EVALUATION OF TAILINGS BEHAVIOUR FOR DAM BREACH ANALYSES

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SHORT ABSTRACT: Dam breach analyses for Tailings Storage Facilities (TSFs) are used to predict the rate and extent of potential runout from hypothetical failures, to guide Emergency Preparedness and Response planning, and to develop appropriate risk mitigation strategies. For TSFs with significant surface ponding, the breach assessment should consider the potential for a fluid flow release of ponded water along with eroded and liquefied tailings. For TSFs with no significant ponding, the breach assessment needs to consider flow slide or slump type failures due to liquefaction of the tailings. Index tests, rheological tests, and Cone Penetration Test (CPT) data can be combined to characterize the variability and expected behaviour of the tailings material. Practical mitigation measures can be used to reduce tailings flowability, enhance impoundment stability, and reduce the risk from a tailings dam breach.

1 INTRODUCTION

Dam breach analyses for Tailings Storage Facilities (TSFs) are used to predict the rate and extent of potential runout from hypothetical failures, to guide Emergency Preparedness and Response planning, and to develop appropriate risk mitigation strategies. Complex hydrodynamic flow modelling is often required to evaluate the potential impacts relating to the failure of TSFs with significant ponding, where a breach could release ponded water along with eroded and liquefied tailings materials in an outflow that could resemble a water flood, mud flood, or mudflow type behaviour (O'Brien and Julien, 1985). For TSFs with no significant ponding, the dam breach analysis needs to consider the potential for flow slide or slump type failure due to liquefaction and/or a sudden loss of confinement of the tailings. The physical processes during a hypothetical dam breach event are complex and evaluating the potential tailings behaviour can be challenging.

The potential for tailings to slump or flow following a loss of confinement is related to the amount of entrained pore water and the brittleness of the saturated materials. Loose saturated tailings with an in-situ moisture content that is significantly greater than the Liquid Limit (i.e., Liquidity index > 1) will have a yield stress less than 1500 Pa (Leroueil et al., 1983; Adams et al., 2017a) and will be highly flowable when unconfined (e.g., Fundão (Morgenstern et al, 2016) and Feijão (Robertson et al, 2019) failures in Brazil in 2015 and 2019, respectively). Conversely, denser saturated tailings with little to no microstructure and with an in-situ moisture content below the Liquid Limit will have a yield stress greater than 1500 Pa making them more viscous and more likely to slump than flow when unconfined.

There are practical limitations to reliance on simple index tests such as moisture content and liquid limit to estimate the strength and flowability of the tailings. Cone Penetration Tests (CPTs) provide an alternative and supportive methodology for determining the liquefied undrained shear strength of in-situ tailings materials (e.g., Robertson, 2022). Thus, CPT data collection and analysis can be a useful tool to aid engineers in characterizing the expected behaviour (strength, flowability, and variability) of tailings to support both the design and the dam breach analysis.

This paper first examines the relationship between simple index tests (such as moisture content and liquid limit) and rheological measurements (such as yield stress) for evaluating the potential for a tailings mass to flow or slump. The application of CPT data for characterizing tailings materials is then discussed, along with the potential to evaluate the average in-situ liquefied undrained shear strength of a tailings mass. Simplified methods are suggested to predict the potential flowability of a tailings material and the volume of material that may become mobilized in a dam breach event. Finally, practical mitigation measures to reduce the tailings flowability, enhance the impoundment stability, and reduce the risk and consequences of a tailings dam breach are briefly discussed.

2 TAILINGS BEHAVIOUR FOR DAM BREACH ANALYSES

2.1 *Behaviour of Sediment Laden Flows*

The behaviour of sediment laden flows was categorized by O'Brien and Julien (1985) and adopted by CDA (Martin et al., 2019; CDA, 2021) based on the sediment concentration (by weight, Cw; and by volume, Cv). With the increasing solids concentration, the flow behaviours are characterized as water floods, mud floods, mud flows, or flow slides (slumping). Figure 1, modified from CDA (2021), illustrates the range in behaviour using photographs and provides the corresponding Cw and Cv ranges for sediments with different specific gravity (G). Cw and Cv can be considered as analogous to the moisture content (MC). The geotechnical MC and corresponding void ratio for G of 3.0 have been included as a secondary horizontal axis along the top of Figure 1 as a reference for the geotechnical community. Soils, with void ratios generally less than about 1.0, are generally categorized as mudflows or flowslides when mobilized depending on their solids concentration.

