Application of the 3D Limit Equilibrium Method in Tailings Dam Breach Analysis

J. Castellanos, S. Yong, V. Martin
Knight Piésold Ltd., Vancouver, British Columbia, Canada

ABSTRACT: This paper presents a case study of a tailings storage facility undergoing closure activities, where three-dimensional limit equilibrium analysis (3D LEA) was used to estimate the breach geometry, breach location, and potential outflow volumes. Data from seismic cone penetration and laboratory testing were used to evaluate the behavior (flowability) and strength of the in-situ tailings. Key factors such as the pre-mine topography, dam geometry, dam materials, tailings properties, and pore pressure conditions were considered in the 3D LEA. The case study highlights the importance of integrating soil mechanics concepts with dam breach analysis methodologies to provide a more meaningful approach for evaluating the potential runout impacts of a slump-type failure mode. The proposed approach can be used to facilitate risk assessments and inform emergency preparedness and response planning.

1 INTRODUCTION

The Global Industry Standard on Tailings Management (GISTM, 2021) emphasizes that the dam breach analysis is an important requirement because the analysis is an essential component of effective emergency preparedness and response planning and is used to inform the consequence classification of the facility and the selection of minimum design requirements. The Canadian Dam Association (CDA) recently published a technical bulletin (CDA, 2021) that outlines the key considerations and a step-by-step procedure for detailed dam breach analyses based on the current state of practice.

Tailings dam breach analysis requires various input parameters to define the breach outflow volume and the breach outflow hydrograph. These input parameters depend on numerous factors including the failure mechanism, the presence and location of the supernatant pond, the breach geometry, the characteristics and susceptibility of the tailings to liquefy and flow, and the site topography. The outflow volume influences the breach development time and the breach geometry. Development of the the outflow hydrograph and estimation of the downstream impacts of the runout also depend on the outflow volume. The breach development time and the breach geometry are often estimated using empirical equations that are based on past failures of water-retaining dams. The existing correlations were developed based on a limited dataset of breach parameters that can be used as part of a sensitivity analysis to estimate the breach outflow hydrograph and possible downstream impacts. Their applicability to tailings dam breaches is limited to erosional type failures of facilities that store a significant pond volume (Cases 1A and 1B, as per CDA, 2021). However, these empirical equations are not considered appropriate for nearly instantaneous breaching processes, such as those initiated by liquefaction of tailings, particularly when the facility does not store a significant pond and the breaching process is not driven by erosion.

Drained or partially drained tailings storage facilities without a permanent pond may contain dense, consolidated tailings with very little strength loss potential (Case 2B, as per CDA, 2021). In these cases, tailings dam failures are expected to result in runouts with relatively low flowability that would resemble slump-type failures. For such conditions, slope stability analysis can provide an alternative and more meaningful approach for estimating both the outflow volume and the breach geometry.

The case study presented in this paper involves a tailings storage facility (TSF) at the Candelaria Mine that is undergoing closure. The closure concept (Sotil et al., 2020) centers on the construction of a waste rock closure cap to enhance consolidation, dewatering, and densification of the underlying tailings. The proposed cap is expected to significantly reduce the potential for the impounded tailings to mobilize and flow in the event of a dam failure. Data from seismic cone penetration testing (SCPT) and laboratory testing (geotechnical and rheological) were used to evaluate the flowability and strength of the tailings. Three-dimensional limit equilibrium analysis (3D LEA) was used to estimate the breach location, breach geometry, and range of potential outflow volumes. Key factors such as the pre-mine topography, dam geometry, dam materials, tailings properties, and pore pressure conditions were considered in the 3D LEA.

2 PROJECT OVERVIEW

The Candelaria Mine is an active open pit copper mine operated by Compañía Contractual Minera Candelaria. It is located in the Atacama region of Chile, approximately 20 km south of Copiapó. The existing Candelaria TSF comprises three dams: Main Embankment, South Embankment, and North Embankment. The existing North Waste Dump buttresses a portion of the Main Embankment. The open pit is approximately 700 m deep and is located approximately 80 m from the downstream toe of the southeastern portion of the Main Embankment. The South Embankment is situated upgradient of the Concentrator and CMP Plant. No mine facilities are present immediately downstream of the North Embankment. Tailings deposition into the Candelaria TSF ceased at the end of 2019 with tailings reaching an elevation of approximately 798.5 masl (metres above sea level). Foundation materials within the Candelaria TSF comprise alluvium that are significantly more permeable than the tailings and provide a drainage zone at the base of the facility. The current Candelaria TSF configuration is shown on Figure 1.

Closure of the decommissioned TSF provides an opportunity for capping to be integrated with the need for long-term waste rock storage, the creation of a stable post-closure landform, and simplifying the design of the long-term storm water management system. This integrated concept is the El Buitre Closure Cap (EBCC) project and is shown on Figure 2.

The EBCC facilitates a progressive transition of an existing saturated tailings deposit into a stable landform that directs storm water around the TSF. Storage of waste rock on the decommissioned TSF will densify the tailings and reduce the susceptibility for a mudflow release if a dam failure occurred. These improvements reduce the risks associated with waste and water management for the facility during closure and post-closure.

