Responsible Design and Other Defences Against Static Liquefaction of Tailings Structures

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Abstract

Static liquefaction is a failure mode contributing to some of the most devastating tailings failures in the last few decades, including those at Samarco (Fundão) in Brazil in 2015, and at Merriespruit and Bafokeng in 1994 and 1974 in South Africa, and many others. While other mechanisms may have also contributed to these failures, the role of static liquefaction is now inarguable.

Static liquefaction occurs when a saturated or partially saturated material experiences a rapid loss of strength due to an undrained loading response resulting from a trigger such as excessive rainfall, rapid loading as a result of high rate of rise, or loss of resistance as a result of excavation or erosion of the downstream toe. Even though static liquefaction is a known and credible failure mode for many tailings structures, this type of failure continues to occur. Many of the above failures could have been prevented if more responsible design approaches and better defences were adopted.

Methods for characterizing tailings deposits, in situ and in the laboratory, as well as methods for assessing their liquefaction potential using cone penetration testing have been well published recently, summarizing leading practice for characterizing and assessing the liquefaction potential of tailings deposits.

The authors have however, found very little published guidance on how to design, build or operate structures to avoid the risk of static liquefaction.

The purpose of this paper is to provide guiding principles for the responsible design, construction and operation of tailings structures such that static liquefaction can be avoided or minimized as a failure risk. This emphasis is now more relevant than ever, if future static liquefaction failures are to be avoided.

Importance of the Static Liquefaction Phenomenon in Tailings

Flow liquefaction resulting from a static trigger, herein termed static liquefaction, is the sudden loss of strength when the shear stress exceeds the undrained shear strength of a loose, cohesionless soil. Static liquefaction poses a significant risk to tailings storage facilities as many designs rely upon developing resistance within the impounded tailings for stability. It is of keen interest because it is a brittle failure mode that can occur with little warning, with seemingly small events causing catastrophic results. The "observational method", widely used in the tailings industry and responsibly applied with considerable merit in the oil sands, provides little to no protection for brittle failure, and for static liquefaction in particular.

There are a wide variety of potential triggers for static liquefaction, including a rising water table, beach loading, dyke raises, removal of confinement, slope steepening and others. These triggers can act on their own or in conjunction with other triggers to cause a liquefaction event. Undrained failures can occur in materials that are permeable and that have, up to a certain point, been following a drained loading path.

It is most challenging to design away the potential triggers of liquefaction and with the brittle (rapid) nature of the transition, there is insufficient time to mount a response. These risks must be properly accounted for in the design process as, by definition, failure will happen too quickly to enact mitigation measures.

The Assessment of Static Liquefaction

Identification of liquefiable tailings

Methods for characterizing tailings deposits, in situ and in the laboratory, as well as methods for assessing their liquefaction potential through the use of cone penetration test (CPT)-based relationships have been well published recently, summarizing leading practice for characterizing and assessing the liquefaction potential of tailings deposits (see the references listed in the essential reading section below). Robertson and others (2017, 2018, 2019) and Fourie & Reid (2018, 2019) have presented comprehensive training courses on the assessment of static liquefaction. Annual courses at the University of Alberta and the University of British Columbia also traverse the topic.

In brief, the most common methods to assess liquefaction susceptibility are based on the measured resistance to either the standard penetration test (SPT) or the CPT. In recent years with the increased availability of cone testing rigs and the increased confidence in the results of the assessment methodologies, liquefactions assessments are more commonly performed using CPT. The assessment of liquefaction susceptibility defines the liquefiable boundary in terms of an offset to the critical state line of -0.05 in terms of void ratio or using a clean sand equivalent normalized cone resistance ($Q_{tn,cs}$) value of 70, which yields a similar boundary (Robertson 2010). Materials with a state parameter of > -0.05 are considered potentially liquefiable (Refer to Figure 1).