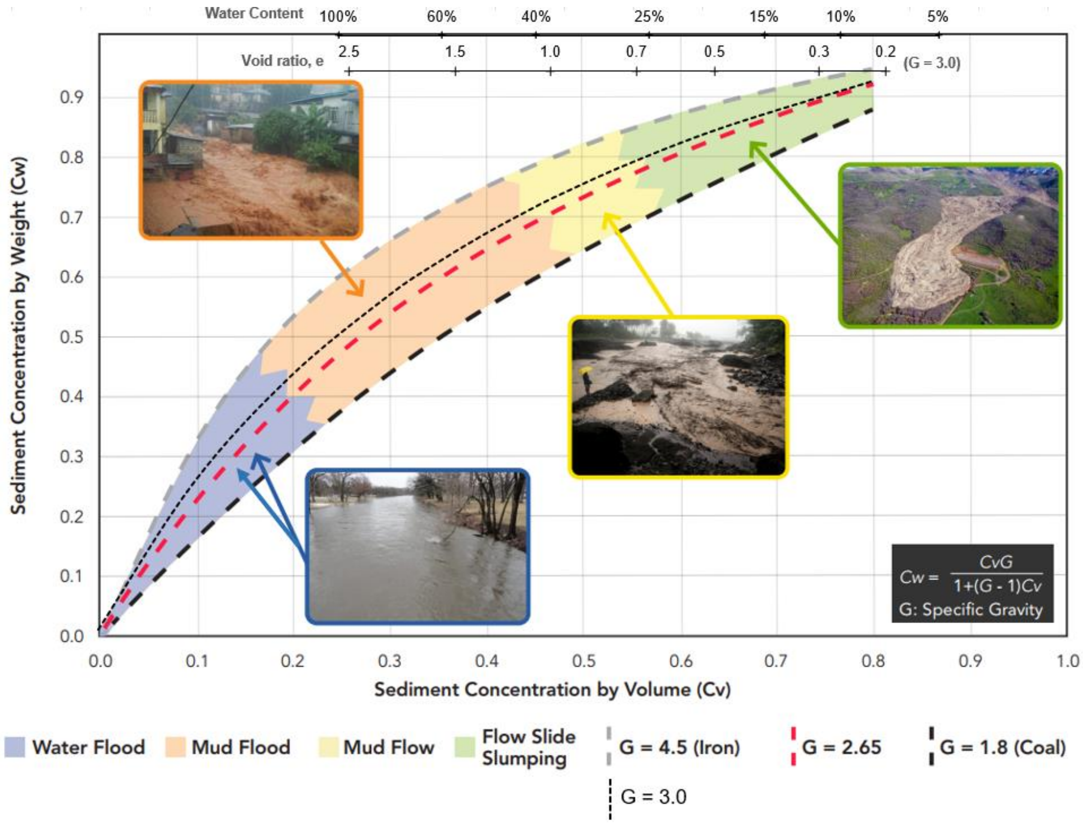

Figure 1 – Flow Types as a Function of Solids Concentration (modified from CDA, 2021; adapted from Julien and O'Brien, 1985)

2.2 *Key Inputs into a Dam Breach Analyses*

Tailings Dam Breach Analyses (TDBAs) involve a series of analyses to evaluate the potential consequences of a failure of a TSF. Martin et al. (2019) first described the new technical bulletin on this topic that was published by the Canadian Dam Association (CDA) in 2021. The CDA bulletin outlines the key steps and the relevant hydrotechnical and geotechnical analyses that should be undertaken as part of a TDBA.

The physical processes in a breach of a tailings dam are complex and may include a flow of fluids including supernatant water along with eroded tailings and/or fluidized tailings, and a flow of liquefied tailings, or slumping of non-liquefied tailings. As such, the key parameters that influence the runout potential and outflow volume are: (1) the presence or absence of a supernatant pond, and (2) the potential of the impounded tailings to experience strength loss (i.e., liquefy) and subsequently flow. Evaluating the potential volume of materials including pond water and eroded tailings that could be released is discussed by CDA (2021) and relates to the volume of pond water present and the volumetric solids content of the tailings materials. The mobilization of tailings through erosion by pond water is not discussed in detail herein.

Evaluating the potential of the impounded tailings to flow or slump is a separate challenge and is the main topic of this paper. Tailings deposits are typically highly variable where their characteristics and behaviour can vary significantly with depth and lateral distance. Two of the key questions that must be addressed early in a TDBA are "How much tailings could liquefy and/or slump?" and "How will the affected tailings behave once mobilized?". The answer to both questions is dependent on the characteristics of the tailings, as well as the physical processes in a dam breach.