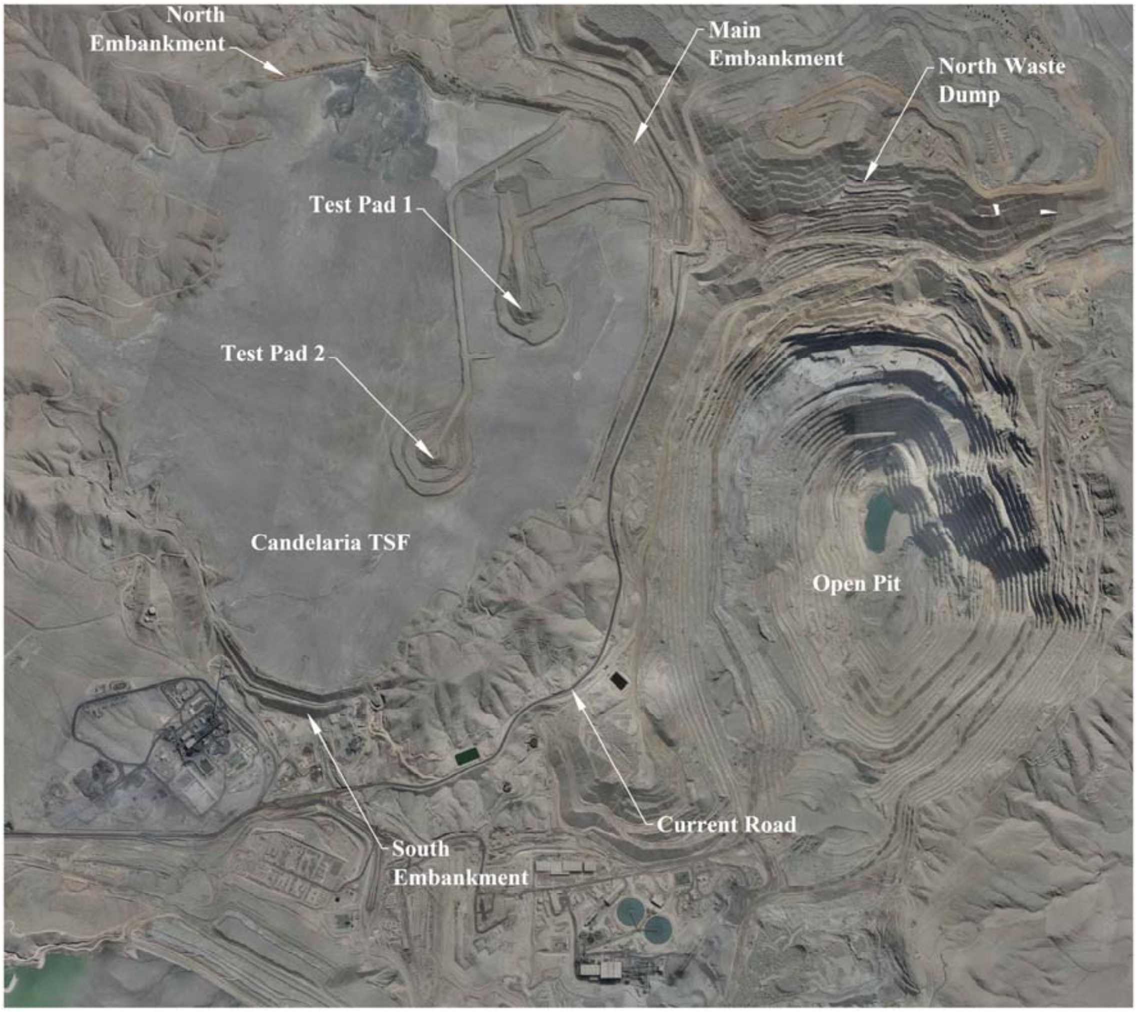

Figure 1. Candelaria TSF overview.

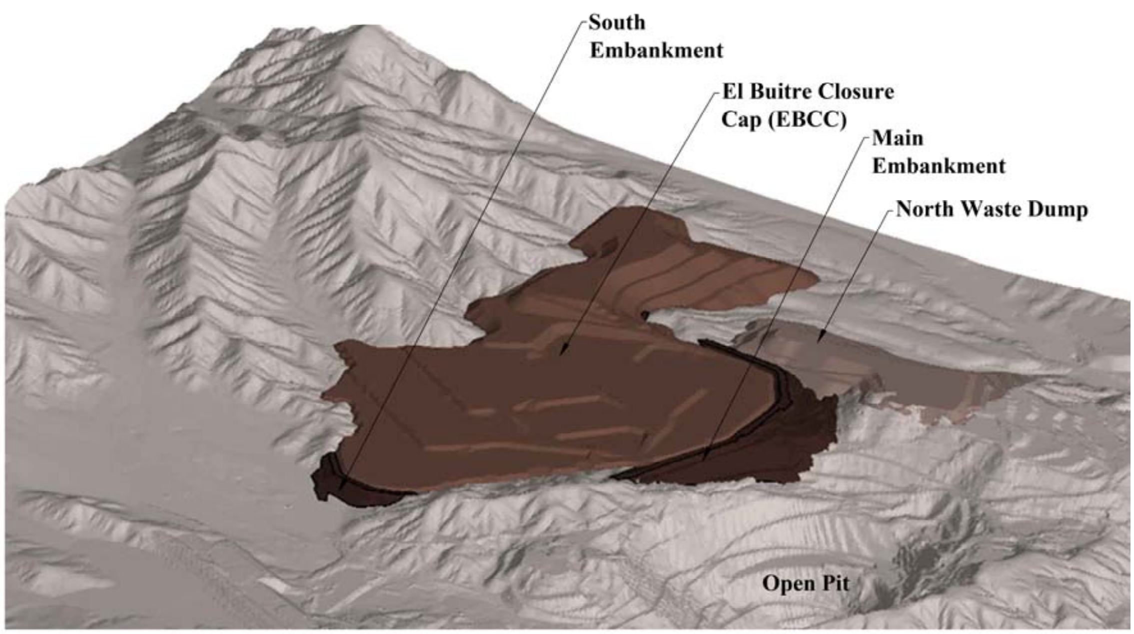

Figure 2. Proposed EBCC configuration.

