framework to assist in defining strategies using a risk-based approach, which has the additional benefits of minimising costs while maintaining acceptable risk levels.

Earthquake Loading

Typically for the design of conventional tailings facilities, it is necessary to demonstrate the stability of the embankment and peripheral materials only. In scenarios where tailings are stacked without a retention structure (dry stack) or if only a small starter dam is placed at the toe of a slope as in a thickened central discharge facility, the stability of the tailings mass itself requires to be evaluated. In particular, this assessment should carefully consider liquefaction, be it static or dynamic. ANCOLD and CDA guidelines provide a robust framework to evaluate seismic impacts on a TSF that is mainly focused on the stability of the retaining structure. ANCOLD recommends the assessment of the tailings mass when it forms part of the embankment (upstream raises). The recommended approaches are the comparison of cyclic resistance ratio (CRR) to the seismically induced cyclic stress ratio (CSR), and the use of critical state-based liquefaction assessment (Jeffries and Been, 2006).

While these approaches may be applied with some adaptation to estimate the stability of dry stacks, they are reliant on a significant assumption regarding the forecast statistics of the in situ material. In the case of the critical state approach, given that dewatered tailings are delivered with reduced amounts of water, it can be assumed that deposited tailings are at or slightly above the critical line (Been and Li, 2009). However, the stack does not always evolve through the life cycle estimated in the design, because overloading of the tailings without reaching appropriate desiccation or self-weight consolidation may drive the designed state path below or at the critical state line. It is therefore important to define operating conditions of the stack and introduce critical controls to be monitored throughout the life cycle of the facility.

Conclusions

The pressure to deliver projects quickly and often within limited budgets creates a tendency to rely on standards-based design criteria which may not always be directly applicable to tailings dams. The focus of this review was on the applicability of the standards-based design approach and how this relates to the design and operation of dewatered tailings facilities.

The extent of physical impact associated with a potential dam break must be fully understood at the outset of the facility design, and the consequence classification of the facility must follow on from this understanding. For this reason, it is essential that plausible failure modes and runout scenarios are considered when conducting dewatered tailings dam break assessments – doing so will avoid misalignments in perceptions of acceptable risks.

There are two ways of managing stormwater on stacked tailings; if the facility is designed to store internal runoff onto the facility, flood criteria are based on the consequence category of the tailings facility. Alternatively,

runoff can be managed by designing a water-shedding landform which would require construction of an external pond; flood criteria in this case would be based on the consequence category of the stormwater pond.

Although pseudo-static analyses are still accepted as a valid assessment of the stability for seismic conditions under CDA and DS248 guidelines, it can be concluded that the stability of a beach slope or a stacked slope may not be optimally assessed using this approach; a focus on liquefaction potential and assessment of the likely loss of shear strength should be given preference.

While a number of gaps and opportunities to streamline and guide a more efficient design of dewatered facilities have been identified, the practical benefits of seeking approval of lowered criteria would need to be balanced against increased regulatory scrutiny and design effort to supersede fall-back design criteria. It is considered that the fall-back methods may lead to increased dam construction and operating costs, while the design of mining dams should be based on a risk-based approach.

The MAC, ANCOLD and CDA all provide excellent good practice guidance (ICMM, 2019) and are in general agreement that the design of a tailings facility should follow a risk-based approach. The Chilean case is different, as there is no specific framework to assess risk to define design criteria in agreement with the risk tolerance of the facility owners and other stakeholders.

References

- ANCOLD (2003) *Guidelines on Risk Assessment*, Australian National Committee on Large Dams Incorporated, Australia.
- ANCOLD (2012a) *Guidelines on Tailings Dams: Planning, Design, Construction, Operation and Closure*, Australian National Committee on Large Dams Incorporated, Australia.
- ANCOLD (2012b) *Guidelines on the Consequence Categories for Dams*, Australian National Committee on Large Dams Incorporated, Australia.
- Been, K, Li, A. (2009) 'Liquefaction and Paste Tailings', in R Jewell, Ab Fourie, S Barrera and J Wiertz (eds), *Proceedings of the 12th International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth, pp. 281-289.
- CDA (2007, Revised 2013) *Dam Safety Guidelines*, Canadian Dam Association, Canada.
- CDA (2014) *Technical Bulletin: Application of Dam Safety Guidelines to Mining Dams*, Canadian Dam Association, Canada.
- Crystal, C, Hore, C, Ezama, I (2018) 'Filter-Pressed Dry Stacking: Design Considerations Based on Practical Experience', in *Proceedings Tailings and Mine Waste 2018 Conference*, pp. 209-2019.
- Fundación Chile (2018) 'Avances y retos para la gestión de los depósitos de relaves en Chile', Programa Tranque, Santiago de Chile.
- Gobierno de Chile (2007) *Reglamento para la aprobación de proyectos de diseño, construcción, operación y cierre de los depósitos de relaves*, DS248, Ministerio de Minería, Santiago de Chile.
- Golder Associates (2016) *Review of Tailings Management Guidelines and Recommendations for Improvement*, report prepared for International Council on Mining and Metals (ICMM) (12/03/2019, https://www.icmm.com/website/publications/pdfs/tailings/161205_review-of-tailings-management-guidelines.pdf).
- Herramen, R (2016) 'Getting soil strength parameters for stiff unsaturated clay', paper presented at AGS-SA 2016 Seminar – Design considerations for cuttings, revetments and retaining structures for unsaturated clay, Adelaide, 19 September.
- Herza, J, Ashley, M and Thorp, J (2017) 'Factor of Safety?-Do we use it correctly?', in *Proceedings ANCOLD 2017*, viewed 10/03/2019, https://www.ghd.com/en/services/resources/PDF/ANCOLD_2017_Ashley_Factor-of-Safety-Do-we-use-it-correctly.pdf.
- Herza, J, Phillips, J (2015) 'Anomalies in the design of mining dams', in *Proceedings ANCOLD 2015*, viewed 10/03/2019, http://www.ghalivgunn.com/en/services/resources/PDF/ANCOLD_2015-Anomalies_in_design_for_mining_dams-HERZA_PHILLIPS.pdf.
- MAC (2017) *A guide to the Management of Tailings Facilities – Third Edition*, Mining Association of Canada, Canada.
- MAC (2019) *A guide to the management of tailings facilities, version 2.1*, Mining Association of Canada, Canada.
- Martin, V, Fontaine, DD and Cathcart, JG (2015) 'State of Practice for Conducting Tailings Dam Breach Studies', in *Proceedings of the Tailings and Mine Waste 2015 Conference*, Vancouver, BC, Canada.
- Olsen, SM, Stark, TD (2002) 'Liquefied strength ratio from liquefaction flow failure case histories', *Canadian Geotechnical Journal*. Vol. 39: 629–247.

Orman, M, Small, C, Al-Mamun, M (2017) *Tailings Dam Classification and Breach Analyses, Perspective from the Canadian Dam Association*, presentation outlining the current state of practice for dam consequence classification and dam-break assessment outlined by the Canadian Dam Association, Amec Foster Wheeler, viewed 13/03/2019, https://www.mtech.edu/mwtp/2017_presentations/wednesday/marc-orman.pdf