2.3 *Estimating the Volume of Tailings that Could Flow or Slump During a Tailings Dam Breach*

One approach to evaluate the volume of tailings that could liquefy and flow and/or slump is to evaluate the stable slope angle with a Factor of Safety (FS) of 1.0. The stable slope could then be projected through the tailings mass beginning at the base of the zone that would become unconfined during a tailings dam breach. It follows that tailings located in areas above the projection of the stable slope angle could liquefy and flow or slump if lateral confinement were removed. This approach is conceptually illustrated in Figure 2.

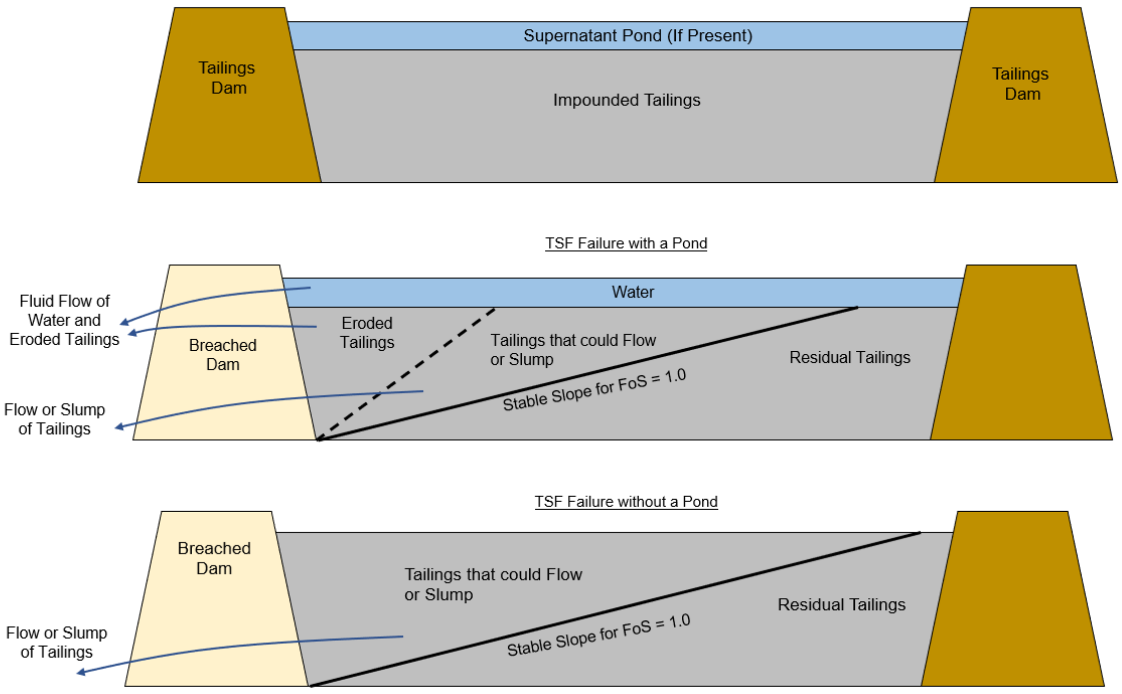

Figure 2 – Conceptual illustration showing different components of tailings dam breach outflows

The stable slope angle could be defined based on the peak or residual strength depending on the mechanics involved in the tailings dam breach. For example, during a rainy day (flood induced) breach, pond water and eroded tailings would be released first, and then additional tailings could flow or slump as a result of a reduction in lateral confinement. In this case the stable slope angle may be best described by a peak strength ratio as the tailings mass itself has not been disturbed. Peak strengths could similarly be used in a sunny day event resulting from a foundation failure and corresponding embankment slump. If the foundation failure were caused by an earthquake or other dynamic type event, it may be reasonable that the tailings mass is similarly affected, and a residual or post-peak strength may be most appropriate to define the stable slope angle. Failure due to static liquefaction may be another scenario where a residual strength is used to define the stable slope angle.