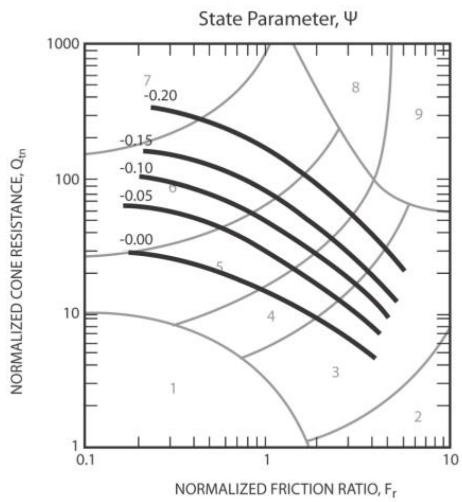

Figure 1: Approximate state boundary lines superimposed upon SBT chart (Robertson 2009)

Strength of liquefiable tailings

Similar to the identification of liquefiable tailings, several methods exist that attempt to quantify the tailings post-liquefied residual strength (Olson & Stark 2003, Robertson 2010, Sadrekarimi 2014). These methods are all based on the results of CPT soundings with pore pressure measurement. Using case histories of flow liquefaction failures, slope stability back analyses were conducted to estimate the strength of the material at the time of failure that would result in the final post-failure configuration.

The assessments by Olson & Stark (2003) and Robertson (2010) are based upon available in-situ test data, split into classes of reliability. Class A and B results are most commonly used in the assessment which comprise CPT measurements taken prior to the failure. The back analyses require simplifications to the stratigraphy and estimates of the momentum effect on the final slope configuration. The assessments were also conducted in two-dimensions. Sadrekarimi (2014) measured the post-liquefied strength ratio through a series of triaxial and direct simple shear tests. These results were compared against a re-analysis of the case histories presented by Olson & Stark (2003) using updated assessment methodologies. These methodologies can be used to assign the residual strength for use in a limit equilibrium-based assessment.

Application of the assessment methodology

The tools discussed in the previous sections are intended for the preliminary evaluation of tailings deposits, to address their susceptibility to liquefaction and to estimate the strength parameters that should be used in a stability evaluation of the facility.

Judgement is required in the application of the methods to design, and care needs to be exercised in understanding the assumptions within the analyses. Caution should be used when applying the strengths as the back analyses considered certain layer thicknesses, employed two-dimensional analysis, assumed that strengths were mobilized across the entire failure plane and also made other limit equilibrium assumptions.

The assessment of liquefaction susceptibility is intended to be used for cohesionless and low plasticity soils that experience a rapid loss in strength at small shear strains (Robertson, 2010). Current practice is to consider that liquefiable materials will liquefy, and that residual strengths should be used in analysis - essentially designing the containment structure to hold a heavy fluid. High plasticity clays also tend to experience strength loss. However, the loss of strength in these materials tends to occur much more gradually than for silty sands and the initiation of strength loss tends to occur at high shear strains. For these materials, peak shear strengths, with consideration for the imposed stress regime in light of the materials' stress history, are typically used in design, for example in the design of subsequent post-failure raises at Mt. Polley (Golder, 2016).

The question arises as to what strength should be selected for intermediate materials that fall in between these two extremes. At a screening level, these materials could be addressed assuming residual strengths and peak strengths. The variance in the required design measures could then be used to justify a laboratory investigation into establishing the in-situ stress conditions and the stress-strain behaviour of the materials. Characterization of these materials can also be complicated by pore fluid chemistry, the presence of polymers (that usually degrade with time) and the presence of bitumen or other organic materials.

In special situations, more sophisticated analysis using numerical tools such as FLAC and the NorSand constitutive model can be considered in a stress-deformation analysis. This requires a thorough investigation of the material behaviour, the stratigraphy, the in-situ stress state and potential stress paths that the material could experience. The benefit of these types of analyses is that failures occur organically. However, the results are heavily dependent on assumptions that the user is obliged to make, especially for a partially constructed facility. These types of analyses are typically undertaken in failure investigations rather than as a design tool used in isolation.

