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Guidelines and recommendations on minimum factors of safety for slope stability of tailings dams

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Article

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Abstract
Recent major upstream raised tailings dam failures have led to a reopening of the discussion of the validity of some of the existing routine practices within the profession. Despite its many shortcomings, deterministic slope stability limit equilibrium analysis is and will continue to be, at least for some time ahead, an important tool for tailings dams' safety assessment. Within this context, this paper presents a contribution to the postulation of minimum factors of safety required for tailings dams' slope stability analysis. A recent review and discussion of limit equilibrium analysis and the guidelines of international standards and current trends, with focus on tailings dams, are presented. Based on this review, and the authors' academic and professional experience, minimum required factors of safety recommendations are proposed. The framework of the recommendations strives to conciliate, in a simple manner, the deterministic minimum required factors of safety with concepts of consequence, uncertainties, risk and characteristics of loose tailings behaviour as a material.

1. Introduction

The recently reported failures of major tailings dams raised from an initial conventional earthwork structure, starter dam, by the upstream method, Mount Polley, Fundão, Cadia and Brumadinho, all owned by high standard mining companies and subjected to inspections and safety assessments following local standards and legislation, have led the profession to open the discussion on the validity of the existing routine practices.

Concomitantly, the legislators have rushed to update and adjust the standards and legislation to knowledge being acquired and made available through the investigations and causation reports of these failures (*e.g.* Morgenstern *et al.*, 2015, Morgenstern *et al.*, 2016; Robertson *et al.*, 2019, Morgenstern *et. al.*, 2019). Morgenstern (2018) stated in the written version of his Victor de Mello Lecture: "At this time, there is a crisis associated with concern over the safety of tailings dams and lack of trust in their design and performance" as well as emphasized during the lecture itself that engineers have to consider that a tailings dam will liquefy if the material deposited is in a contractive condition: "if it can it will [liquefy]".

Few countries, like Brazil, took a radical step and legislated to banish upstream method tailings dams, postulating a time framework for all existing upstream dams to be decharacterized, with decharacterization having to follow stricter requirements than decommissioning.

High level academic research also focused on relevant topics, contributing to better understanding of the behaviour of loose saturated and contractive tailings stored in very complex structures due to the variability, both spatial and in time, of the disposed materials.

The profession is facing this enormous challenge in hundreds of abandoned or being decommissioned tailings dams, as well as in ongoing facilities. While the use of complex numerical simulations with sophisticated soil models as a tool to back decisions is becoming more frequent (*e.g.* Li and Wang, 1998; Pestana and Whittle, 1999; Taborda *et al.*, 2014; Jefferies and Been, 2016; Reid 2020), the routine of practicing engineers is still based on stability verifications and interpretation of monitoring data based on threshold limits implicitly associated to limit equilibrium analysis. Standards all over the world still refer to and/or build on the concept of compliance to safety requirements

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to minimum values of factor of safety, and will continue to do so for some time ahead.

Definition of factors of safety result from a comparison of ultimate resistances in relation to acting loads; it can be emphasized that they really refer to safety against instability in the various verifications that a structure may require to comply with equilibrium verifications.

In order to structure the main aim of this paper, a short summary of what is believed to be the origin and/or root of this concept in applied geomechanics was sought.

In the landmark book, "Theoretical Soil Mechanics", Terzaghi mentions in its Introduction that the working hypotheses of Soil Mechanics are as useful as the Theory of Structures in Civil engineering, with the uncertainties involved in the assumptions of computations that need to be anticipated by engineers when considering the differences between reality and his concept of the situation requiring his full attention.

The working hypothesis of the Theory of Structures is based on complying with the principles of static equilibrium. Terzaghi postulates that "the solution of a problem is rigorous if the computed stresses are strictly compatible with the conditions for equilibrium, with the boundary conditions, and with the assumed mechanical properties of the materials subject to investigation". And, this concept on how to deal with safety of earthworks and foundations was probably originated earlier, with discussions on earth pressures on retaining walls.

When approaching discussions on the stability of slopes, Terzaghi starts by looking at the base failure of a vertical cut, and only afterwards proceeds to discuss inclined slopes. The estimation of a factor of safety against base failure, as well as the calculation of the excavation base heave, start by the calculation of the critical cohesion for the local soil, all focusing on guaranteeing equilibrium. A recommendation of a factor of safety of 1.5 is presented without detailed discussion of why this value was selected. When discussing the horizontal equilibrium of strutted excavations, a value of factor of safety of 2 is brought, mentioning "specifications".

Taylor (1948) in his landmark book Fundamentals of Soil Mechanics, has a specific item discussing Factors of Safety in the chapter on Stability of Slopes. He reports that "much criticism has been levelled in the past at improper use of *factors of safety* and the incomplete definitions that have sometimes been given to such factors. However, any quantitative stability analysis must make use of some measure of the degree of safety. It must be realized that many types of failure are possible with respect to a system as a whole and also that many types are possible with respect to individual points or individual parts of the system. It thus appears that there is no such thing as *the* factor of safety and that when a factor of safety is used its meaning should be clearly defined. For this reason, considerable care will be used in defining the factors of safety used herein". Taylor uses the wording of a margin of safety being specified so that "the working values must be smaller than those given above", those being related to the available shear strength of the soil in a slope. He also proposes that the margins of safety may be different for the two components of the shear strength, recommending a value of 1.5 in the cohesion component, and 1.26 in the tangent of the friction angle, and postulates that it is usually preferred that the two factors have the same value. Comparison of the value of factor of safety with respect to shear strength with that used in steel and other structural materials is made. The concern of the "low degree of dependable accuracy in shearing strength determinations in soils" is brought and discussion that the value of 1.37 that results from the equalization of the factor on the cohesion and on the friction angle on his example, should be considered too small. But Taylor concludes "it is a typical value, however, and many embankments, which according to engineering practice are safe, have safety factors smaller than this value. The fact that the usual margin of safety that can be specified in stability analyses is often no larger than the probable amount of inherent error in the procedures used is alone sufficient to show that soil mechanics is not an exact science".

Additionally, it is worth mentioning that, according to Meyerhof (1994), the concept of factor of safety was first used in geotechnical design by Bélidor and Coulomb in the 18th Century.

This brief historical introduction highlights the fact that selecting the safety conditions and reducing the risk of failure of a structure is a controversial topic since the early works of soil mechanics, requiring continuous scrutiny and judgment. A conceptual view of required factors of safety for slope stability shared by the authors is put forward for discussion and debate, based upon academic and professional experience and recently revised guidelines of international standards on tailings dams.

2. Guidelines and recommendations from international standards

In order to better understand the status in which the profession is basing, studying and discussing the evaluation of safety conditions of existing, operating or to be decommissioned tailings dams, a critical review of the main recommendations, as provided by international standards, as well as by recognized and influencing entities, is necessary. As mentioned, the failures of Mount Polley (Morgenstern *et al.*, 2015), Fundão (Morgenstern *et al.*, 2016), Cadia (Morgenstern *et. al.*, 2019) and Brumadinho (Robertson *et. al.*, 2019) have, in the recent past, led to relevant changes in attitudes, propositions and requirements, trying to prevent additional catastrophes.

Minimum required factor of safety recommendations from various landmark sources are briefly presented and described herein. Priority was given to recommendations postulated specifically for mining and tailings dams, but relevant publications for embankment and rockfill dams in general were also included.

2.1 International Council of Mining & Metals' Global Tailings Standard (ICMM, 2019, draft)

After and in the light of Brumadinho's catastrophic event, the ICMM has published a draft version for an international standard for tailings facilities. Consultation to the geotechnical community was performed in the end of 2019 and is now closed.

Even though no specific minimum required factor of safety recommendations are provided, from a conceptual standpoint some important requirements are postulated. Initially, despite requiring the Operator to study and assess the potential consequences of the tailings facility's failure and considering it for various activities and decisions, the standard also states that:

> *"PRINCIPLE 4: Design, construct, operate and manage the tailings facility on the presumption that the consequence of failure classification is 'Extreme', unless this presumption can be rebutted"*

According to the proposed standard, design should normally assume 'Extreme' consequences of failure, and thus, would not depend on the assessment of consequence categories, unless otherwise specifically justified. The justifications for applying other consequence categories are defined as:

> *"a) The knowledge base demonstrates that a lower classification can be applied for the near future, including no potential for impactful flow failures; and*
>
> *b) A design of the upgrade of the facility to meet the requirements of an 'Extreme' consequence of failure classification in the future, if required, is prepared and the upgrade is demonstrated to be feasible; and*
>
> *c) The consequence of failure classification is reviewed every 3 years, or sooner if there is a material change in any of the categories in the Consequence Classification Matrix, and the tailings facility is upgraded to the new classification within 3 years. This review should proceed until the facility has been safely closed and achieved a confirmed 'landform' status or similar permanent non-credible flow failure state."*

In other words, tailings facility related activities - and thus minimum factor of safety postulation - may assume lower consequence categories only if one of the abovementioned requirements is met. It is important to notice that this principle refers directly to the concept of consequence, but not to the notion of probability of failure, which is also an important design consideration and is considered in other principles of the publication.

Regarding the decision to rebut the 'Extreme' consequence hypothesis, it is postulated that it:

> *"shall be taken by the Accountable Executive or the Board of Directors (the 'Board'), with input from an independent senior technical reviewer or the ITRB [Independent Tailings Review Board]. The Accountable Executive or Board shall give written reasons for their decision."*

The standard states as a principle that design criteria should be adopted to minimize risk. The criteria should be clearly selected and identified and should be adequate to minimize risk of the adopted Consequence Category.

Specifically regarding factors of safety, it postulates:

> *"REQUIREMENT 6.2: Apply factors of safety that consider the variability and uncertainty of geologic and construction materials and of the data on their properties, the parameters selection approach, the mobilized shear strength with time and loading conditions, the sensitivity of the failure modes and the strain compatibility issues, and the quality of the implementation of risk management systems."*

That is, uncertainties, loading scenarios and quality of risk management are explicitly required to influence Factor of Safety selection. Influence of the Consequence Category is not explicitly stated.