3 DAM BREACH SCENARIOS

In accordance with the CDA guidelines (CDA, 2021), hypothetical dam breach scenarios are typically developed for fair-weather and flood-induced conditions. A flood-induced scenario assumes that failure occurs due to an extreme hydrological event. However, water ponding on the surface of the Candelaria TSF will not be possible since the closure design routes storm water around the TSF. The EBCC will lead to desaturation of the underlying tailings, which further reduces the risk of a failure triggered by an extreme flood event. A fair-weather scenario assumes that failure occurs due to normal hydrological conditions. The fair-weather scenario considered for the Candelaria TSF assumes that liquefaction of the tailings would occur during the dam breach, regardless of the triggering mechanism.

Loose and saturated tailings have low liquefied undrained strengths, low yield stresses, and can become highly flowable when unconfined. These materials can experience significant and rapid strength loss (undrained conditions) due to static or dynamic liquefaction. Past dam breach events have demonstrated catastrophic failures can occur nearly instantaneously when site conditions are detrimental (e.g., steep upstream construction methods, high phreatic levels, etc.). The 2019 Feijão failure in Brazil (Robertson et al., 2019) is one example.

Conversely, densified tailings with a low water content have higher liquefied undrained shear strengths and are associated with higher yield stresses. Mobilization of such material due to a breach event could more likely lead to a slumping failure than a mudflow. Development of the EBCC will densify and dewater the tailings in the Candelaria TSF; thus, reducing the strength loss potential and the flowability of the tailings. In this case, the physical process occurring during a dam breach are expected to be similar to those described for Case 2B (CDA, 2021).

Considering the site conditions of the Candelaria TSF and properties of its tailings, use of the limit equilibrium analysis was proposed to identify the potential breach location and estimate the volume of the tailings, dam materials, and capping rockfill (EBCC) that could mobilize during a breach event. Completing the analysis in 3D allows for important 3D effects to be incorporated, including geometrical controls of the original ground topography, the curved alignment of the Main Embankment, the dendritic pattern of the underlying alluvium, the irregular geometries of the proposed North Waste Dump and EBCC, and the curvature of the phreatic surface.

4 TAILINGS CHARACTERIZATION

4.1 *Field Program*

A trial program was developed to evaluate the Candelaria tailings response to surcharge loading and to characterize the in-situ improvements resulting from waste rock placement (Sotil et al., 2020). The trial program involved the construction of two waste rock test pads (Test Pad 1 and Test Pad 2 shown on Figure 1) with a height of 30 m to simulate the surcharge loading. Test Pad 1 is constructed on the sandy beach tailings adjacent to the Main Embankment, while Test Pad 2 is constructed on finer-grained tailings (slimes) adjacent to the historical supernatant pond. Two-phase Site Investigation (SI) and laboratory testing programs were completed to define the strength, compressibility, and permeability of the tailings. Changes to the tailings properties were evaluated by comparing the in-situ and laboratory testing results from before (Phase 1) and after (Phase 2) construction of the test pads. The SI programs included geotechnical drilling, SCPT, and sampling for geotechnical and rheological testing.

4.2 *Index Properties*

Tailings samples were found to comprise silt and sand with fines content (particles finer than 0.075 mm) varying from 35% to 98% and an average specific gravity of approximately 3.0. Particle size distributions from sampling drill core indicated interlayering of fine-grained and coarse-grained tailings at both test pad locations. The samples were non-plastic to slightly plastic with a plasticity index of less than 4, and with a measured liquid limit in the range of 16 to 20. X-ray diffraction of tailings samples indicated compositions of predominantly silica-based minerals and less than 8% clay minerals (100% smectite). Micro-photographic images showed that particles were generally sub-angular with no signs of bonding.

4.3 *Moisture Content*

The stresses imposed by the test pads generally reduced the void ratio of the tailings, thereby increasing the density and decreasing the moisture content. The average moisture content measurements, represented by the solid lines on Figure 3, indicated that the tailings moisture content generally decreased after surcharge loading from the test pad construction.