Essential reading on liquefaction assessment

There are a number of useful references that provide information and background for undertaking a liquefaction assessment. In the authors' experience, the following references are essential reading for any engineer undertaking liquefaction assessment:

- Fear & Robertson (1995) - Estimating the undrained strength of sand: a theoretical framework.
- Jefferies & Been (2016) – Soil liquefaction: a critical state approach.
- Jefferies et al. (2019) – Report on NTSF Embankment Failure: Cadia Valley Operations for Ashurst Australia
- Morgenstern et al. (2016) – Report on immediate causes of the failure of the Fundão Dam.
- Olson & Stark (2003) – Yield strength ratio and liquefaction analysis of slopes and embankments.
- Robertson (2010) – Evaluation of flow liquefaction and liquefied strength using Cone Penetration

Test.

- Sadrekarimi (2014) – Static liquefaction-triggering analysis considering soil dilatancy.
- Sadrekarimi (2016) – Static liquefaction analysis considering principal stress directions and anisotropy.

Rationale for Precaution and Defence

Liquefaction is a brittle failure mode. The observational method, widely used in the tailings industry and responsibly applied with considerable merit in the oil sands and elsewhere, provides little to no protection for brittle failure, and for static liquefaction in particular. Defences must be provided through other means.

The numerical tools that are currently available are valuable, but they have several limitations as discussed above. Properly accounting for the combinations of events that could lead to failure also promotes a precautionary design approach.

The guidance provided below focuses on what precautionary steps can be taken during design, construction and operation, to mount a defence against liquefaction failure.

A. Precautionary Principles for Responsible Design

1. Decide to not store water or fluid tailings behind tailings dams

Mount Polley, Fundão and other recent tailings failures are reiterating the lessons of the past 50 years: do not store water behind tailings dams. Instead, store water behind water dams and aim at a zero-pond approach for tailings containment. A new corollary is now being added: aim for the storage of tailings which are inherently stable behind tailings dams and store liquefiable tailings against more conventional dams. Boswell & Sobkowicz (2015) list this as a Best Available Technology (BAT).

The ravages of time, climate change and other factors have shown in cold and northern climates how difficult it is to maintain water storage and thermal stability at the same time (Proskin et al. 2017).

The message is abundantly clear: if possible, avoid storage of water or liquefiable tailings behind tailings dams.

2. Identify all potential triggers for liquefaction

Identify all weak zones in the foundation, anticipated short and long term groundwater conditions, and other factors about the foundation, the dyke and the pond contents that could lead to a triggering mechanism for static liquefaction. Design to avoid those factors, as much as possible, and where not possible, provide several layers of mitigation.

3. Wherever possible, eliminate strain softening as a trigger

It is important to understand the variability of the foundation and dyke construction materials, and incorporate that into design. In particular, the complexity of the foundation for a large structure may demand much more than a single site investigation, in order to fully characterize and understand its behaviour. Instead, an iterative and integrated campaign approach is recommended, that evolves as new understandings are gleaned from previous test results, as early performance becomes evident, and as design changes occur. Good design and economic design are both derived from a full understanding of the hazards that are facing the structure. Typically, an increased investment in ground investigation results in a more cost effective design and at worst it may have cost a little more to gain a more reaffirmed understanding. Contrast this with an under-scoped investigation that fails to adequately capture the complexities of the foundation materials, resulting in increased cost, delay, increased potential for failure, or at worst, another failure such as occurred at Mount Polley.

4. Design the dam with a robust size of non-liquefiable zone

This will depend on the height of the dam, the dyke slope (heavily dependent on foundation conditions), and the strength of the contained tailings. The proposed dyke section should be plotted up in natural scale (never, ever visualize a dam using exaggerated scale drawings). The non-liquefiable zone should then not look like a “shell” or a “skin” or a “wall"; it should clearly be a significant structural component of the dyke. There is no hard number for this, but to start, size the non-liquefiable zone to be 5 to 10 times as wide at its base as the dyke is high, and either staying with that width or narrowing slightly towards the top of the dyke. The flatter the dyke slope, the wider (horizontally) the non-liquefiable zone should be. This is just for preliminary sizing during the concept stage; the width of this zone should be adjusted as the design progresses and is subject to various analyses.

5. DO NOT design on the basis of avoiding triggering liquefaction

Design on the basis that if a loose sandy zone can liquefy, it will. The dyke must be designed and built to perform adequately if that happens.