Additionally, it mentions:

> *"REQUIREMENT 6.3: Identify and address brittle failure mechanisms with conservative design criteria and factors of safety to minimize the likelihood of their occurrence, independent of trigger mechanisms."*

This quote highlights an important point: if the behaviour of the tailings material leads to potential brittle failure liquefaction, factors of safety should be conservatively postulated, independently of the trigger mechanism for this behaviour.

Moreover, when describing Consequence Categories, the standard states that "Where the consequence of failure includes loss of life, tailings facilities must be designed, built and operated so that there is a negligible likelihood of failure". However, only a table of Consequence Category-dependent earthquake and flooding loads are prescribed, but not minimum required factors of safety.

The Consequence Category classification of tailings facilities is referred to a matrix, based on provisions by ICOLD (Bulletin 121, 2001), with the highlight that it may change with time. Table 1 reproduces the referred matrix.

As indicated in the matrix, the Consequence Category classification is evaluated based on potential population at risk (PAR), potential loss of life (PLL), and impacts related to the environment, health, society, culture, infrastructure

Table 1. ICMM's consequence category matrix (ICMM, 2019).

Dam failure consequence classification	Incremental losses (ICMM DRAFT)					
	Potential population at risk	Potential loss of life	Environment	Health, social & cultural	Infrastructure & economics	Livelihoods
Low	None	None expected	Minimal short-term loss or deterioration of habitat or rare and endangered species.	Minimal effects and disruption of business. 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$1 M	Up to 10 household livelihood systems disrupted and recoverable in the short term. No long-term non-recoverable loss of livelihoods.
Significant	Temporary only	None expected	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$10 M	Up to 10 household livelihood systems disrupted and recoverable in the longer-term; or up to 100 household livelihood systems disrupted and recoverable in the short-term. No long-term non-recoverable loss of livelihoods
High	10-100	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^2 - 20 km^2. 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$100 M	Up to 10 household livelihood systems lost and non-recoverable; or up to 50 household livelihood systems disrupted and recoverable over the longer-term; or up to 200 household livelihood systems disrupted and recoverable in the short term.
Very High	100-1000	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^2. 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 longer-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$1 B	Up to 50 household livelihood systems lost and non-recoverable; or up to 200 household livelihood systems disrupted and recoverable over the longer-term; or up to 500 household livelihood systems disrupted and recoverable in the short term.

Dam failure consequence classification	Incremental losses (ICMM DRAFT)					
	Potential population at risk	Potential loss of life	Environment	Health, social & cultural	Infrastructure & economics	Livelihoods
Extreme	> 1000	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^2. 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 longer-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. > US$1B	More than 50 household livelihood systems lost and non-recoverable; or more than 200 household livelihood systems disrupted and recoverable in the longer-term; or more than 500 household livelihood systems disrupted and recoverable in the short term.

and economics, and livelihoods. The estimation of such impacts is complex in itself and shall not be discussed in depth in the present paper. Readers may refer, for example, to ANCOLD (2012). It is interesting to notice that the matrix does not allow for combination of criteria - for example, extreme environmental impacts with minor risk to life - simply assigning, for each criterion, a correspondent description for the consequence severity.

2.2 ANCOLD's guidelines on tailings dams - Planning, design, construction, operation and closure - Revision 1 (ANCOLD, 2019)

This publication dates from after the Brumadinho's catastrophic event and provides guidelines for various aspects of tailings dams design and management.

The guidelines foresee Dam Failure Consequence Category assessment, and some aspects of design are re-

Table 2. ANCOLD's Severity Level impact assessment (ANCOLD, 2019).

Damage type	Minor	Medium	Major	Catastrophic
Infrastructure (dam, houses, commerce, farms, community)	< \$10 M	\$10 M-100 M	\$100 M-\$1 B	> \$1 B
Business importance	Some restrictions	Significant impacts	Severe to crippling	Business dissolution, bankruptcy
Public health	< 100 people affected	100-1000 people affected	< 1000 people affected for more than one month	> 10,000 people affected for over one year
Social dislocation	< 100 person or < 20 business months	100-1000 person months or 20-2000 business months	> 1000 person months or > 200 business months	> 10,000 person months or numerous business failures
Impact area	< 1 km^2	< 5 km^2	< 20 km^2	> 20 km^2
Impact duration	< 1 year	< 5 years	< 20 years	> 20 years
Impact or natural environment	Damage limited to items of low conservation value (*e.g.* degraded or cleared land, ephemeral streams, non-endangered flora and fauna). Remediation possible.	Significant effects on rural land and local flora & fauna. Limited effects on: (A.) Items(s) of local & state natural heritage. (B.) Native flora and fauna within forestry, aquatic and conservation reserves, or recognized habitat corridors, wetlands or fish breeding areas.	Extensive rural effects. Significant effects on river system and areas A & B. Limited effects on: (C.) Item(s) of National or World natural heritage. (D.) Native flora and fauna within national parks, recognized wilderness areas, RAMSAR wetlands and nationally protected aquatic reserves. Remediation difficult.	Extensively affects areas A & B. Significantly affects areas C & D. Remediation involves significantly altered ecosystems.

Table 3. ANCOLD's recommended consequence category. Adapted from ANCOLD (2019).

Population at risk	Severity of damage and loss			
	Minor	Medium	Major	Catastrophic
< 1	Very low	Low	Significant	High C
≥ 1 to < 10	Significant (Note 2)	Significant (Note 2)	High C	High B
≥ 10 to < 100	High C	High C	High B	High A
≥ 100 to < 1000	(Note 1)	High B	High A	Extreme
≥ 1000	(Note 1)	Extreme	Extreme	

Note 1: With PAR excess of 100, it is unlikely Damage will be minor. Similarly, with a PAR in excess of 1000 it is unlikely Damage will be classified as Medium.,

Note 2: Change to "High C" where there is the potential of one or more lives being lost. The potential for loss of life is determined by the characteristics of the flood area, particularly the depth and velocity of flow.

Note: A, B and C are subdivisions within the HIGH Consequence Category level with A being highest and C being lowest.

Table 4. ANCOLD's minimum required factor of safety recommendations (ANCOLD, 2019).

Loading condition (Note 1)	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	Consolidated undrained Strength
Short term undrained (no potential loss of containment)	1.3	Consolidated undrained Strength
Post-seismic	1.0-1.2 (Note 2)	Post seismic shear strength (Note 3)

Note 1 See Section 6.1.3 [of reference publication] for description of loading conditions.
Note 2 To be related to the confidence in selection of residual shear strength. 1.0 may be adequate for use with lower bound results.
Note 3 Cyclically reduced undrained/drained shear strength and/or liquefied residual shear strength for potentially liquefiable materials.

lated to the defined Category, such as earthquake loading, freeboard and storm storage allowance. However, the prescribed minimum factors of safety are not related to consequence categories, but to loading conditions, as traditionally done for conventional embankment dams.

The Dam Failure Consequence Category definition procedure is somewhat more complex than that described previously for ICMM (2019).

- Firstly, the "Severity Level" shall be postulated - as minor, medium, major or catastrophic - based on a table (reproduced hereafter on Table 2) that takes into account estimated damage upon failure related to infrastructure, business, public health, environment, social dislocation, impact area, impact duration.
- Then, the Population at Risk (PAR) must be estimated. This metric relates to the potential damage to human life.
- Both the aforementioned metrics are then inputted to a second table, which yields the Dam Failure Consequence Category. Such table is reproduced in Table 3.

It is important to notice that this methodology for assessing Consequence Category differs from that described in ICMM (2019) in the sense that it allows for 'decoupling' the impact related to human life. For example, it is possible to assess the combination of low impact to human life and catastrophic impact to the environment.

It is worth noticing that in this case duration of the impact is an input parameter for the Severity Level, which would allow, for example to consider tailings with and without potential for acid drainage in the assessment.

Table 4 presents the recommended minimum required factor of safety values. Guidance on the shear strength considerations is also provided.

Specifically for static liquefaction, which is a crucial verification for contractive tailings stability, despite not being explicitly indicated in the previous table, it is stated:

> *"Several trigger mechanisms are well documented, such as a rapid change in loading, change in the state of drainage or deformation of the structure. However, the assessment of trigger mechanisms for static liquefaction is very difficult. Accordingly, a conservative approach to stability assessments involving materials susceptible to static liquefaction would be to assume that triggering does occur. The Factor of Safety for static liquefaction should be considered with reference to Table 8 [the table above] of these guidelines, allowing the static-liquefaction condition to be equivalent to the post-seismic loading condition. For a stability assessment of high consequence dams, it is also considered necessary to assume undrained conditions for contractive materials regardless of whether or not the undrained behaviour is expected."*

Table 5. CDA's Screening Level target factors of safety for slope stability of mining dams - static loading - construction, operation, and transition phases (CDA, 2019).

Loading condition	Minimum factor of safety	Slope
During or at end of construction (prior to commencing of tailings deposition or impoundment of water)	1.3	Downstream and Upstream
During operation of a mining dam when impounding water and/or tailings. Also, during construction of dam raises.	1.5	Downstream and Upstream
Long term (steady state conditions with respect to the dam configuration and seepage, normal reservoir level)	1.5	Downstream and Upstream
Full or partial rapid drawdown	1.3	Upstream slope

Table 6. CDA's screening level target factors of safety for slope stability - seismic loading - construction, operation, and transition phases (CDA, 2019).

Analysis method	Minimum factor of safety	Slope
Post-seismic	1.2	Downstream and Upstream
Pseudo-static	1.0*	Downstream and Upstream

* Unless deformations due to seismic loadings are assessed and are acceptable.

Table 7. CDA's screening level target factors of safety for slope stability - post liquefaction shear strengths - construction, operation, and transition phases (CDA, 2019).