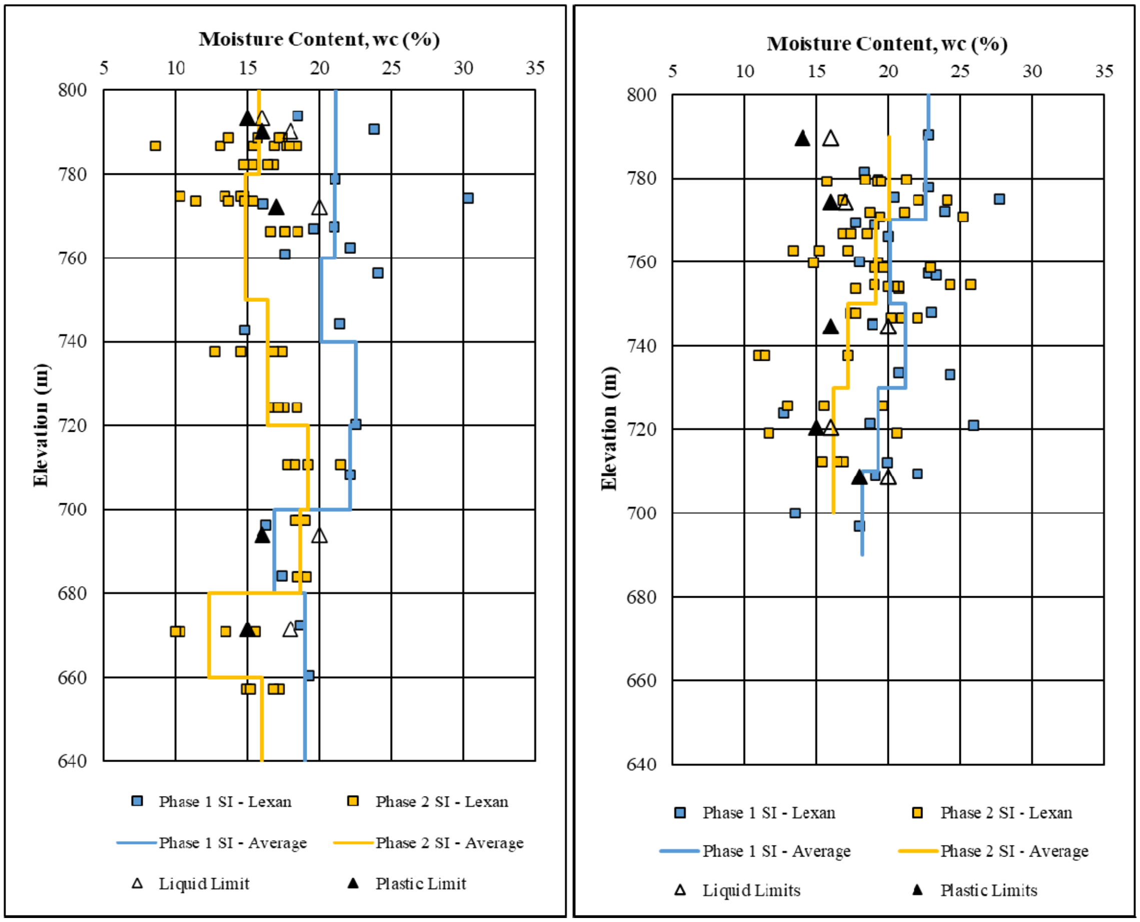

Figure 3. Moisture content results at Test Pad 1 (left) and Test Pad 2 (right).

4.4 *Tailings Densification*

The field data indicated that the increase in effective stresses, due to test pad construction, resulted in increases in density and stiffness, which imply increases in peak and liquefied undrained shear strengths. The improvement in the tailings properties was more pronounced in the looser tailings (upper 30 m) and even more pronounced below Test Pad 2 where the shallow tailings were looser than the tailings underlying Test Pad 1.

The change in the in-situ state of the tailings was analyzed using the soil behaviour type (SBTn) charts developed by Robertson (2021). Figures 4 and 5 show the SBTn charts for the upper 30 m of tailings at Test Pad 1 and Test Pad 2, respectively. The shift in the data distribution indicates a reduction in the tailings potential for strain softening and an increase in the residual undrained strength ratio after surcharge loading.

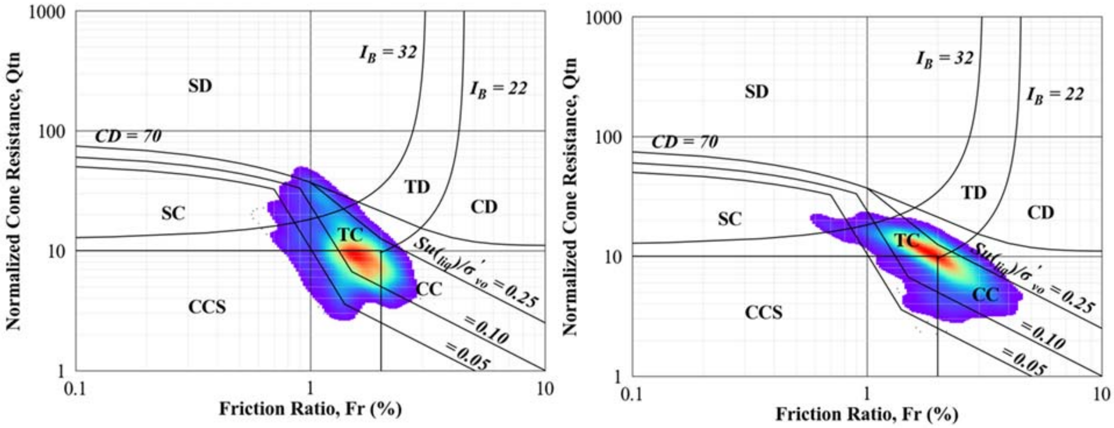

Figure 4. SBTn plots (Robertson, 2021) before (left) and after (right) Test Pad 1 construction.