6. Incorporate substantial drainage in the design

Provide as many drains as possible for the dyke and beached materials (including at, or in the foundation). The better the drainage, the better the density will be when the dyke is constructed (if performed hydraulically) and when the beaches are poured.

7. Characterize material upstream of the non-liquefied zone

Determine the most likely case (MLC) and reasonable worst case (RWC) strengths for the material upstream of the non-liquefied zone. The MLC strength might be drained but representative of a loose sand (or silty sand); the RWC strength would of course be the liquefied case. Avoid being overly optimistic about these strengths during the initial design phases.

8. Characterize material in the non-liquefied zone

Likewise, determine MLC and RWC strengths for the material in the non-liquefied zone that are compatible with the identified failure modes and expected strain in the dyke and foundation.

9. Employ strain compatible and reliable downstream berm support

If downstream berms are required, use material that can be placed and compacted to a known condition, with well-understood material properties. These outside dyke zones and berms should have a ductile stress-strain response and be strain-compatible with whatever failure mechanisms are anticipated, so that this portion of the dyke can be instrumented, and all credible failure modes properly monitored. In particular, if the material in these zones is too soft or too loose, so that large deformations are required to develop their peak strengths, other portions of the dyke (such as the foundation under the upstream and middle portion of the dyke) may reach and pass peak strength. Large deformations and high deformation rates are to be avoided to prevent triggering liquefaction.

10. Use deformation analysis to identify zones of weakness

Since limiting deformations is such an important part of the design, reliance should not be placed on limit equilibrium stability analyses alone. Also, deformation analyses should be completed to identify areas where deformations might be significant and trigger liquefaction of overlying tailings. Again, design these areas to keep any potentially liquefiable material well away from the structural part of the dyke.

11. Pursue Best Available Technology (BAT) and Best Applicable Practice (BAP)

Process and tailings engineering technologies which serve to reduce liquefaction risk include:

- Substantial reduction in water content of the tailings prior to or during disposal.
- Avoidance of storage of water within tailings facilities, and storage within dedicated reservoirs or recycle water dams instead.
- Deposition of tailings stabilized by chemical or other means.
- Reduction of risk by compartmentalization (to reduce consequences), while also being careful to avoid the risk of cascading failures.
- Pursuit of in-pit or underground disposal (backfill), which potentially reduces the consequences of a failure.

- Adoption of an appropriate level of (extreme) precaution, in dealing with very high or extreme consequences and risks.

Further detail is provided by Boswell & Sobkowicz (2015) in listing and describing Best Available Technology (BAT) for reducing consequences, offering a context for Best Applicable Practice (BAP), and suggesting the key differences between the application of BAT versus BAP.

12. Perform a comprehensive FMEA and formally reduce liquefaction risk

Carry out a Failure Modes and Effects Analysis (FMEA) to identify all design, construction and operational conditions that could contribute to liquefaction of dyke zones (and other failure modes). In addition, build multiple layers of mitigation into the design, construction and operations of the dyke to deal with those conditions. The intimate involvement of groups that will construct and later operate the dyke is critical.

A formal process for evaluating tailings designs to fundamentally reduce liquefaction risk should be employed. While processes such as Failure Modes and Effects Analysis (FMEA) are useful, they cannot be allowed to merely develop a register of risks and mitigation measures for an existing design. The risk reduction requirements should address all aspects from early scoping through technology selection, and possible redesign, to closure.

Specific monitoring and surveillance precautions and actions required for mitigation of static liquefaction risk, should be systematically documented in an updated OMS manual.

Update this exercise every few years to attune new staff in the organization to the sensitivities of the design, and to identify any new design, construction and operational conditions that could contribute to liquefaction of dyke zones, and build multiple layers of mitigation into the design, construction and operations of the dyke to deal with those conditions.

B. Precautionary Principles for Responsible Construction

1. Develop appropriate and relevant specifications

Work out specifications for dyke and non-liquefied zone density. Determine how these will be achieved and both the QC and QA controls that will be employed to confirm them.

2. Employ advanced laboratory testing to confirm material properties

Determination of MLC and RWC properties for both potentially liquefiable and non-liquefiable zones will require advanced laboratory testing of material covering the full gamut of fines content, grain size distributions, etc.