Loading condition	Minimum factor of safety	Slope
Seismic	1.1	Downstream and Upstream
Static	1.1	Downstream and Upstream

That is, for static liquefaction the downstream slope of a tailings dam should be verified with the residual post-liquefaction shear strength of the potentially liquefiable materials targeting a factor of safety of 1.0-1.2, depending on the confidence in residual strength selection. It is important to highlight that despite the table reading "Post-seismic" the recommendation for this "post liquefaction" verification is valid regardless of the liquefaction trigger being seismic or not. Moreover, contractive materials should be considered with undrained behaviour, "regardless of whether or not the undrained behaviour is expected", that is, independently of the trigger mechanism and if it allows partial or reduced drainage during the shearing process - which is in line with ICMM's Global Tailings Review, previously discussed.

It is important to point that, despite explicitly presenting recommended minimum values, the guidelines state that there are no "rules" for acceptable factors of safety, because they need to account for the consequences of failure and the uncertainties involved.

Additionally, various guidelines are postulated for stability analysis, including aspects of liquefaction, analysis / shear resistance considerations / types, earthquakes, etc.

2.3 Canadian Dam Association's application of dam safety guidelines to mining dams (CDA, 2014) and revision (CDA, 2019)

This publication by CDA complements their Dam Safety Guidelines (CDA, 2013) by providing specific guidance on tailings dams. Various provisions on safety from a broad point of view are provided. Specifically for the section regarding slope stability and minimum required factors of safety, a revision was prepared in 2019, after the catastrophic event in Brumadinho.

The discussion presented hereafter is related to the 2019 revision.

Table 5, Table 6 and Table 7 are presented with values referred as "screening levels" of factors of safety, which "if met, are generally viewed as acceptable practice", but "if they are not met, further investigation and analyses, supplemented by analyses and comprehensive use of the observational method, can be used to reduce uncertainty and support lower targets".

Table 7 refers to analyses to be performed with post liquefaction shear strengths. The selection of the type of shear strength parameters to be applied for the analyses related to the values in Table 5 and Table 6 is further discussed in the publication, and briefly summarized hereafter.

Regarding the peak undrained shear strength assessment associated to static liquefaction, in line with the propositions of the ICMM standard (2019), the CDA 2019 revision postulated:

> *"The undrained shear strengths are applicable to both the dams that are under construction and dams that have reached a steady-state operating condition. The undrained failure mode describes material behaviour under shearing during which pore water pressures change and the strength changes, and so this stability check is still required for dams that may not be considered to have a "trigger" for undrained shearing."*

That is, the undrained stability check is required regardless of the likelihood of an associated trigger. The document considers that the drained strength may be overestimated at the time of failure, regardless of the trigger, and "the true factor of safety calculation for dams with contractive elements should be based on undrained loading condition".

In summary, it is proposed that, for dams with contractive materials, factors of safety associated to potential triggers for static liquefaction - including creep - may be checked, but even if no trigger is expected, a verification with peak undrained strength parameters should still be performed.

Similar recommendation is proposed for stability verifications with residual post liquefaction undrained shear strength parameters, which refer to Table 7:

> *"A post-peak analysis should be performed independent of the results of the triggering assessment, to understand the consequences if a loss of strength occurs. Then it can be assessed if a trigger analysis can be performed with confidence and if it is appropriate given the magnitude of the risk, or if simply the precautionary approach assuming post-peak strengths should be used."*

Table 8. CDA's factors of safety for slope stability - static assessment (CDA, 2013).

Loading condition	Minimum factor of safety [Note 1]	Slope
End of construction before reservoir filling	1.3	Upstream and downstream
Long term (steady-state seepage, normal reservoir level)	1.5	Downstream
Full or partial rapid drawdown	1.2-1.3 [Note 2]	Upstream

Note 1. Factor of safety is the factor required to reduce operational shear strength parameters to bring a potential sliding mass into a state of limiting equilibrium (using generally accepted methods of analysis).
Note 2. Higher factors of safety may be required if drawdown occurs relatively frequently during normal operation.

Table 9. CDA's factors of safety for slope stability - seismic assessment. (CDA, 2013).

Loading condition	Minimum factor of safety
Pseudo-static	1.0
Post-earthquake	1.2-1.3

That is, the CDA 2019 revision brought forth the explicit indication of the verification of stability residual post liquefaction shear strengths, considering that "the strengths used for the calculation are a lower bound of the post peak strengths that could be realized". This is relatively in tune with other post-Brumadinho recommendations by ANCOLD (as previously presented) and Brazilian Legislation (as presented hereafter).

In line with most standards and guidelines, the provided factors of safety are regarded as a means to manage risk, and it is stated that they should be based on considerations of both probability and consequence.

Further commentary on the proposed "screening level" values is provided in detail in the document, such as assumed hypotheses, premises, and justifications. A relatively thorough commentary on parameter selection is also presented.

CDA's other publication, Dam Safety Guidelines (2007, 2013 Edition), on the other hand, provides safety guidelines to dams in general, and thus is not specific to mining or tailings dams. Nonetheless, regarding safety and safety factors, some relevant comments are provided. The publication states that:

> *"[...] the level of safety cannot easily be measured using traditional methods. Specific methods, standards and procedures have been adopted with the expectation that, in following the prescribed approach, the desired safety objective will be achieved although the level of protection is still not actually known."*

In that sense, the guidelines detail both the traditional, deterministic, minimum factor of safety approach, and the risk based approach, arguing that they complement each other to a certain degree. The publication acknowledges that the traditional approach historically shows success and is essential to dam safe design and management.

Under the observation that the quantitative definition of minimum factors of safety is based primarily on empirical evidence, experience and engineering judgement, and that they take into account the reliability of inputs, probability of loading condition and the consequences of failure, Table 8 and Table 9 are presented. The tables refer to dams in general, and not specifically tailings dams, and are somewhat different from those presented specifically for tailings dams (Table 5, Table 6 and Table 7).

2.4 SEMAD - FEAM's term of reference for the decharacterization of upstream tailings dams (SEMAD-FEAM, 2020)

The term "decharacterization" in the title of the document refers to decommissioning a facility taking it to a condition in which it cannot be characterized as having been a tailings dams before - a more restrictive final condition.

Shortly after, and as a direct response to Brumadinho's catastrophic event, the government of the state of Minas Gerais, Brazil (state where intense mining activity exists and Brumadinho is located) legislated that all upstream tailings dams within the state have to be decharacterized in a time framework. In this context, the Minas Gerais state regulator, SEMAD-FEAM (State Secretary for Environment and Sustainable Development - State Foundation for the Environment, freely translated by the authors from Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável - Fundação Estadual do Meio Ambiente.), issued a term of reference with minimum requirements for the design of upstream tailings dam's decharacterization. The document complements Law 23.291 of February 2019, which instituted the State's Dam Safety Policy for Minas Gerais.

The publication foresees the development of a diagnosis of the current conditions of the structure, prior to decharacterization. This diagnosis includes the potential identification of alert / emergency levels, which in turn affects features of the design requirements and activities.

However, regardless of the conclusions of the diagnosis, it is demanded that the design must comply to a minimum factor of safety for the condition at the beginning of

Table 10. ABNT's minimum required factors of safety for tailings dams (ABNT, 2017, free translation by the authors).

Stage	Failure type	Slope	Minimum factor of safety
End of construction [a]	Dam and foundations	Upstream and downstream	1.3
Operation with normal operation condition flow net, maximum reservoir level	Dam and foundations	Downstream	1.5
Operation with extreme condition flow net, maximum reservoir level	Dam and foundations	Downstream	1.3
Operation with rapid drawdown of the reservoir water level	Dam	Upstream	1.1
Operation with normal condition flow net	Dam	Downstream	1.5
		Between berms	1.3
Seismic loading, with maximum reservoir level	Dam and foundations	Upstream and downstream	1.1

[a] Successive raising stages of tailings dams cannot be analysed as "end of construction", and must adhere to the minimum factors of safety defined for the operational conditions.

the decharacterization works of (direct quotes of terms as free translation by the authors):

- 1.3 for "undrained peak conditions", referring to limit equilibrium stability analyses applying undrained peak shear strength parameters;
- 1.1 for "undrained residual conditions", referring to limit equilibrium stability analyses applying undrained post liquefaction residual shear strength parameters.

These provisions are somewhat more explicit and stringent than those of the current Brazilian Standard NBR 13028:2017 for the design of tailings dams, as described in the following item. Nonetheless, the Term of Reference states that decharacterization designs shall abide by the guidelines provided in the aforementioned standard.

However, once again, more explicit and stringent requirements are postulated for the minimum required factors of safety for design situations that foresee that an embankment and reservoir will remain after the decharacterization process. The minimum required values are postulated as (direct quotes of terms as free translation by the authors):

- 1.5 for "drained failures", for values obtained for limit equilibrium stability analyses where drained shear strength parameters are applicable;
- 1.5 for "peak undrained failures", for values obtained for limit equilibrium stability analyses where undrained peak shear strength parameters are applicable;
- 1.1 for "residual undrained failures", for values obtained for limit equilibrium stability analyses where undrained post liquefaction residual shear strength parameters are applicable.

It should be noted that the factor of safety value required for an analysis in undrained conditions, and peak shear strength parameters, is equal to that for drained analysis, in tune with the uncertainties existing in either case. The typical consideration of undrained analysis when used for the construction of embankments over soft clayey materials, allowing for a lower value of factor of safety at the end of construction as consolidation with time increases the shear strength properties of the clays, is not associable to the case of contractive sandy tailings. It must also be acknowledged that upon decharacterization the level of monitoring and maintenance decreases - increasing uncertainties - and the restriction of the project's limited lifetime is also eliminated - potentially increasing the overall probability of this loading condition occurring.

2.5 ABNT's NBR 13028:2017 Standard - Mining - Preparation and presentation of design of tailings, sediments and/or water dams - Requirements (ABNT, 2017)

The Brazilian standard for the design of tailings dams, along with other recommendations, presents some criteria for the analysis and verification of slope stability of its structures. This standard is referred to by Brazilian legal documentation, and, therefore, is associated to all legal requirements and discussions within the country.

A brief discussion on loading and shear strength type - drained or undrained - and analysis type - total or effective stresses based - is provided.

Table 10 with minimum required factors of safety is presented, based on loading conditions.