Both the peak and residual strength ratio are expected to vary based on MC (density) and plasticity of the tailings. Based on experience, the peak undrained shear strength ratio may range from approximately 0.1 for loose saturated coarse tailings sands to as high as 0.2 to 0.3 for denser saturated coarse tailings sands or saturated fine tailings with some plasticity. Similarly, the residual strength ratio could be as low as 0.04 to 0.05 for loose saturated tailings that are susceptible to liquefaction, or as high as 0.15 to 0.2 for denser saturated tailings or tailings with some plasticity. Plastic tailings with a high plasticity index (difference between the liquid and plastic limits) may be more ductile and exhibit much higher residual strength ratios that are closer to the peak undrained strength ratio provided there is no microstructure.

Once mobilized, the extend of the tailings flow or slump would be impacted by the overall energy in the system (i.e., due to gravity), the characteristics of the tailings and their flowability, and the characteristics of the downstream environment. These are complex processes that are not directly addressed herein. In general, the tailings flow or slump during a breach would be well mixed and remolded and would be expected to settle at slope angles equal to or less than the average post-failure residual slope angle. Lower slope angles could be expected for materials that are mixed with water along their flow path or for materials that flow along steep terrain.

2.4 *Simplified Approach to Estimate the Stable Slope Angle*

A simplified and potentially conservative approach to estimate the stable slope angle for the tailings scarp and define the volume of tailings that could flow or slump (illustrated on Figure 2) is to apply an infinite slope model. The infinite slope model is given in Equation 1, where the Factor of Safety (FS) is defined as a function of the strength of the tailings (tan φ'), the slope angle (β), and the ratio of the saturated (γ_{sat}) to buoyant (γ') unit weight of the material. The stable slope angle can then be evaluated by setting the FS = 1. The strength of the tailings in Equation 1 is shown as the tangent of the friction angle, φ', however in reality this is a strength ratio that could be peak or residual depending on the evaluated behaviour of the tailings.

$$FS = \frac{\gamma'}{\gamma_{sat}} \frac{tan\phi'}{tan\beta} \tag{1}$$

Using the infinite slope approach, and assuming a unit weight ratio (γ'/γ_{sat}) = 0.5, the stable slope angle is one half of the peak or residual strength of the tailings. Based on the range of values summarized in Section 2.3 above, this could range from as low as 5% to 15% for peak strength ratios ranging from 0.1 to 0.3, or from as low as 2% to 10% for residual strength ratios ranging from 0.04 to 0.2.

The infinite slope model is a powerful simplification of the physical processes involved in the potential flow or slump of tailings resulting from a rapid reduction in confinement and should be used only with careful consideration of the inherent assumptions and limitations. The infinite slope model assumes that there is steady state seepage parallel to the slope which is almost certainly not true during or immediately following a dam breach event. A single value is used to represent the strength of the tailings which can vary significantly with depth or lateral distance within a facility. Similarly, the unit weight ratio (ratio of the buoyant unit weight γ' to the saturated unit weight γ_{sat}) can vary significantly with depth, lateral distance, and location relative to the static water level. The implications of such a simplification must be carefully considered when interpreting the results.

More complex approaches could include using two dimensional (2D) or three dimensional (3D) stability models to support definition of a failure volume for dam breach analysis (e.g., Castellanos et al., 2022). As with any method, the level of accuracy and potential conservatism would be related to the accuracy of the inputs and the expected or measured variability in the tailings mass.

3 USE OF INDEX AND RHEOLOGY MEAUREMENTS TO EVALUATE TAILINGS BEHAVIOUR

Benchtop simulations of the behaviour of unconfined tailings provide useful insight into the range of potential behaviour of a tailings mass with varying MC. Figure 3 shows the benchtop behaviour of a tailings at three different MC and yield stresses. As expected, the tailings are most flowable at high MC with low yield stress and transition to slump type behaviour as the MC decreases with resulting higher yield stress using the Boger slump analysis technique. These results correspond to the range of sediment laden flows described by O'Brien and Julien (1985) and are illustrated in Figure 1.

→ Decreasing Moisture Content (MC) →
Increasing Yield Stress

Figure 3 – Benchtop simulation of behaviour of tailings with variation in moisture content (MC) (images after Adams et al, 2018)

MC, yield stress, and specific gravity are not the only factors controlling the potential for flow or slump type behaviour in soils and tailings. The mineralogical composition also plays a key role. Adams et al. (2017) showed that the relationship between MC and yield stress varies with the clay sized fraction in the tailings. In reality, it is both the clay mineralogy and grain size distribution that impacts the behaviour of a soil or tailings, and this can be inferred by the clay sized fraction in some cases.