3. Appoint an Engineer of Record and define responsibilities

It is now accepted practice that a designated Engineer of Record be appointed to take responsibility for the construction and performance of the dyke. This responsibility is not however, in isolation. Boswell & Martens (2017) describe in detail the role of the Engineer of Record and summarize the other roles and requirements required of key personnel within an integrated dam safety management system.

4. Specify and build structural portions of the dyke accordingly

Ensure that portions of the dyke that need to be "structural" are actually specified as such, and built that way:

- All tailings that need to meet certain density specifications actually do, and are discharged in areas that are well-drained and/or track-packed.
- Upstream and downstream berms and ramps meet sufficient density specifications and are not just dumped waste. Material in these zones does not just provide weight; it must also provide strength and limit deformation.

5. Provide continuity for the Operations Phase

Consider what group will be responsible for the early/starter dyke construction. Their key engineers and construction staff should be involved in the FMEA (previous point). They should also have a designated Engineer of Record who takes responsibility for the construction and performance of the dyke. Proper transition of this responsibility to a different person during Operations should also be considered and implemented.

C. Precautionary Principles for Responsible Operation

Among many important considerations, some of the primary operational defences against static liquefaction are preventive, rather than curative: these important defences are quite mundane and are often overlooked. These defences are described below.

1. Develop multiple precautions for the initial deposition, or start-up phase

Examine the initial behaviour of discharge into the pond - where will the tailings flow and where will the initial pond form? Design dyke elements that are robust in this area and keep any potentially liquefiable material, e.g. beach below water (BBW), well away from the dyke structural zones. Precautions and additional preparation may include:

- Build the starter dyke in the area where the initial pond will form out of structural material, to a sufficient elevation and geometry to preclude potentially liquefiable material from close proximity to the dyke, where it might otherwise introduce risk and fragility.
- Include extra berms or ramps on the upstream side of the dyke to generate the requisite geometry. These should be constructed of compacted fill, not waste, as they will need to meet a certain strength specification.
- Consider an "engineered pond bottom", essentially reversing the natural slope of the ground, to force the initial pond well away from the dyke.
- This approach is particularly useful when the designer anticipates a lot of "off spec" tailings in the start-up phase of the plant and/or the need to store water in the tailings pond before start-up.

2. Design and operate the pond to be at a minimum size

This requires careful thought and much interaction with Operations staff so that they understand how important it is, and so they themselves design and build robust systems for removing water from the pond (e.g. using suction dredges rather than pumps when high sediment water is expected). Precautionary actions in regard to pond size might include:

- Minimizing the need for raw water import and maximizing water recycling opportunities.
- Anticipating any need to store water in the tailings area prior to start-up, i.e. during the initial construction phase.
- Anticipating the need to import additional water during high flow times in adjacent rivers so that water importation during low flow times or scarcity is avoided. There must be an allowance in the water inventory to store this extra water without impacting the dyke and beach operations (for example, through off-channel storage).
- If it becomes necessary to store water from other sources (e.g. groundwater) in the tailings pond, make allowance for this in the tailings plan as well, without compromising beach length and dyke design requirements.

3. Provide sufficient tailings contingency storage capacity

In addition to anticipating water storage needs, provide a tailings storage contingency within the tailings plan (6 months is typical) so that under minor upsets beach lengths can still be maintained. This is a critical aspect of tailings planning – as important as providing sufficient pond freeboard - and should not be ignored nor compromised. It should be formally recognized as a part of the tailings plan.

4. Design for specific beach above water (BAW) lengths

Assiduously monitor BAW lengths during Operations. Short-term tailings plans should project pond levels and beach lengths, and immediately implement plan changes to avoid encroachments. It is unacceptable to violate beach length/density requirements and then later "recover". This builds potentially liquefiable zones into what should be consistently a structural, non-liquefiable material.

5. Confirm that Beach Above Water (BAW) is truly non-liquefiable

Regularly confirm that BAW zones are non-liquefiable and adjust operations (e.g. by increasing deposition area, reducing rates of rise, or through implementing or increasing track-packing) where necessary.