Some measure of ambiguity on the applicability of the presented values is introduced by the standard's text. On one hand it is stated that the values (free translation by the authors) "must be obtained, independent of the type of analysis and loading conditions". On the other hand, shortly after, it also states that (free translation by the authors):

> *"For stability analyses that utilize undrained strength parameters, the minimum safety factors should be established by the designer, based on good engineering practice"*

2.6 Chilean Ministry of Mining's Regulations for the approval of design, construction, operation and closure of tailings dams (Ministerio de Minería, 2007)

This publication is a Chilean government decree establishing legal requirements for tailings dams within the country.

It is worthy of note that upstream tailings dams are legally banned in Chile since the failure of El Cobre N. 1 in 1965 (Valenzuela, 2015).

Slope stability analyses are explicitly required to be presented in the design. A total of 4 "precision phases" (free translation of the term by the authors) is defined, according to the importance of the evaluation and the risks that the reservoir poses to neighbouring areas. They are:

- Phase I: static slope stability analyses (or pseudo-static) considering liquefaction of all tailings;
- Phase II: static slope stability analyses (or pseudo-static) with simplified estimation of the pore pressures;
- Phase III: dynamic analyses based on dynamic property testing of the soils, including displacement calculations;
- Phase IV: analysis for closure conditions, including critical loading condition events and time-dependent effects on the properties of the dam.

Only for phases I and II a minimum required factor of safety value, of 1.2, is postulated, recalling that design of dams and large reservoirs constructed on areas with high seismicity should necessarily focus on loss of stability due to a loss of strength of the embankment and foundation material.

Table 11. Hezra and Phillips' Modified minimum FoS example table. (Hezra and Phillips, 2017).

Level of uncertainties in data, assessment, loading conditions, etc.	Consequence category		
	Low	Significant	High
Low	1.3	1.5	1.5
Medium	1.4	1.5	1.7
High	1.5	1.6	Note 1

Note 1: High consequence dams with high uncertainties in the input data, assessments and loading conditions should not be designed until the level of uncertainties is reduced.

2.7 South African Bureau of Standards' mine residue code of practice (SABS, 1998) and South African Government's Mining Residue Regulations (South African Government Department of Environmental Affairs, 2015)

The South African Bureau of Standards' Mine Residue Code of Practice from 1998 is an important guidance document for the management of tailings facilities. The document provides objectives, principles and minimum requirements for good practice along various stages of a tailings dam life cycle, especially dam safety.

Minimum design requirements are postulated, which include design calculation for structural adequacy, including safety factors and slope stability analysis. However, the publication does not postulate specific values for minimum required factors of safety.

In 2015 the Government of South Africa established new Mining Residue Regulations regarding "the planning and management of residue stockpiles and residue deposits from a prospecting, mining, exploration or production operation". Within SABS 0286 (SABS, 1998) "mine residue" is defined as "any waste tailings derived from any mining operation or from the processing of any material" (excluding overburden from opencast mining operations and residue used as a support medium in an underground mine) and

Table 12. Fell *et al*'s Baseline recommended minimum acceptable factors of safety and load conditions. (Fell *et. al*, 2015).

Slope	Load condition	Reservoir characteristic	Minimum factor of safety
Upstream and Downstream	End of construction steady state seepage	Reservoir empty	1.3
Downstream	Maximum flood	Reservoir at normal maximum operating level (Full Supply Level)	1.5
Downstream	Drawdown	Reservoir at maximum flood level	1.5, free draining crest zones, 1.3 otherwise
Upstream		Rapid drawdown to critical level	1.3

Notes: (1) These factors of safety apply to design of new high consequence of failure dams, on high strength foundations, with low permeability zones constructed of soil which is not strain weakening, using reasonably conservative shear strengths and pore pressures developed from extensive geotechnical investigations of borrow areas, laboratory testing and analysis of the results and using the methods of analysis detailed above [in the reference publication]. It is assumed there will be monitoring of deformations by surface settlement points during construction and during operation of the dams.,
(2) "High permeability crest zones" means the pore pressures in zones near the crest will respond to reservoir level as it rises. For dams with a low permeability earthfill core, the pore pressures will not respond to reservoir rise and lower factors of safety may be acceptable.

Table 13. Fell *et al*'s Factors which influence the selection of factor of safety and their effect on the baseline minimum factor of safety. (Fell *et. al*, 2015).

Factor	Description	Recommended change to the baseline minimum factor of safety
Existing (*vs.* new) Dam	A lower factor of safety may be adopted for an existing dam which is well monitored and performing well	0 to -0.1
Soil or weak rock foundation	A higher factor of safety may be needed to account for the greater uncertainty of the strength	0 to +0.2 for effective stress +0.1 to +0.3 for undrained strength analyses.
Strain weakening soils in the embankment or foundation	A higher factor of safety may be needed to account for progressive failure, and greater displacements if failure occurs	0 to +0.2
Limited (little or no good quality) strength investigation and testing, particularly of soil and weak rock foundations	A higher factor of safety should be used to account for the lack of knowledge. Detailed investigations will be required to confirm conditions.	+0.1 to +0.3 for effective stress analyses, +0.3 to +0.5 for undrained strength analyses.
Contractive soils in the embankment or foundation	A higher factor of safety may be needed to account for the greater uncertainty in the undrained strength	+0.1 to +0.3 for undrained strength.

Note: These figures are given for general guidance only. Experienced Geotechnical Professionals should use their own judgment, but note the principles involved in this table.

"residue deposit" is defined as "that portion of a facility that is the temporary or final depository for mine Residue".

Regarding design considerations for residue stockpiles and deposits, the regulations state that a factor of safety of 1.5 must be achieved. Deviation from this value is only accepted if there are valid technical reasons, in which case adequate motivation must be provided and design must be reviewed by a competent and knowledgeable person.

2.8 Hezra and Phillips' design of dams for mining industry (Hezra and Phillips, 2017)

Even though the publication of individual authors does not bear the same weight as that of associations and institutions, this publication is worthy of note because it presents recommendations for minimum factors of safety related to uncertainties and consequence categories, being specific to tailings dams.

The paper presents a discussion on the safety of tailings dams and the factor of safety (FoS). The authors present an example table for minimum required factors of safety adjusted to both consequence categories and uncertainties, reproduced hereafter in Table 11.

It is important to highlight that the authors present the table as an example, and state that "Different loading conditions would require different adjustments of the minimum FoS. Additional research will be required to define the levels of uncertainties using objectively measured indicators".

2.9 Fell *et. al*'s Geotechnical Engineering of Dams (Fell *et. al*, 2015)

Once again, it must be acknowledged that this publication is due to specific authors and not an association or institution. However, it is worthy of note because it bears recommendations for factors of safety with regard to uncertainties for dams in general, that is, not specific to tailings dams.

Firstly, the authors present Table 12, with minimum required factors of safety according to loading conditions.

Even though the values themselves are fairly traditional, it is interesting to notice that the authors state that they apply specifically to dams with high consequences associated to failure, which implies a consequence category (see Note 1 of the table).

The authors also specify that the values apply to new dams, and to some required features, which imply measures of uncertainty (see Note 1 of the table). With regard to those measures of uncertainty, the authors provide another table, Table 13, with recommended changes to the baseline minimum required factor of safety values.

2.10 NRCS's technical release 210-60 - Earth dams and reservoirs (NRCS, 2019)

This publication by the United States Department of Agriculture's National Resources Conservation Service describes design procedures and provides minimum requirements for planning and designing earth dams. Thus, it does not refer specifically to tailings dams. However, it is worth mentioning that it was released on 03/2019, shortly after Brumadinho's catastrophic event.

Table 14. NRCS's Static Slope Stability Criteria. (adapted from NRCS, 2019).

Design condition	Primary assumption	Remarks	Applicable shear strength parameters	Minimum facor of safety
1. Construction Stability (upstream or downstream slope)	Zones of the embankment or layers of the foundation expected to develop significant pore pressures during construction	Low-permeability embankment soils should be tested at water contents that are as wet as likely during construction (usually wet of optimum). Saturated low permeable foundation soils not expected to consolidate fully during construction. Existing dams with additional fill placed above saturated low-permeability zones.	Unconsolidated; Total stress consistent with preconstruction stress state	1.4 for failure surfaces extending into foundation layers 1.3 for embankments on stronger foundations where the failure surface is located entirely in the embankment
	Embankment zones and/or strata not expected to develop significant pore pressures during construction	Embankment zones, foundation strata, or both comprised of material with a permeability high enough to drain as rapidly as they are loaded	Effective stress	
2. Rapid drawdown (upstream slope)	Drawdown from the highest normal pool to the lowest gated outlet	Consider failure surfaces both within the embankment and extending into the foundation Low-permeability embankment and foundation soils that will have limited drainage during reservoir drawdown	Lowest of effective stress or consolidated, total stress; consistent with pre-drawdown consolidation stresses (See Fig. 5-1 [of ref. publication])	1.2; and 1.1 for near surface (infinite slope) failure surfaces in cohesionless soils
		Embankment zones, foundation strata, or both comprised of material with a permeability high enough to drain as the reservoir is drawn down	Effective stress	
3. Steady seepage	Reservoir water surface at highest normal pool. Phreatic surface developed from the highest normal pool; typically the principal spillway crest	Consider failure surfaces within both the embankment and extending into the foundation. Foundation analysis may require separate phreatic surface evaluation, particularly in sites with confined seepage that results in uplift at the downstream toe.	Effective stress	1.5; and 1.3 for near surface (infinite slope) failure surfaces in cohesionless soils
4. Flood surcharge	Reservoir at freeboard hydrograph level. Steady seepage phreatic surface incorporating increased pore water pressure that may occur from flood detention and pore water pressure from short term seepage resulting from reservoir surface above the normal pool elevation	Consider failure surfaces within both the embankment and extending into the foundation.		1.4; and 1.2 for near surface (infinite slope) failure surfaces in cohesionless soils
		Embankment zones, foundation strata, or both comprised of material with a permeability high enough to drain rapidly with changes in reservoir elevation	Effective stress	
		Low-permeability embankment and foundation soils that will have limited drainage as the increased reservoir load is applied	Lowest of effective stress or consolidated, total stress (See Fig. 5-1 [of ref. publication])	

Table 15. USACE's minimum required factors of safety: New Earth and Rock-Fill dams (USACE, 2003).