The liquid limit (LL) is one way of measuring the behaviour that accounts for the clay mineralogy and grain size distribution. The LL is conceptually defined as the water content at which the behaviour of a clayey soil changes from a plastic state to a liquid state. The transition from plastic to liquid behavior is gradual over a range of water contents, and the undrained shear strength of the soil at the liquid limit is estimated to be between 1 to 2kPa. There are several standard methods to determine the LL (e.g., Casagrande and Fall Cone) and this test is readily available and cost effective at most geotechnical laboratories.

Figure 4 shows the variation in the yield stress versus the ratio of the MC to the LL for 10 samples collected from two different projects. Three samples were collected from a tailings mass at a Copper mine in South America (Cu Tails) and seven samples were collected from a tailings mass at a Copper Gold mine in North America (Cu-Au Tails). The yield stress was measured using a vane yield test (Cu-Au Tails) or a rotational viscometer (Cu Tails). The LL for each sample is provided in the legend along with an indication as to the grain size distribution, either as a percentage of fines (including silt and clay sized particles smaller than 0.075 mm) or a percentage of clay sized particles (smaller than 0.002 mm). The yield stress measured in the laboratory for rheology testing is essentially the same as the unconfined remolded undrained shear strength, since rheology tests are carried out on remolded samples.

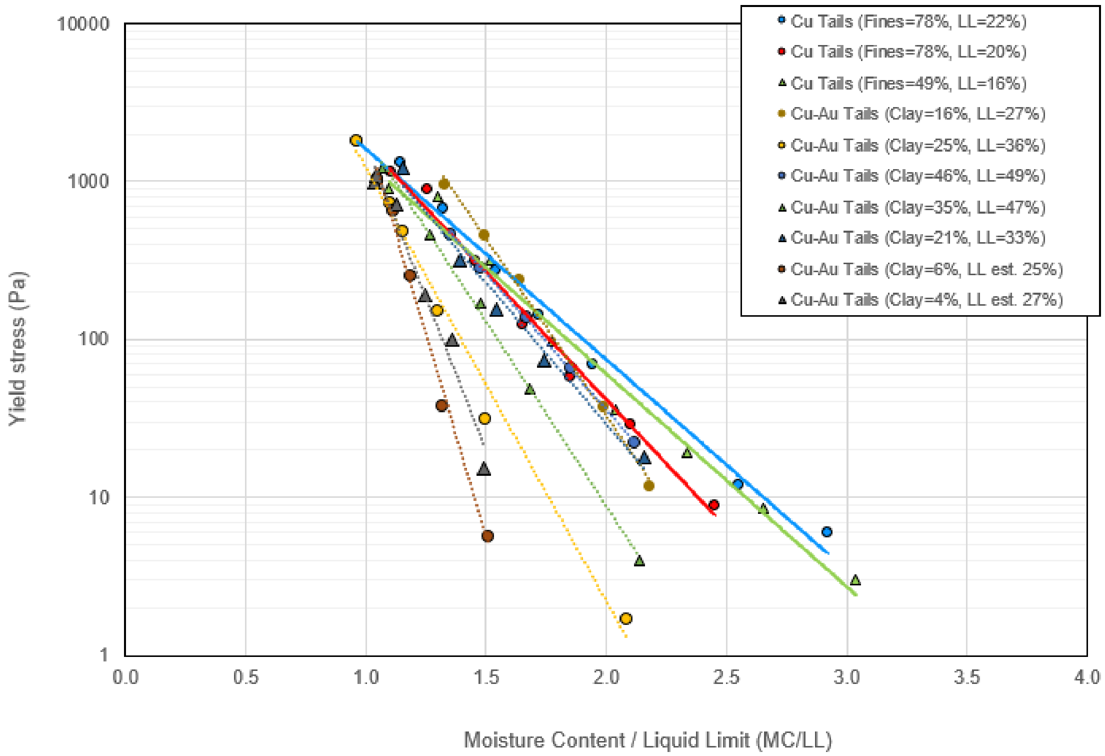

Figure 4 – Variation in yield stress with the ratio of the moisture content to the liquid limit for two different projects

The data in Figure 4 converge when the moisture content is equal to the LL (MC/LL = 1.0) and the yield stress at this point is between 1000 and 2000 Pa (1 to 2 kPa). This agrees with data presented by Leroueil and Tavenas (1983) for Eastern Canadian Clays where the yield stress at a liquidity index of 1.0, corresponding to the point where the moisture content equals the liquid limit, ranges from 1 to 2 kPa. A yield stress of 1 to 2 kPa is commonly referenced as the undrained strength at the LL (e.g., Carter and Bentley, 2016) and the transition from fluid like to soil like behaviour. Materials with a yield stress above 1 to 2 kPa are more likely to slump instead of flow.