6. Assiduously develop and preserve beach freeboard

A distinction should be made at the outset, between total freeboard and beach freeboard. As the name implies, beach freeboard is the amount of freeboard provided by the beach alone.

As illustrated in Figure 2, total freeboard provides the (as-measured) overall defence against overtopping, and may be rapidly improved by elevating the crest of the dam.

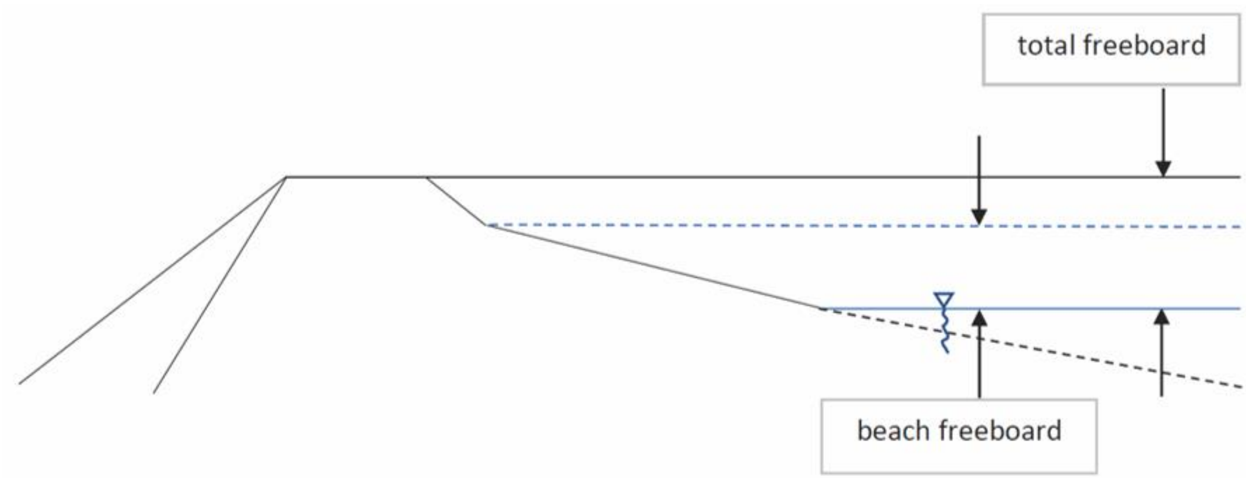

Figure 2. An illustration of the meaning of beach freeboard, vertical scale exaggerated (Boswell & Sobkowicz 2018)

Beach freeboard is much harder won but provides a number of additional benefits including:

An additional defense against liquefaction

Tailings deposited on a subaerial beach, or beach above water (BAW), is usually not liquefiable, whereas tailings deposited sub-aqueously or beach below water (BBW) is usually liquefiable. There are exceptions to this rule, depending on climate, mineral type, particle size distribution, slurry specific gravity, mechanical compaction, but the trend is valid.

Improved slope stability

Existence of a long beach provides greater separation between the outer embankment and the pond, and consequently improved control of phreatic surface within the tailings and resulting embankment slope stability.

7. Beware of negligent and indiscriminate cost cutting measures which escalate the risk of liquefaction failure

Such measures may include:

- Delaying buttressing and remedial measures.
- Delaying the development of extension areas which are needed to reduce rate of rise.
- Storing water rather than treating or releasing water from inventory.
- Allowing contingency storage capacity to be reduced or consumed.

Boswell (2016) provides a more detailed list of cost cutting errors as summarized from interviews with 15 leading tailings practitioners worldwide.

8. Understand the critical role of deposition history in determining tailings behaviour

Even for tailings deposits constructed very recently, available records of deposition are often unrecorded, unavailable or not suitable to fully reconstruct the deposition history. Improvements in aerial photography and the use of drone photography have provided some insight into the general history of the deposition and rate of rise. However, if the tailings deposit has demonstrated large and unexpected material variability, or shows the presence of weak layers within the deposit, the deposition history should be determined in greater detail.