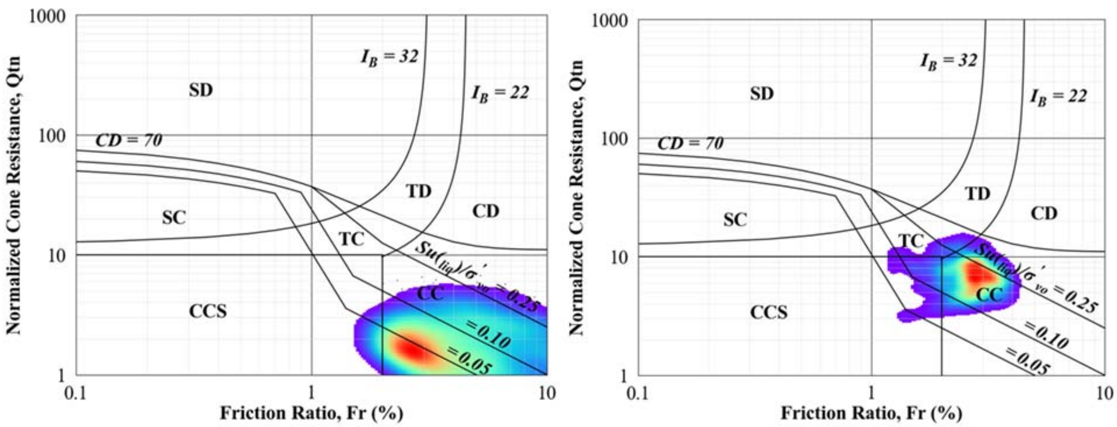

Figure 5. SBTn plots (Robertson, 2021) before (left) and after (right) Test Pad 2 construction.

Results from the laboratory testing program were in agreement with those from the SCPT data interpretation, which confirmed an improvement in the tailings behaviour and indicated reduced brittleness (increased ductility) and increased undrained shear strength. A detailed evaluation of the influence of increased confining stresses (i.e., from surcharge loading) on the undrained behaviour of the Candelaria tailings is presented by Sully et al. (2022).

4.5 *Tailings Rheology*

The relationship between the yield stress, viscosity, and solids concentration for a given material provides an indication of how the material will mobilize and flow at a high moisture content when unconfined. As the tailings densify and transition from a slurry to a soil, the yield stress increases sharply below the critical moisture content.

The relationship between the tailings flowability and the moisture content can be demonstrated by the Boger slump test. Photo results of testing conducted on samples collected during the Phase 1 SI program are shown on Figure 6, which show that the tailings become less fluid at lower moisture contents as the solids content increases. The average moisture contents measured during the SI programs (Figure 3) suggest low flowability of the tailings, particularly after test pad construction.

It is acknowledged that the Boger slump test is limited to an assessment of static conditions and does not accurately reflect the tailings flowability under dynamic conditions. In general, higher moisture contents are required for tailings to flow under static loading conditions compared to dynamic loading conditions.

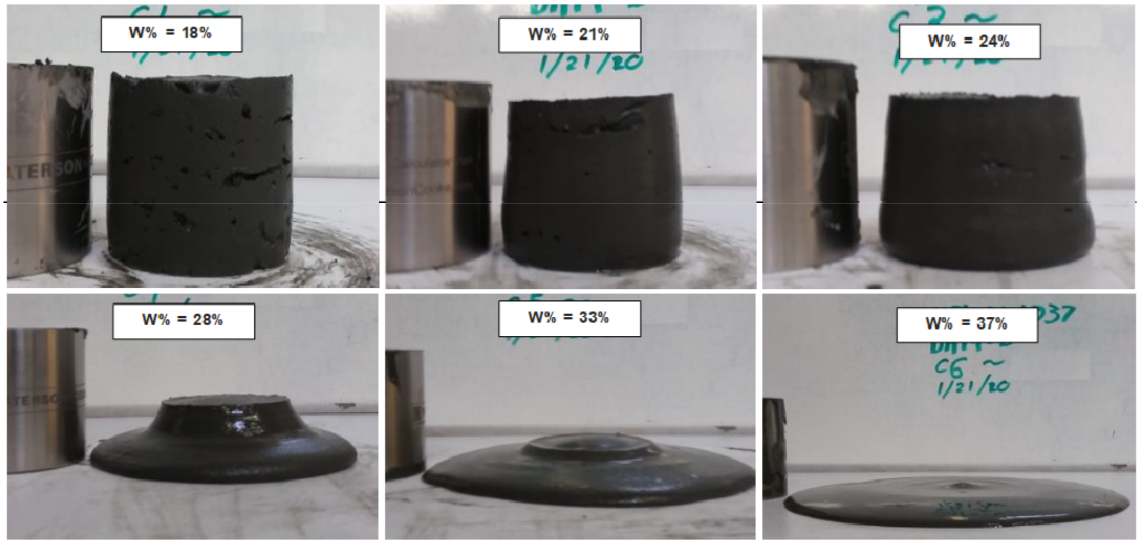

Figure 6. Boger slump test results with varying moisture content.