The data diverge as the yield stress decreases. The moisture content at a yield stress of 10 Pa, (e.g., slightly higher than that of condensed milk; McKenna et al., 2016), varies from approximately 1.5 to almost 3 times the LL for the dataset illustrated in Figure 4. At this low yield stress, the tailings are very flowable and behave more as a fluid than a solid with hydrodynamic forces playing a larger role in the behaviour than interparticle forces. Figure 4 also shows that some soils are sensitive to strength loss with small changes in moisture content (i.e., small changes in void ratio). This is consistent with research based on Critical State Soil Mechanics for sands (e.g., Jefferies and Been, 2016).

Index testing and rheological testing such as MC, specific gravity, LL, and yield stress are useful tools to evaluate the generalized behaviour of soils at different MC. In general, soils with higher LL require higher MC to flow while soils with lower LL will flow at lower moisture content. However, these simple tests alone do not provide enough information to develop the required inputs for a TDBA such as the post-failure stable slope angle.

4 USE OF CONE PENETRATION TESTING (CPT) TO EVALUATE TAILINGS BEHAVIOUR

4.1 *Overview of CPT*

Cone Penetration Testing (CPT) is becoming more widely available and is rapidly becoming the standard for investigation of soft soils including tailings. The CPT involves advancing an instrumented cylindrical probe with a conical tip into the ground at a constant rate. The resistance felt at the tip and along the sides of the probe are measured along with the pore pressure measured just behind the tip. Measurements of tip resistance (q_t), sleeve friction (f_s), and dynamic pore pressure (u_2) are typically recorded every 1 to 2 inch (2.5 to 5 cm) and can be used to interpret the characteristics and behaviour of the materials encountered at the time of the CPT test using well established correlations. Several correlations have been developed based on case histories, and in situ and laboratory testing. Most correlations have a theoretical basis but remain semi-empirical due to the complexities of real soils.

In addition to the main measurements described above, additional measurements can be made during a CPT, such as pore pressure dissipations (PPD) during a pause in the penetration to measure the time rate of dissipation (e.g., the time for 50% dissipation, t_{50}), the equilibrium water pressure (u_o), and the consolidation characteristics of the soil, as well the shear wave velocity (Vs). These measurements require additional time to complete depending on the ground conditions. The CPT pushing equipment can also be used to install instrumentation (such as Vibrating Wire Piezometers), or in some cases, collect samples for inspection or laboratory index testing.

Because of the near continuous nature of the CPT, the data is well suited for statistical analyses and can be used to evaluate the variability within a soil or tailings deposit where CPT data sets are available at multiple locations. CPT testing can also be advanced rapidly compared to traditional drilling and sampling but may become challenging in soils that are interbedded with very coarse materials (gravels) or stiff cemented layers. CPT correlations are based on back analysis of case histories, account for in situ stress conditions and soil structure, and can better evaluate variability within a deposit. As such, CPT correlations are sometimes judged to be more representative than other methods such as discrete sampling and laboratory testing. It can be difficult to collect, transport and test samples in the laboratory without causing disturbance that alters the state and structure of the soil. This is especially true for low plastic soils such as tailings that can be loose and thus challenging to sample and transport in an undisturbed state.

4.2 *Use of CPT for Dam Breach Analyses*

Of the many soil properties that can be estimated by the CPT, the shear strength of the tailings as well as their in-situ state, either contractive or dilative, are the most useful for utilization in a dam breach analysis.

Many correlations are available to estimate the peak and residual shear strength ratios of tailings from the CPT. Peak strength ratios are typically estimated using a cone factor (e.g., Robertson and Cabal, 2014) that is calibrated to the site using field vane or laboratory testing results. Robertson (2022) recently updated a previously published method (Robertson, 2010) to evaluate the susceptibility of soils to undrained strength loss that could result in flow liquefaction and to estimate the residual strength ratio of soils using the CPT data. This method estimates the residual (or liquefied for liquefiable materials) strength for a variety of soils ranging from sand-like to clay-like behaviour. The previous approach (Robertson, 2010) and other similar approaches (e.g., Olson and Stark, 2003) were developed primarily for clean sands and may underestimate the strength for clay-like soils that may behave in more of a ductile manner.