The selection and stability/deformation analysis of critical cross sections requires significant interpolation of field data, construction and operational records, phreatic surfaces, and the use of engineering judgement in order to determine the extent of liquefiable tailings, the extent and character of weak clay layers, and the likely pore pressure response to triggering.

In the event that the actual geometry and performance of key weak layers within the structure is markedly different from that which has been inferred, the design may be too conservative, or worse still, non-conservative.

A series of telephone and site interviews using questionnaires may be useful to amplify the understanding of the scheme deposition history, and in order to more accurately predict the structure behaviour. In addition, historical aerial or satellite photography (if possible, at monthly intervals) may be examined in order to establish deposition in which supernatant was not decanted, the largest pond size, extent of accumulation of clay, bitumen, frozen ground and other interruptions of effective beaching, on the deposit, and degree of continuity between potential weak layers.

9. Rigidly apply limits to rate of rise as a critical operational precaution

Pollock et al. (2014) show that oil sands tailings beach above water (BAW) deposition at annual rates of rise in excess of 10 metres per year, which is not track-packed, is liquefiable. One of the reasons for this is insufficient time for drainage of new tailings beach.

Exceeding the established safe rate of rise limits will increase the risk of creating weak or liquefiable layers in beach above water (BAW), or subaerial deposition, and may limit the future tailings storage capacity. Mitigation of problem layers after the fact is time consuming, expensive and of limited effect.

It is usually preferable, but typically unachievable in practice, for deposition rates of rise to be slowing down rather than accelerating, as the dyke rises. Within reasonable norms, the slower the structure is built, the higher its maximum potential final safe height is likely to be.

It is recommended that a safe rate of rise be established for a structure, and that instantaneous and monthly rates of rise be measured, and recorded, as well as lift thickness. Widely differing rates of rise in different areas of the structure should also be avoided and replaced with consistent, scheduled, rotated and regular deposition across the entire surface.

One of the authors of this paper showed in a series of papers at T&MW conferences (Boswell 2009, 2011, 2015, 2017), the benefits which accrue from consistent adherence to rate of rise controls and limits in tailings deposition practice. Advice included the following:

- Calculation of allowable rates of rise for each deposit and each material.
- Establishment of allowable limits for rate of rise, and maximum height, based on the dewatering and consolidation characteristics of the tailings material.
- Measurement of incremental and average rates of rise.
- Strict compliance with seasonal, annual and overall rate of rise limitations.
- Adjustment of trigger levels and limits to cater for unseasonal or extreme precipitation.

10. Monitor closely

Monitor the dyke for movement, particularly in the foundation, and continually evaluate the implications of that movement in regard to the potential for triggering liquefaction in the dyke (in addition to other failure modes). Monitoring of changes in pore water pressure is just as critical and may, in some cases, provide an earlier warning (than deformation) of a developing problem.

11. Ensure continuity of responsibility through to Closure

Consider what group will be responsible for Operations, subsequent phases of Construction, and Closure.

Their key engineers and construction staff should be involved in updating the FMEAs. At all times, there must be a designated Engineer of Record who takes responsibility for the construction and performance of the dyke. This requirement stands until the tailings facility is decommissioned or closed/reclaimed. Proper transition of this responsibility to a different person from Operations to Closure should also be considered and implemented where necessary.

Conclusion

Many practising engineers should now be familiar with the risk of static liquefaction. However, there appear to be too many who still are unaware of the extreme gravity of this risk. Hopefully, the many courses and papers now focused on the subject (notably also at this conference) should help to urgently remedy this industry weakness.

In regard to design and remediation however, reliable and published guidance has been wanting. Perhaps we are still digesting the urgency and importance of the problem.

The intention of this paper has been to present remedies and defences for three areas: design, construction and operation. This is not the step-wise detail necessarily needed, but at the very least represents an initial list of guiding principles to alert the practising engineer to the tools that are now available, while also providing a 30 point checklist of precautions against static liquefaction.

Acknowledgements

We wish to express our thanks to our clients, our associates in the industry, and our colleagues at Thurber Engineering for their support, and to Dawit Abraha and Mauricio Pinheiro in particular, for their collaboration and insight which contributed to this paper.

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