Vane testing was carried out to develop the relationship between the tailings yield stress and the tailings moisture content (or solids content). Results from the testing indicate a sharp increase in yield stress (and a reduction in flowability) as the moisture content decreases towards the liquid limit, as shown on Figure 7. Higher vane yield stresses are expected to result in reduced flowability and a slump-type failure mode once the material passes the inflection point on the yield stress vs. moisture content curve (Adams et al. 2017; Adams et al., 2022). The average moisture contents measured during the Phase 2 SI program (Figure 3) indicate that the Candelaria tailings will be within the low flowability zone after surcharge loading, as indicated in Figure 7.

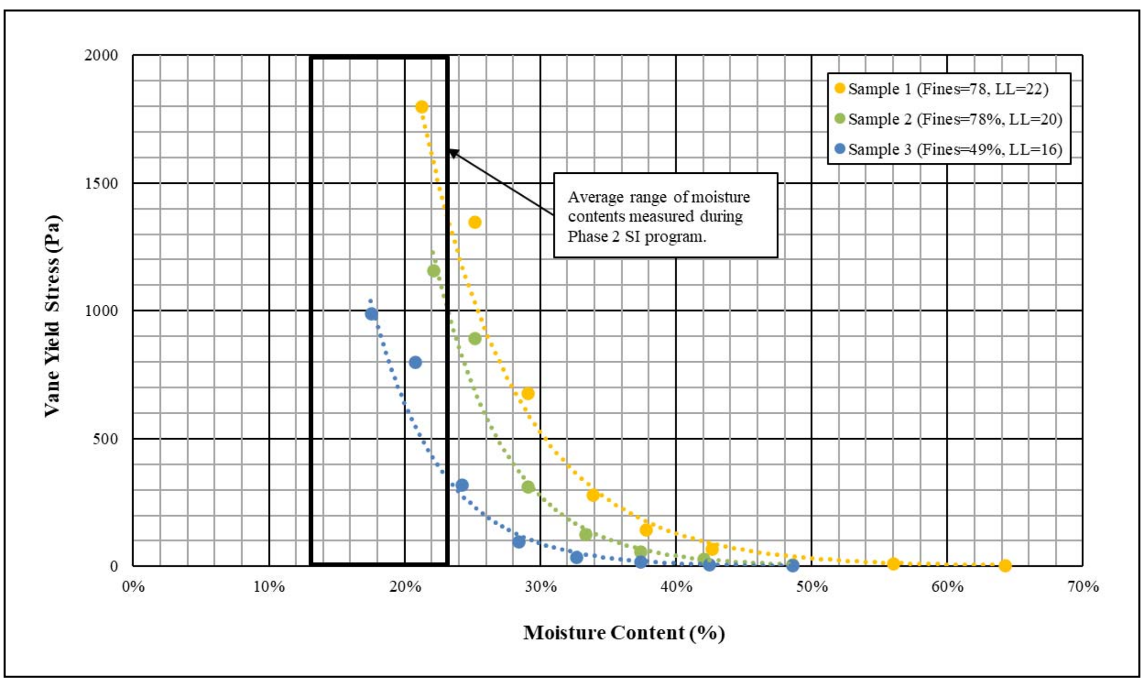

Figure 7. Vane testing results.

4.6 *Outflow Type*

O'Brien (1986) studied the physical behaviour for different flow types and found that as the solids concentration increases, the material transitions from a slurry-like to a soil-like behaviour. Materials with low solids concentrations will move faster and farther, as the released materials could flow like water or like mud floods. In general, materials with higher solids concentrations (above 76% by weight or 55% by volume) do not show fluid behaviour and are associated with slumping or flow sliding (CDA, 2021).

Although flow behaviour can be estimated based on the solids content, the solids content alone does not define the runout response. The downstream conditions (e.g., topography, the presence of water bodies, etc.) and the tailings susceptibility to flow liquefaction play important roles in defining the runout process and impact zone. Furthermore, solids and water contents can change throughout the breaching process, particularly for breaches involving a surficial pond (Cases 1A and 1B, as defined by CDA, 2021).

Solids concentrations for samples collected during the Candelaria Phase 2 SI program (after loading) have been estimated from measured moisture contents and are plotted on Figure 8. These data support the interpretation that, after stress densification (post-EBCC construction), the tailings will likely behave as a non-flowable material.