Analysis condition[1]	Required minimum factor of safety	Slope
End-of-construction (including staged construction)[2]	1.3	Upstream and Downstream
Long-term (steady seepage, maximum storage pool, spillway crest or top of gates)	1.5	Downstream
Maximum surcharge pool[3]	1.4	Downstream
Rapid drawdown	1.1-1.3[4, 5]	Upstream

[1]For earthquake loading see ER 1110-2-1806 for guidance. An Engineer Circular "Dynamic Analysis of Embankment Dams " is still in preparation.,
[2]For embankments over 50 feet high on soft foundations and for embankments that will be subjected to pool loading during construction, a higher minimum end-of-construction factor of safety may be appropriate.
[3]Pool thrust from maximum surcharge level. Pore pressures are usually taken as those developed under steady-state seepage at maximum storage pool. However, for pervious foundations with no positive cutoff, steady-state seepage may develop under maximum surcharge pool.
[4]Factor of safety (FS) to be used with improved method of analysis described in Appendix G [of reference publication].
[5]FS = 1.1 applies to drawdown from maximum surcharge pool; FS = 1.3 applies to drawdown from maximum storage pool.

Specifically, on the topic of static slope stability analyses, among other recommendations, a table with minimum required factors of safety is provided, and reproduced hereafter in Table 14. Remarks and guidance on applicable shear strength parameters are also provided.

A particular feature of this publication is the prescription of specific minimum values for infinite slope analyses, when applicable for the stability of near surface failure surfaces in the exterior slope of embankments with cohesionless soils.

Another element to consider is that lower factors of safety for construction stability are allowed for cases where foundations are stronger and the potential failure surfaces are restricted to the embankment. This may be interpreted as an allowance for a lower stability margin in the light of lower uncertainties, probably associated with engineered construction materials submitted to QC/QA, which is not the case of tailings dam construction.

Guidelines are also provided for dynamic / seismic stability. Regarding specific provisions for factors of safety, the publication indicates 1.2 as the required minimum value for post-earthquake static stability, when there is potential for significant loss of strength under earthquake loading, therefore for residual or post liquefaction shear strength.

2.11 USACE's slope stability - Engineer manual (USACE, 2003)

This publication by the US Army Corps of Engineers presents recommendations for the analysis and design of slopes in general, regarding their stability. Thus, recommendations are not specific to tailings dams.

Regarding minimum required factors of safety, the manual states that the values are based on design practice developed by USACE during several decades.

Emphasis is put on the fact that appropriate factors of safety postulation should consider the uncertainties of the conditions being analysed and consequences of unacceptable performance. Likewise, it is stressed that criteria for existing dams may be different from those dams to be designed and constructed, with emphasis on investigation, observation, monitoring and performance evaluation, as uncertainties are reduced.

Indeed, the table with minimum required factors of safety presented in the manual is specifically referenced to "New Earth and Rock Fill Dams". The table is reproduced hereafter as Table 15. For existing dams and other types of slopes, the values are regarded as "advisory".

For dams used in pump storage schemes or similar applications where rapid drawdown is a routine operating condition, higher factors of safety, *e.g.*, 1.4-1.5, are appropriate. If consequences of an upstream failure are great, such as blockage of the outlet works resulting in a potential catastrophic failure, higher factors of safety should be considered

2.12 USBR's design standards no. 13: Embankment dams - Chapter 4: Static stability analysis (USBR, 2011)

This publication by the US Bureau of Reclamation presents recommendations for the analysis and design of embankment dams in general, regarding their static stability analysis. Thus, recommendations are not specific to tailings dams.

Recommended minimum factors of safety are provided based on loading conditions. It is stated that deviations from the recommended values may be acceptable if supported with appropriate justification.

It is also stated that the minimum values need to consider the: design condition being analysed; consequences of failure; reliability of parameter estimation; presence of structures within embankment; reliability of investigations;

stress-strain compatibility of embankment and foundation materials; probable quality of construction control; embankment height and judgment based on past experience with earth and rockfill dams.

Another comment worthy of note is that the standard considers that "The factor of safety indicates a relative measure of stability for various conditions but does not precisely indicate actual margin of safety."

Table 16 is presented, with the recommended minimum factor of safety values.

2.13 FERC's engineering guidelines for the evaluation of hydropower projects - Chapter 4 - Embankment dams (FERC, 2006)

The USA's Federal Energy Regulatory Commission produced various documents on risk management and risk-informed decision making for dams. The institution's publication that provide actual guidelines on minimum required factor of safety values is the Engineering Guidelines for the Evaluation of Hydropower Projects.

As specified by the title, the guidelines refer to hydropower, and not mining projects. Still, due to the importance of FERC, the publication is considered relevant.

In line with most publications, the guidelines state that minimum required factor of safety values should depend on uncertainties - specifically the measurement of shear strength, likelihood of the assumed loading, assumptions in the method of analysis, construction quality, confidence on data, etc. - and the consequences of failure - specifically impact on human life, property damage, impairment of project functions, etc.

Despite these conceptual considerations, Table 17, with specific minimum required values "generally required by FERC" is provided.

2.14 CBdB's guide to dam safety (CBdB, 2001)

The Guide to Dam Safety, prepared by the Brazilian Committee for Dams (CBdB) in 2001, provides guidelines on various aspects of the safety of dams in general. Regarding tailings dams, it is simply stated that they may have additional requirements, which should be specifically evaluated by specialists.

For slope stability analyses, the publication provides Table 18 with "normally acceptable" minimum factor of safety values for static slope stability assessment.

In line with other publications, it is stated that lower values may be adopted in specific cases, as long as they are

Table 16. USBR's Minimum factors of safety based on two-dimensional limit equilibrium method using Spencer's procedure. (USBR, 2011).

Loading condition	Shear strength parameters*	Pore pressure characteristics	Minimum factor of safety
End of construction	Effective	Generation of excess pore pressures in embankment and foundation materials with laboratory determination of pore pressure and monitoring during construction	1.3
		Generation of excess pore pressures in embankment and foundation materials and no field monitoring during construction and no laboratory determination	1.4
		Generation of excess pore pressures in embankment only with or without field monitoring during construction and no laboratory determination	1.3
	Undrained strength		1.3
Steady-state seepage	Effective	Steady-state seepage under active conservation pool	1.5
Operational conditions	Effective or undrained	Steady-state seepage under maximum reservoir level (during a probable maximum flood)	1.2
	Effective or undrained	Rapid drawdown from normal water surface to inactive water surface	1.3
		Rapid drawdown from maximum water surface to active water surface (following a probable maximum flood)	1.2
Other	Effective or undrained	Drawdown at maximum outlet capacity (Inoperable internal drainage; unusual drawdown)	1.2
	Effective or undrained	Construction modifications (applies only to temporary excavation slopes and the resulting overall embankment stability during construction)	1.3

*For selection of shear strength parameters, refer to Appendix A [of reference publication].

Table 17. FERC's minimum required factor of safety guidelines (FERC, 2006).

Loading condition	Minimum factor of safety	Slope to be analysed	Shear strength envelope
End of construction condition	1.3	Upstream and Downstream	
Sudden drawdown from maximum pool	> 1.1*	Upstream	
Sudden drawdown from spillway crest or top of gates	1.2*	Upstream	
Steady seepage with maximum storage pool	1.5	Upstream and Downstream	
Steady seepage with surcharge pool	1.4	Downstream	
Earthquake (for steady seepage conditions with seismic loading using a pseudo static lateral force coefficient)	> 1.0	Upstream and Downstream	

The values in the table are referred to analyses with peak shear strengths, and the publication considers liquefaction mainly in association to earthquakes, not in the static liquefaction perspective.

Table 18. CBdB's minimum required factors of safety for static slope stability assessment. (CBdB, 2001, free translation by the authors).

Factors of safety, static evaluation		
Loading conditions	Min. factor of safety	Slope
Steady state seepage with reservoir at the normal maximum level	1.5	Downstream
Rapid drawdown	From 1.2 to 1.3	Upstream
End of construction, before filling the reservoir	From 1.25 to 1.3	Downstream and Upstream

OBS: Higher factors of safety may be required if rapid drawdown occurs with relative frequency during normal operation.

justified, for example through demonstration of good performance with monitoring or more sophisticated analysis. Likewise, situations in which higher factor of safety values may be needed are stated.

The need to take into consideration data reliability, adequacy and limitations of analyses, failure consequences and deformation restrictions when postulating minimum required factors of safety is also highlighted.

Regarding liquefaction, the publication states that susceptible materials should be identified, but the method for their identification is not detailed. If said materials are identified, it is indicated that post-liquefaction stability analysis should be performed.

2.15 Eletrobrás' criteria for the civil design of hydroelectric plants (Eletrobrás, 2003)

The publication by Eletrobrás in 2003 presents criteria for the various design disciplines involved in the design of a hydroelectric plant's dam. Thus, the publication refers to embankment and rockfill water dams, rather than tailings dams.

Brief comments on analysis and shear strength parameter type are provided, as well as on loading scenarios and earthquake loading to be considered in the analyses.

Table 19 is presented with minimum required factors of safety depending on loading conditions. Guidance on the

Table 19. Eletrobrás' minimum required factors of safety (Eletrobrás, 2003, free translation by the authors).

Case	Factor of safety	Shear strength	Observations
End of construction	1.3 (a)	Q or S (b)	Upstream and Downstream Slopes
Rapid drawdown	1.1 to 1.3	R or S	Minimum value for dilatant soils
	(c)		Maximum value for soils that contract upon shearing
Steady state seepage	1.5	R or S	Downstream Slope
Seismic analysis	1.0	R or S	Upstream and Downstream Slopes

(a) For dams higher that 15m on relatively weak foundations apply minimum factor of safety of 1.4.
(b) In zones where no pore pressure is foreseen apply shear strength from S type tests.
(c) In cases where drawdown is frequent consider factor of safety of 1.3.

type of test to estimate shear strength parameters is also provided.