5 PRACTICAL MITIGATION MEASURES TO REDUCE TAILINGS FLOWABILITY

There are several practical mitigation measures that can be used to dewater, densify, and reduce the flowability of a tailings mass. The first and easiest approach is to remove all free surface water. This will allow the upper tailings to consolidate and desiccate and will also remove a key driving force if a dam breach event occurred.

Significant water remains trapped in the voids of the tailings even after the free surface water is removed. This water can be removed by providing additional drainage and/or inducing consolidation. Additional drainage is usually easiest to install during the initial construction of a TSF, such as via an underdrainage system; however, many existing TSFs do not contain these features. Additional drainage could be installed in the later stages of a TSF, such as via installation of horizontal drains; however, this must be considered on a case-by-case basis while considering the potential impacts on the overall stability of the TSF.

Consolidation loading is another option to densify and dewater fine grained tailings. Consolidation loading involves constructing a fill cap over the tailings surface to apply a weight and induce consolidation of the underlying tailings. Adams et al. (2017b) provides data from a field trial program in Canada showing the impact of constructing a 10 m high fill pad (surcharge load) over tailings slimes (fine grained tailings). These data include pore pressure measurements, and changes in moisture content and CPT tip resistance resulting from the applied loading. Robertson et al. (2022) and Sully et al., (2022) report detailed field measurements illustrating significant changes in the tailings structure resulting in increases in the CPT tip resistance, increases in shear wave velocity, and increases in peak undrained and residual strengths following consolidation under a fill pad at a project in South America. Adams et al. (2019) provides design calculations for consolidation loading on a TSF in the United States including the predicted increase in solids content versus depth for different fill pad heights (loads). Consolidation loading has the greatest impact on the tailings closer to the surface and a lesser impact on the tailings at depth, which are denser to begin with. The benefits of consolidation loading diminish quickly for fill pad heights above approximately 10 to 20 m (applied loading of roughly 200 to 400 kPa), because consolidation varies with the logarithm of the effective stress. The benefits of consolidation loading when the MC can be decreased to become less than the LL is illustrated in Figure 4.

6 CASE HISTORY EXAMPLE

This case history involves a copper gold mine located in North America. CPT measurements were collected in the same area 6 years apart. During the 6-year interval between measurements, a fill pad was constructed to consolidate, densify, and reduce the moisture content of the underlying tailings. During the same period, the supernatant water pond was removed, and dewatering activities were completed in sandier portions of the tailings mass. As such, the recent CPT measurements reflect the changes in the tailings state and strength that have been achieved following these stabilization measures.

Figure 5 illustrates the following:

- The tip resistance and pore pressure measured by the CPT in year six (left two plots). Green indicates sand and silt zones while red indicates zones of sensitive fines. Blue indicates clay rich zones.
- The variation in residual strength interpreted from the CPT and the median residual strength vs. depth for data collected in Year 0 and Year 6 (third plot from left).
- The variation in moisture content with depth compared to the liquid limit in Year 6 (fourth plot from left).
- The variation in residual strength ratio (ratio of residual strength to vertical effective stress) (right most figure).

The residual strength was estimated following Robertson (2022) to account for variations related to sand-like or clay-like behavior indicated on the tip resistance vs. depth plot (leftmost plot). The initial CPT measurements in Year 0 are shown in grey and the most recent measurements, taken 6 years later following the implementation of the stabilization measures, are shown in black. The water levels for each year and corresponding tailings surface or stabilization load are indicated as dashed black lines with blue upside down triangles on the figures.