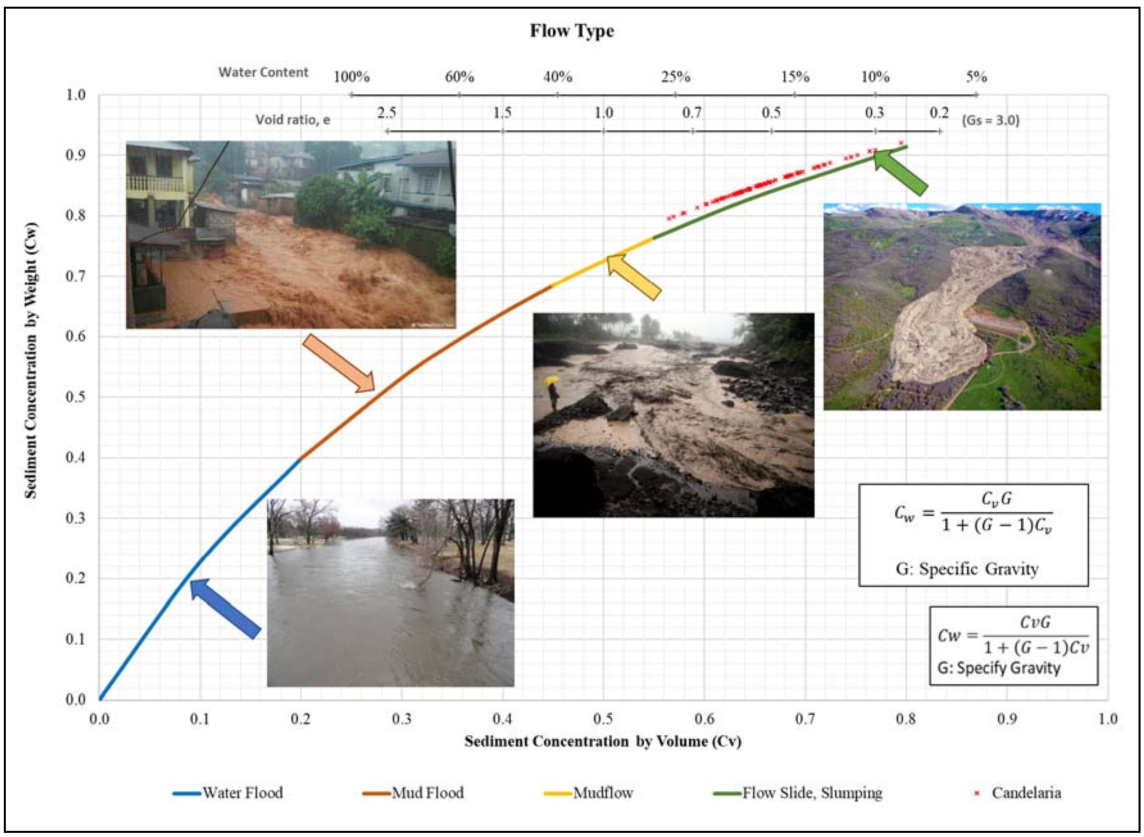

Figure 8. Flow type as a function of solids concentration (modified from Martin et al., 2019).

5 THREE-DIMENSIONAL LIMIT EQUILIBRIUM ANALYSIS (3D LEA)

5.1 *Stability Model*

The 3D LEA model components are shown on Figure 9. A simplified phreatic surface was defined based on available data from vibrating-wire piezometers installed during the Phase 1 SI program. Material strength parameters used in the analyses were based on information obtained in previous studies, data collected during the Phase 1 and Phase 2 SI programs, and supplementary laboratory testing programs.

Figure 9. 3D stability model.

5.2 *Potential Breach Locations*

A review of slip surfaces with the lowest Factors of Safety (FoS) was first conducted to identify the location of critical failure surfaces within the embankment fills. As shown on Figure 10, the locations with the lowest FoS (less than 2.0) correspond to localized and surficial slips that do not involve the stored tailings materials and are not associated with a failure scale that could result in a loss of containment. The locations of these slips were used to identify the weakest areas in the embankments and to guide the selection of large-scale slip surfaces that could represent potential breach volumes of significance.

The hypothetical breach location for the Main Embankment is situated above the open pit and between the North Waste Dump to the north and a rock ridge to the south (Figure 9). This breach location was used to constrain the maximum depth of the slip search results. Large-scale slips are predicted in the northern portion of the dam but are shallower and involve a larger volume of embankment and waste rock materials with a smaller proportion of tailings due to the buttressing effect of the North Waste Dump.

Analysis of the South Embankment indicates the lowest FoS are within the eastern portion of the dam, which also implies the location that the deepest breach could develop. The breach location for the South Embankment is constrained by the underlying bedrock topography.

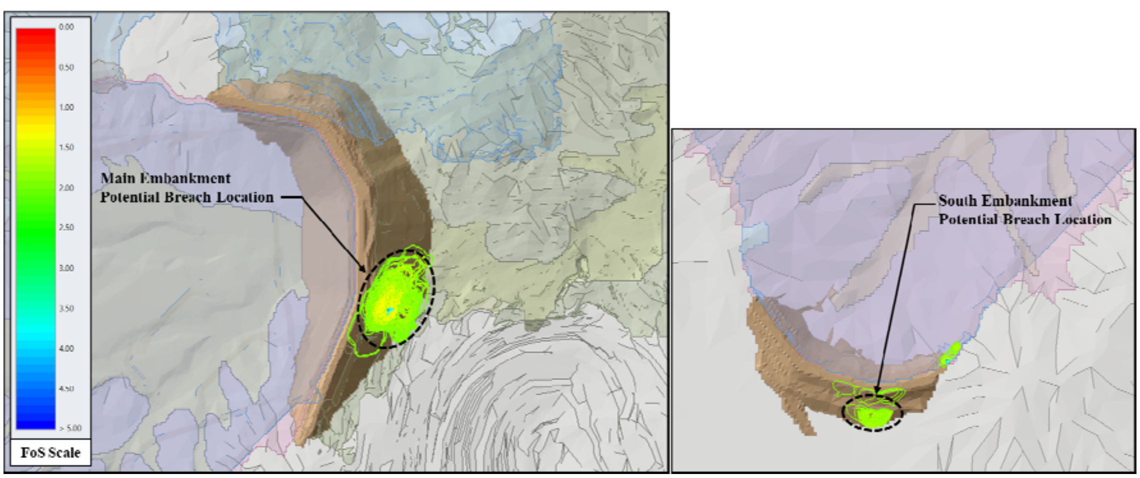

Figure 10. Potential breach location – Main Embankment (left) and South Embankment (right).