It is worth mentioning that Eletrobrás' recommendations for seismicity criteria have been frequently used for tailings dams in Brazil.

2.16 Summary of the recommendations

From a conceptual standpoint, traditionally recommendations from standards and guidelines state that minimum required factors of safety are a means / tool for managing risk, and thus should be defined based on elements of uncertainty / probability and consequence. However, from a practical standpoint, usually no detailed or specific guidance is provided on how to consider the impact of those elements other than that experience and sound engineering judgement must be applied.

As previously attempted in works by Hezra and Phillips (2017) and Fell *et. al.* (2015), this work proposes recommendations on how to practically apply measures of uncertainty and consequence to the postulation of adequate minimum required factors of safety as obtained from limit equilibrium analysis. That is, taking the broadly philosophically accepted concepts to a practical level.

Regarding tailings dams, some rather clear important trends are noticeable in post-Brumadinho standard and guideline reviews. Mainly, they are:

- The requirement of checking for undrained behaviour considering both peak and residual (post-liquefaction) undrained shear strengths regardless of an associated triggering mechanism being expected;
- Emphasis on consequence assessment influence on design, management and analysis elements and sophistication.

For illustration, a summary table on recommended minimum required factors of safety for tailings dams is presented hereafter (Table 20). Terminologies, methodologies, hypotheses, applicability, remarks, etc. vary from publication to publication, and even though they are bundled together in the following table for the sake of simplicity, they should be considered in the light of the specifics of each publication. For those specifics, the preceding items of this work, or the publications themselves should be referred to.

Additionally, it is worth mentioning that it is expected that ICOLD will soon release a new publication with guidance on factors of safety for tailings dams, which may add to the information presented in Table 20.

It is important to highlight that most publications (except for the legislations) usually postulate the recommended values as a general base, which may be adapted by the engineer, if properly justified.

Lastly, it is known that other important institutions are in the process of discussing and, eventually, reviewing their guidelines and recommendations. For those ongoing reviews, the aforementioned general post-Brumadinho trends usually seem to apply: the explicit recommendation or requirement of post-liquefaction analyses and minimum required factors of safety; the recommendation or requirement of undrained shear strength analyses regardless of specific trigger identification (with minimum factors of safety of 1.3, 1.5, for example); etc.

3. Limit equilibrium analysis

The most commonly adopted method for evaluating the stability of tailings dam embankments, as well as natural, cut and earthfill slopes, under static and pseudo-static conditions in both two and three dimensions is the limit equilibrium method. Several procedures are currently adopted in engineering practice, considering that they all explicitly satisfy force and moment equilibrium of the sliding mass (*e.g.* Bishop, 1955; Morgenstern and Price, 1965; Spencer, 1967, Sarma, 1973, among others). These procedures allow identification of potential failure mechanisms and derive global factors of safety for a particular geotechnical situation based on the general Mohr-Coulomb yield criterion, allowing use of drained, undrained or residual shear strength parameters. The factor of safety is calculated simply as the ratio of the shear strength to the shear stresses required for equilibrium.

Recently, more advanced numerical modelling for slope stability analysis has become common, allowing to predict deformation and pore pressure distribution fields within the soil mass, in addition to limit state conditions. In finite element calculations various schemes for strength reduction are applied to assess the equivalent factor of safety or to estimate the surplus of resistance provided by the input soil or tailings shear strength parameters with relation to what would lead to slope failure. As a result, different methods of analysis may yield different factors of safety depending on the complexity of the problem to be modelled, adding an uncertainty in the decision making process.

Design problems relating simple geometries to textbook material responses may produce similar results. Conversely, problems with complex geometries coupled to complex mechanical soil responses, especially when dealing with post-failure strain softening and progressive failure, would not necessarily yield comparable factors of safety.

In fact, from a theoretical viewpoint, it should be understood that the classical limit equilibrium method only considers the ultimate limit state of the slope and provides no assessment on the development of progressive landslide failure. Although extension of limit equilibrium principles to analyse the stability of strain-softening slopes has been proposed over the years, considering different algorithms to describe the Mohr-Coulomb elasto-plastic soil strength reduction from peak to residual (*e.g.* Law and Lumb, 1978; Miao *et al.*, 1999; Zhang and Wang, 2010), the severe limitations of the classical limit equilibrium method are only circumvented by numerical simulations with

Table 20. Summary of minimum required factors of safety for tailings dams.

Loading condition		ANCOLD (2019)	SEMAD - FEAM (2020)	CDA (2019)	ABNT (2017)[*5]	Chile (2007)	S. Africa (2015)
Long-term, normal operation / reservoir level / conditions		1.5 (drained parameters)	- / 1.5[*1] (drained parameters)	1.5[*2]	1.5 / 1.3[*6]	-	-
Operation with extreme reservoir level / flow net		-	-	-	1.3	-	-
Short-term undrained (potential loss of containment)		1.5	-	-	-	-	-
Short-term undrained (no potential loss of containment), or during / end of construction		1.3	-	1.3	1.3	-	-
Rapid drawdown		-	-	1.3	1.1	-	-
Seismic / Pseudo-static		-	-	1.0[*3]	1.1	-	-
Post-seismic		1.0-1.2	-	1.2	-	-	-
Static liquefaction (regardless of trigger)	Peak undrained shear strength	-	1.3 / 1.5[*1]	-	-	-	-
Post liquefaction undrained shear strength	1.0-1.2	1.1 / 1.1[*1]	1.1[*4]	-	-	-	
Unspecified		-	-	-	-	1.2[*7]	1.5

Notes:
(*1) Values refer to: (prior to decharacterization) / (after decharacterization).
(*2) Also applicable during construction of dam raises.
(*3) Unless deformations due to seismic loading are assessed and acceptable.
(*4) Also applies to liquefaction associated to seismic loading.
(*5) For undrained shear strength parameters, values should be defined by the designer.
(*6) Values refer to: (downstream slope) / (between berms).
(*7) Upstream tailings dams are banned where the publication applies, pseudo-static analysis highlighted.
References:
ANCOLD (2019) - Guidelines on Tailings Dams - Planning, Design, Construction, Operation and Closure
SEMAD - FEAM (2020) - Term of Reference for the Decharacterization of Upstream Tailings Dams
CDA (2019) - Application of Dam Safety Guidelines to Mining Dams Revision (2019)
Ministerio de Minería (2007) - Chilean Ministry of Mining's Regulations for the approval of design, construction, operation and closure of tailings dams
South African Government Department of Environmental Affairs (2015) - South African Government's Mining Residue Regulations.

strain-softening models such as those proposed by Jefferies (1993); Potts *et al.* (1997), Conte *et al.* (2010), among others. The common design practices of using simple analytical methods, at the expense of more sophisticated numerical analysis, associated with low safety factors cannot guarantee a sufficient safe level of the structure for the combination or superposition of the shortcomings in mathematical modelling and the uncertainties in material properties.

Summarizing, a global factor of safety broadly defines the load-bearing capacity of a structure but the actual value depends on the calculation method, whereas the extent to which the calculated value ensures the safety and positive behaviour of a structure will depend on other factors such as the material constitutive model, the accuracy of different soils or tailings strength parameters, the assumed hydrogeological conditions, among other factors. Under the scenario described for static downstream slope stability calculations, the general recommendation is to perform drained and undrained strength analyses and adopt a minimum static factor of safety of 1.5 for the condition that yields the coefficient against instability lower limit, called factor of safety. This general recommendation stands since the 1990s (*e.g.* Carrier, 1991; Szymansky, 1999). However, using factors of safety even greater than 1.5 for static analysis could be justified for dams in higher consequence categories as the values presented in standards and bibliography are minimum values to be pursued.

Conservatism in design and/or posterior verifications should be considered as a general rule in the design of upstream method Tailings Storage Facility (TSF) given the uncertainties in estimating the constitutive parameters, the spatial variability of tailings, and the complex geomechanical behaviour emerging from flow instability, as well as the enormous environmental and social/civilian consequences. For this reason, probabilistic slope stability analysis and risk assessment should be used as complementary to the deterministic method, providing a tool for considering uncertainties of the soil parameters within a range and according to a probability distribution (*e.g.* Griffiths and Fenton, 2004; El-Ramly *et al.*, 2005; Espósito and Palmier, 2013).

4. Recommendations for appropriate values of factors of safety in limit equilibrium analysis

The principle of complying with minimum acceptable factors of safety when assessing the stability of embankment dams of any type or for any use has been gradually adjusted throughout the years. The recent major accidents reported from 2015 to 2019 enforced regulators and industry to question and to review international standard guidelines and the recommended minimum acceptable factors of safety for the different loading conditions that apply to these embankments. The preceding discussion has demonstrated that there is still no acceptable consensus for recommended threshold values.

Currently there are three possible alternatives to design or verify the stability of an operating or abandoned upstream method TSF structure:

a) Adopt prescribed minimum values of factors of safety as related to different loading conditions, without explicitly linking these values to recommended values to consequence categories.

b) Assume the conservative approach of defining factors of safety for ‘Extreme’ consequences of failure, regardless the real consequence categories of the structure as evaluated in specific additional and parallel studies.

c) Adopt minimum values of factors of safety embracing the overall design uncertainties together with the failure consequences to population at risk downstream of the structure.

The principles of minimum values of factor of safety linked to and dependent from the overall uncertainties in design and operational management, and on dam failure consequences are calling attention and have been addressed in several recent publications (*e.g.* Fell *et al.*, 2015; Hezra and Phillips, 2017).

As far as the uncertainties are concerned, tailings storage facilities can be divided into three basic categories, as postulated in Table 21. Information summarized herein works as a basic qualitative classification approach for risk assessment, in line with ICOLD recommendations, intended to evaluate the technical requirements related to dam design, construction and operation (Bulletin 121, ICOLD, 2001). The features described within the table are further discussed in the Appendix.