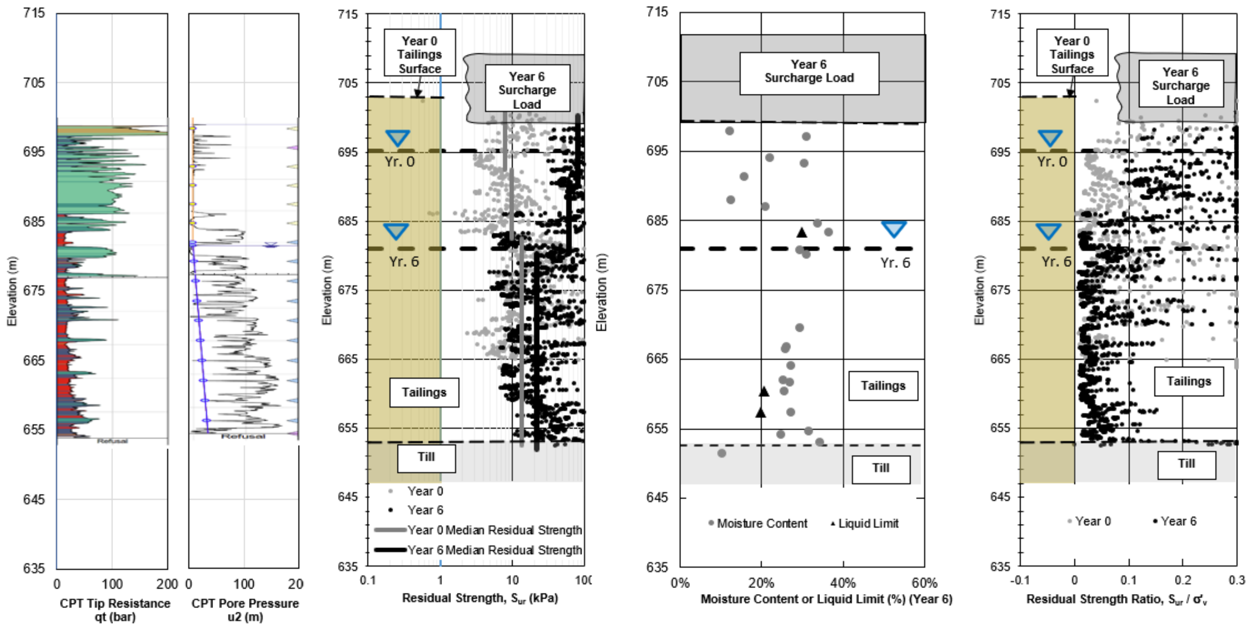

Figure 5 – CPT measurements and interpreted residual strength profiles before (grey) and following (black) stabilization measures for a Copper Gold Tailings Facility in North America

The CPT measurements in Figure 5 indicate the following:

- The residual strength and residual strength ratios are highest near the surface and generally decrease to low values at depth.
- For Year 6, the residual strength is highest when the MC is less than the LL The residual strength is comparatively lower when the MC is greater than the LL.
- Stabilization measures including consolidation loading and dewatering resulted in the most significant increase in residual strength ratio in the upper 10 to 20 m of the tailings, with lesser impact at depth.

The CPT data demonstrate a marked increase in the median residual strength and an increase in the residual strength ratio following the stabilization measures. This would result in a higher post-failure stable slope angle and a lower volume of tailings that could flow or slump during a dam breach event.

Following the stabilization measures, the lower bound average residual strength ratio in the upper approximately 10 m of the tailings column is estimated to be greater than approximately 0.1, while the average residual strength ratio in the lower tailings ranges by location from approximately 0.03 to 0.06. These data could be used in an infinite slope model or a more advanced stability model to estimate the volume of tailings that could flow or slump during a dam breach event. A case history where a more advanced 3D stability model was used to support definition of a failure volume for a TDBA is provided by Castellanos et al. (2022).

7 SUMMARY

A key input to a TDBA is the volume of tailings that could flow or slump following a loss of confinement during a dam breach event. The potential for the tailings to liquefy and flow, or to slump is related to the characteristics of the tailings, their moisture content, and their yield stress. In general, tailings with higher moisture contents have lower yield stresses and are more flowable compared to tailings with lower moisture contents. Tailings with higher liquid limits are more ductile and require higher moisture contents to flow compared to tailings with lower liquid limits. Though moisture content and liquid limit are relatively common and easy laboratory measurements, there are practical limitations to using these parameters to evaluate the spatial variability in a tailings deposit due to the number of samples that would need to be collected and tested.

Further, though the moisture content and other laboratory tests such as rheological measurements can give an indication as to the potential behaviour (to flow or to slump), they do not provide measurements that can be readily used in a TDBA.

The (CPT) is another common and widely available measurement tool that can be used to collect large amounts of data relatively quickly. The CPT evaluates the variability with depth, and the lateral variability can be evaluated by advancing the CPT at different locations. Methods are available to evaluate the strength of the tailings from CPT, including peak (Robertson and Cabal, 2014) and residual (Robertson, 2022) strength ratios. The peak or residual strength can be readily applied to estimate the volume of tailings that could mobilize and flow or slump using simple to complex stability based methods.

Various mitigation measures, including removing the supernatant pond, providing underdrainage, and consolidation loading, can be applied to dewater and densify the tailings. These measures reduce the risk of failure and reduce the potential volume of tailings that could liquefy or slump, consequently reducing the downstream impacts in case the failure occurred.

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