In summary, the categories proposed in Table 21 may be described as:

- Category I: TSF for which design, construction and operation features lead to negligible or lower level of uncertainty for engineering decision making regarding safety;
- Category II: TSF for which design, construction and operation features lead to an intermediate level of uncertainty for engineering decision making regarding safety;

Table 21. Classification system for qualitative risk assessment of tailings dams. (ICOLD, 2001).

Category	I	II	III
Characterization	Site-specific detailed characterization	Routine field and laboratory testing of tailings and foundations	Insufficient site characterization of tailings and foundations
	Advanced lab testing		
Analysis to back design or evaluation of safety	Numerical analysis with appropriate constitutive stress-strain models together with high quality limit equilibrium analysis	Limit equilibrium analysis	Limit equilibrium analysis
Instrumentation	State-of-the art with continuous reading, transfer of data and interpretation	Cost-effective monitoring	Limited instrumentation
Operation	Expert construction supervision and inspection	Routine construction supervision	No historical construction process.
	Controlled water management	Occasional deviation from ideal operation, leading to beach length, freeboard, water balance in non-compliance	Saturation of critical zones
	Robust long-term asset management planning process	Observation of standards and management procedures	Maintenance planning and management process not implemented

- Category III: TSF for which design, construction and operation features lead to higher or critical level of uncertainty for engineering decision making regarding safety.

High level engineering expertise and judgment is required to take full advantage of this classification system. A factor of safety of 1.3, although accepted in some countries, is not endorsed by all national standards, and in the authors view this value could only be accepted for temporary structures or short-term conditions with no potential loss of containment. A higher factor of safety should be applied even for low risk slopes on tailings dams that fully comply with the design precept that the phreatic surface is fully controlled, and should not daylight in the embankment downstream slope and should be well below the embankment face and in the tailings deposit, with maintenance of the internal drainage systems assuring the long term safety of the structure.

In addition, the authors recall that the residual (post-liquefaction) undrained shear strength ($S_{u,r}$) of a material, soil or tailings, is a strain rate-dependent strength phenomenon in which the viscous component is a function of volumetric strain rate and void ratio (*e.g.* Schnaid *et al.*, 2014; Schnaid, 2021). The undrained residual strength has also been referred to as the undrained steady-state shear strength (Poulos, 1981), the undrained critical shear strength (Seed, 1987) or the liquefied shear strength (Olson & Stark, 2002). Estimating $S_{u,r}$ of a liquefied material, soil or tailings, which behaves as non-Newtonian fluid, whose viscosity decreases drastically with increasing shear strain rate, is still an unresolved issue. Currently, *in situ* test interpretation (CPTU, full penetrometers and FVT) gives only rough estimates of $S_{u,r}$, which limits our ability to approach static liquefaction stability through total stress analysis, because the difficulties in measuring the very low strengths mobilized under brittle response when the material loses strength rapidly, moving from peak to residual, and the possible slip at the element boundary along the failure surface (Schnaid, 2021). For this reason, up to present, engineers have relied on back-analysis procedures (Seed & Harder, 1990; Olson & Stark, 2002; Robertson, 2010; Sadrekarimi, 2014) in which liquefied shear strength $S_{u,liq}$ is rationalized with relation to the pre-failure vertical effective stress and is related to original cone penetration resistance, prior to the liquefaction phenomena. The uncertainty in estimating this key design parameter inherently enforces a choice for factors of safety higher than 1.5 for peak undrained shear strength in static limit equilibrium analysis, which, in the view of the authors, would indirectly lead to at least marginal safety in post-liquefaction conditions.

As for the consequence-based dam safety principle, it will be increasingly used for the design of tailings dams. In undertaking a consequence category assessment, the information provided in Table 22 can be used as a guideline to estimate appropriate factors of safety (Simplified from ICMM, 2019).

Minimum required factors of safety should then be established from the assessment of the combination of management / uncertainty conditions - according to categories I, II, or III from Table 21, in line with ICOLD (2001) - and consequence category - according to categories A, B or C from Table 22, adapted from ICMM (2019).

Once both categories are defined for the TSF, they may be applied to define the recommended minimum required factors of safety as proposed in Table 23. The table also accounts for the TSF lifecycle stage, for which is important to highlight that it is assumed that new TSFs shall be designed ensuring management / uncertainty conditions of Category I.

Values listed in this table apply to both static drained and undrained loading conditions that can prevail in the short term and/or long term and are applicable to the design of new structures and during dam's operation life, as well as for decommission, decharacterization and closure of existing structures. Established for slope stability analysis using limit equilibrium methods, these recommended factors of safety are proposed based on some fundamental concepts.

Under the complex hydrogeological environment of tailings dams, the uncertainties in material properties and the potential loss of containment, it is unreasonable to accept design factors of safety lower than 1.5 for both long-term drained or short-term undrained conditions. As for the proposed factors of safety of existing structures, a more detailed explanation is required to fully appreciate the suggested values safety greater than 1.5.

Being a widely used term in dam engineering, decommissioning a water storage dam means completely removing or breaching the structure in such a way that it can no longer retain or store water. When applied to tailings dams, the term decommissioning is assigned to an engineering process that seeks to shut down a structure and involves activities such as reshaping the slope of downstream or upstream dikes, implementing cover and surface drainage systems, revegetating the covered areas, all of which should be implemented according to specific guidelines and procedures for environmental protection and closure plans (*e.g.* Geological Survey of Finland., 2008; ICOLD, 2011; 2013).

Similarly, dam decharacterization is also related to the closure phase of a structure, but it specifically refers to the process by which a dam ceases operating as a tailings containment structure to be used for other purposes. Introduced in Brazil by the Dam Safety Policy provisions for the State of Minas Gerais, issued on February 2019, it implies that during the physical decharacterization works the structure is removed by excavating the tailings for subsequent disposal in caves or filtered stacks, or is entirely adapted so that the remaining structure will no longer be a dam, being reincorporated into the surrounding geographical environment. Alternatively, one may consider that decharacteri-

Table 22. Consequence categories based on potential loss of life (PLL) and severity of damage and loss, adapted and simplified from ICMM (2019).

Category	Consequence	
	Severity of Damage and Loss	Potential Loss of Life (PLL) / Severity of Damage and Loss
A	Relevant	PLL: None expected *Environment:* No significant loss or deterioration of habitat. Contamination of fauna with no health effects. Material has low potential hazardous characteristics. Restoration possible within 1-5 years. *Health, Social & Cultural:* Significant disruption of business, services or social dislocation (< 500 people). Low likelihood of loss of relevant socio-cultural assets and low likelihood of health effects. *Infrastructure & Economics:* Loss limited to less relevant / infrequently used facilities and infrastructure. Up to US$ 10 M. *Livelihoods:* disruption of up to 10 household livelihood systems recoverable in the longer term or up to 100 recoverable in the short term. No non-recoverable loss of livelihoods.
B	High	PLL: 1-50 *Environment:* Significant to important loss or deterioration of critical habitat / species. Material has moderate to high potential hazardous characteristics. Area of impact 10-20 km^2. Restoration possible but difficult and likely requires significant to long time. *Health, Social & Cultural:* 500-1000 people affected by disruption of business, services or social dislocation. Disruption and/or minor loss of relevant socio-cultural assets. Potential for short term and/or minor long-term human health effects. *Infrastructure & Economics:* High to very high losses affecting relevant to important infrastructure, facilities or employment. Significant relocation / compensation to communities. US$ 10 M to 500 M. *Livelihoods*: non-recoverable loss of up to 25 household livelihood systems, or; longer term recoverable disruption of up to 100 household livelihood systems or; short term recoverable disruption of up to 250 household livelihood systems.
C	Catastrophic	PLL: > 50 **Effects greater than those described for Category B**, for example: *Environment:* Major to catastrophic loss or deterioration of critical habitat / species. Material has high to very high potential hazardous characteristics. Area of impact > 20 km^2. Restoration / compensation impossible or possible but very difficult and requires a long / very long time. *Health, Social & Cultural:* > 1000 people affected by disruption of business, services or social dislocation for > 1 year. Significant loss / destruction of relevant socio-cultural assets. Potential for severe and/or significant longer-term human health effects. *Infrastructure & Economics:* Very high to extreme losses affecting important to critical infrastructure, services or employment. High to very high relocation / compensation to communities and or very high social readjustment costs. US$ > 500 M. *Livelihoods:* number of household livelihood systems impacted greater than those of Category B.

zation involves transforming an upstream dam into a downstream structure.

In existing well-maintained structures, operating under expert construction supervision and inspection, decommissioning and decharacterization are performed under the specific requirement of meeting the safety regulations from updated Standards. Design for decommissioning embraces the same risk management associated with building new dams and should, therefore, follow the same factors of safety recommended in design of new structures.

On the other hand, in decommissioning a vulnerable structure (Categories II and III on Table 21) engineers have to handle various challenges emerging from deficiencies in construction and operation, insufficient data to obtain complete and objective characterization of tailings and foundations, heterogeneity of the tailings as produced from

Table 23. Recommended factors of safety for static short term and/or long term undrained and drained analyses.

Category	Design	Operation to closure		
	New upstream or downstream structures	I - Well-maintained upstream structures	II	III
Consequence category	A	1.5	1.5	1.5
	B	1.5	1.5	1.7
	C	1.5	1.5	1.8

Note: Management / uncertainty category (I, II or III) may be defined from Table 21, in line with ICOLD (2001). Consequence category (A, B or C) may be defined from Table 22, adapted from ICMM (2019).

different ore and beneficiation processes along time, malfunction and deterioration of the dam, among other factors, in order to ensure that it remains stable for all conceivable load combinations and structural reinforcement phases. These uncertainties inherently increase the probability of failure in each stage decommissioning scenario, which is partially compensated by the higher factors of safety listed in Table 23, *i.e.* factors of safety in limit equilibrium analysis, if numerical simulations cannot be performed, larger than the minimum value of 1.5 for both short and long term conditions are necessary to minimize the likelihood of accidents during the process of decommissioning or decharacterization, and avoid major human consequences if they occur.

In addition, adoption of higher factors of safety for dams under Categories II and III has major implications when considering static and cyclic liquefaction-triggered stability analysis in tailings. A critical element of liquefaction assessment is the uncertainty associated to the residual (liquefied) undrained shear strength ($S_{u,liq}$), which limits our ability to approach liquefaction stability through routine total stress analysis. Factors of safety equal or greater than 1.7 for static short term analyses using undrained peak shear strength ($S_{u,p}$) implicitly circumvent this limitation because a safer design for peak strength works as a minimum requirement to satisfy the recommended factors of safety for static liquefaction (of the order of 1.1 as has been discussed by many professionals). Under a more conservative approach, liquefaction stability assessment is still required to manage liquefaction related risk, but errors in predicting $S_{u,liq}$ when performing deterministic analysis become less critical.

A final comment refers to seismic stability assessment of tailings dams. Countries across the world rely on codes of practice to establish minimum levels of safety requirements against earthquakes in order to ensure structural performance. Over decades, there has been considerable research in this topic and a critical review of loading conditions associated to pseudo-static or post-seismic analyses is not covered by the current discussion and proposals.

In respect to Table 23, lower factors of safety may be acceptable when geotechnical design is improved by making extensive use of finite element and finite difference techniques coupled to appropriate constitutive modelling, and proper knowledge of the behaviour of the structure and the tailings contained is gained. This is especially relevant in cases where tailings do not sustain a constant value of deviatoric stress under undrained shearing leading to high strain softening and subsequent failure by flow liquefaction. However, it should be recognized that numerical analysis is an expert field requiring skills, judgment and experience other than mathematical expertise (see ANCOLD, 2019).

5. Conclusions

This paper explores early works on the subject and presents a proposal of guidelines that try to help select suitable minimum design factors of safety for tailings dams slope stability analysis using limit equilibrium calculations. The proposed values are more conservative than what has become standard in international practice for vulnerable structures where consequence, uncertainties, risk and characteristics of loose tailings increase engineering design challenges.

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Appendix

The authors recognize that subjectivity exists in qualitative risk assessments, leading to different interpretations from users from different backgrounds and/or technical culture. Trying to minimize the impact of this fact, a tentative, and at the same time more precise description of the Categories listed in Table 21, allowing for a more consistent qualitative risk assessment of tailings dams, is proposed herewith. These are the views of the authors and cannot be seen as a prescription without the users own judgement.

Site Characterization

Category I

- Geological complexity of the site is well-defined for soils and rock formations.
- Topographical, hydro-geological, geotechnical and geo-environmental information acquired and documented.
- Extensive and continuous ground investigation programs implemented periodically during the construction and life-time operation.
- Site-specific detailed characterization - encompassing at least but not only:
  - CPTUs, with pore-pressure dissipation curves performed at depths to full stabilization to identify perched water tables and complex flow patterns.
  - In Hole seismic geophysical tests, like Cross Hole or Down Hole, S-CPTU seismic CPTUs; S-DMT, as well as Surface Geophysical Methods.
  - Complementary tests such as DMT (Marchetti dilatometer), SBPM (self-boring pressuremeter tests) and FVT (vane tests).
- Advanced laboratory testing, with detailed analysis of constitutive parameters of tailings and foundations., comprising:
  - Undisturbed samples, preferably using stationary piston samplers and the Gel-Push sampler when recommended.
  - Reconstituted samples (problem of aging generating structure is a pending issue after the Brumadinho failure).
  - Consolidated undrained tests, isotropically and anisotropically consolidated, CIU and CAU on saturated samples as well as on partially saturated samples. Compression and extension tests.
  - Direct simple shear tests, DSS.
  - Cyclic triaxial tests.

Category II

- Basic geological topographical, hydro-geological, geotechnical and geo-environmental information, following basic standards and international specifications.
- Routine field and laboratory testing of tailings and foundations.
  - SPT, CPTUs with routine dissipation tests. Vane tests in close arrays to better interpret that data.
  - Disturbed samples from continuous soil samplers or small diameter thin-wall samplers to calculate the void ratio variation with depth from water content measurements taken below the water table.
  - Reconstituted samples to test on CIU and DSS tests.

Category III

- Insufficient site characterization of tailings and foundations, not in compliance with the standards postulated for Category I.
  - No detailed knowledge of the tailings dam foundations, the starter dam and raising dikes; their internal drainage system and the global internal drainage concept.
  - In situ SPT and CPTU with routine dissipation tests.

Analysis to back design or evaluation of safety

Category I

- Numerical analysis with appropriate constitutive stress-strain models together with well-established limit equilibrium analysis.
  - Use of critical state soil mechanics (CSSM).
  - Introduction of sensitivity analyses to understand and evaluate change of conditions, as a trigger of static liquefaction.
  - Develop limit equilibrium analysis for shear strength associated to the collapse surface of the tailings.
  - Proper alert levels defined for the interpretation of the monitoring program.

Category II

- Limit equilibrium analysis based on average constitutive parameters.
  - Conventional series of limit equilibrium analysis, both in drained and undrained analyses; circular and polygonal potential failure surfaces minimizing value of FS.
  - Difficulties in postulating alert levels for all the instruments, not only associated to displacements.

Instrumentation

Category I

- State-of-the art with continuous reading, transfer of data and interpretation.
  - Electric Piezometers and Water level indicators automated with readings at short periodicity.

- Inclinometers, either manual or vibrating wire in place inclinometers.
- Interferometric technologies for surface displacement monitoring - such as InSAR and Ground Based Radar - have seen and are seeing a significant popularization in Geotechnical Engineering practice as a whole and in mining applications.
  - These are considered to be useful tools for effective monitoring, if used correctly.
  - Nonetheless, their limitations should always be highlighted and considered for interpretation. For example, usually the displacement measurements refer only to a given orientation axis or plane related to the line of sight of the equipment, potentially implying a bias. Also, authors state that changes in surface conditions - for example, moisture, temperature, and especially vegetation - may lead to significant noise and errors in measurements (Thomas *et al.*, 2019; Robertson, *et al.*, 2019, Gama, *et al.*, 2013).
  - Thus, these tools are valuable, but should be used with due care provided that precision is within the acceptable range. In the same sense that geophysical *in situ* tests should be interpreted together with traditional borehole data in the light of a geological model, interferometric data should be interpreted together with other monitoring techniques - such as topographic monitoring, DGPS, visual inspection, etc. - and by a team of professionals that are proficient both in the measured geotechnical physical behaviours and in the interferometric technology applied.
- Flow meters in the exit/outlet of all internal drainage devices.

Category II

- Cost-effective monitoring.
  - Electric Piezometers and Water level indicators read manually.
  - Inclinometers read manually.
  - Topographic survey marks read by precision topography.
  - Flow meters in the connections of main drainage ditches and bottom exit of the drainage system.

Category III

- Limited instrumentation.
  - Mechanical instrumentation systems including standpipe Casagrande piezometers, water level indicators, flow meter at the bottom exit of the internal drainage system and topographic survey marks.

Operation

Category I

- Expert construction supervision and inspection.
  - Thorough, robust, and formal implementation of Quality Control (QC), Quality Assurance (QA) and Construction *vs.* Design Intent Verification (CDIV), with high standards and capacitation of involved professionals.
  - Preparation of Site Inspection Manuals, with well-established methodology and straightforward procedures, types and frequency of QA/QC test work, inspection, recording and reporting requirements.
  - Periodic (*e.g.* annual) preparation of a detailed Construction Records Report.
  - Implementation of formal change management systems to evaluate, review, approve and document all changes to design, construction, operation and monitoring.
  - Assignment and due empowerment of a qualified Engineer of Record. Conduct annual construction and performance reviews through the Engineer of Record or a senior independent technical reviewer. An independent senior technical reviewer shall also conduct periodical Dam Safety Reviews.
- Controlled water management.
  - Development and implementation of water balance and water management plans, taking into account all relevant information and criteria, and all stages of the tailings facility lifecycle.
  - Proper monitoring, recording and management of relevant parameters and phenomena (*e.g.* seepage, flow, etc.). Both dam and environmental safety should be provided for.
  - Operators properly trained and periodically retrained. For higher consequence facilities, the team includes a qualified civil or geotechnical engineer.
- Robust long-term asset management planning process.
  - Development of a "*Life of Mine Plan*", integrating all the processes, systems, procedures and other activities required for safe and economical tailings storage facility, considering all stages of the lifecycle, according to recognized standards and guidelines. Provision of all the necessary planning data and information. Plan reviews should be periodically (*e.g.* annually) conducted.
  - Develop and formally implement a Tailings Management System (TMS) as well as an Environmental and Social Management System (ESMS), and perform periodic audits to verify those systems, considering all stages of the facility lifecycle.
  - Conduction and regular update of risk assessment with multidisciplinary team applying best practice methodologies. Provide a robust, state of the art sys-

tems for the management, communication and disclosure of such risks.

- Development, implementation and periodic (*e.g.* annual) update of an Operations, Maintenance and Surveillance Manual with context and critical controls for safe operations and proper record of inspections, findings, etc.

- Refine the design, construction and operation along the facility lifecycle through lessons learned from ongoing work and the evolving state of the art.

Category II

- Routine construction supervision.
  - Construction supervision is provided for, but inspection and the level of control, documentation, robustness, etc. do not fully meet the standards postulated for Category I.
- Occasional deviation from ideal operation, leading to beach length, freeboard, water balance in non-compliance.
  - Some level of water control is provided, but standards postulated for Category I and not fully met, in a manner that allows for occasional non-compliance.
- Observation of standards and management procedures.
  - Standards and management procedures are established / recognized and observed for the current tailings storage facility operation.
  - However, a comprehensive, long term asset management planning process is not fully implemented as described for Category I.

Category III

- No historical construction processes.
  - No formal documentation or record of the construction process, supervision and inspection is available.
- Saturation of critical zones.
  - Non-existing or ineffective water management leads to identifiable saturation of critical zones within the tailings storage facility.
- Maintenance planning and management process not implemented.
  - No formal and standardized planning and management process is implemented for the tailings storage facility.