5.3 *Estimated Outflow Volumes*

A range of possible outflow volumes for each embankment was estimated by selecting slip surfaces based on the inferred breach locations. It is acknowledged that the stability analysis generates slips surfaces representative of the initial failure or mobilized volume, which do not account for potential retrogressive failures. However, this case study also considers larger slips, despite the higher FoS, as a way to account for possible retrogression once the tailings are mobilized following the breach.

The selected slip surfaces for the Main Embankment are shown on Figure 11. Slips that involve primarily embankment fill are associated with FoS values greater than 2.5, while slips that extend into the tailings are associated with much higher FoS values. The selected slips range in volume from approximately 12 x 10^6 m^3 to 50 x 10^6 m^3 (including approximately 1 x 10^6 m^3 to 20 x 10^6 m^3 of tailings) with corresponding FoS ranging from 2.8 to 5.8.

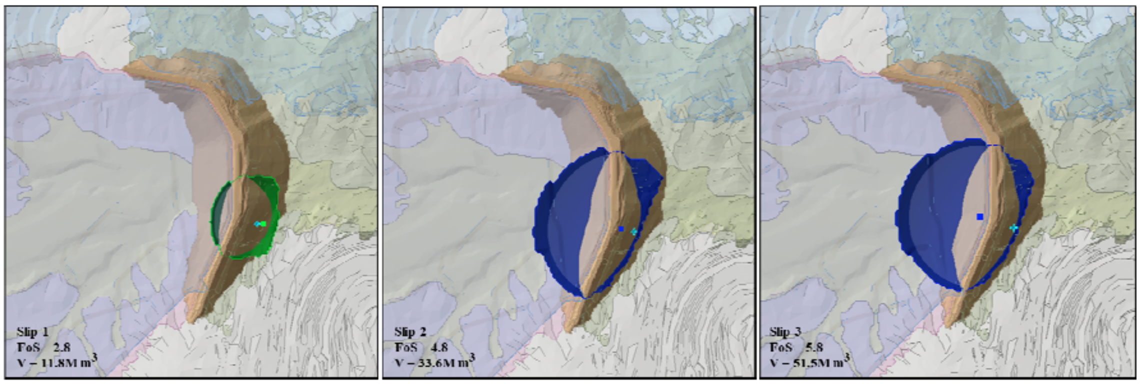

Figure 11. Main Embankment – 3D LEA Slip Surfaces

The total outflow volumes for the South Embankment are estimated to range from approximately 1.5 x 10^6 m^3 to 5 x 10^6 m^3 (including approximately 0.1 x 10^6 m^3 to 2 x 10^6 m^3 of tailings) and are associated with FoS values of 2.9 to 5.8. The selected slips for the South Embankment are shown on Figure 12. The lower FoS values are associated with the smaller slips, which also involve a smaller volume of tailings. Slips 1 and 2 indicate deeper breach locations, but smaller volumes of tailings. Slips 3 and 4 involve larger volumes but with shallower and wider breach geometries and greater volumes of tailings released.

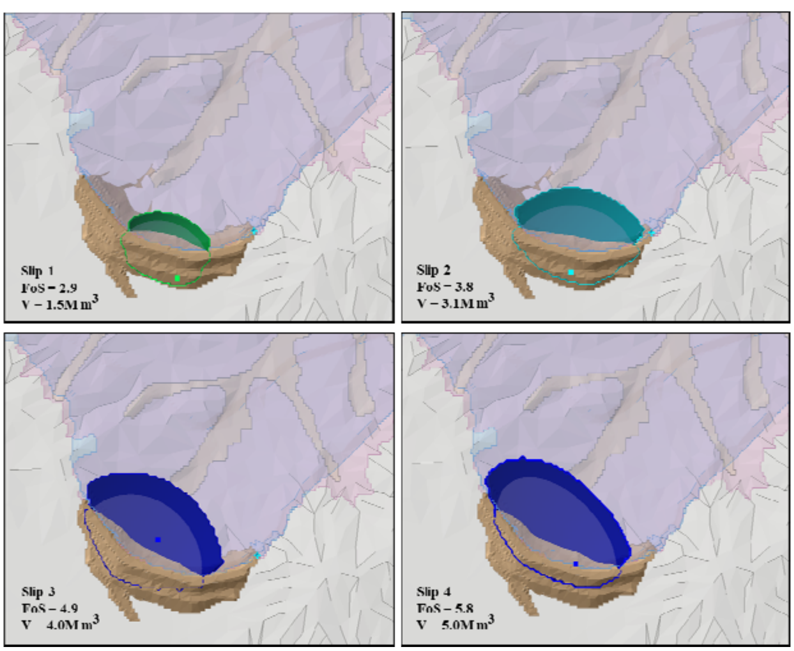

Figure 12. South Embankment – 3D LEA slip surfaces.

5.4 *Credibility of Dam Breach Results*

GISTM (2020) recommends that failure scenarios for dam breach assessments be selected based on credible failure scenarios, particularly if the assessment is conducted to inform emergency preparedness and response planning. Determination of credible failure scenarios is part of the risk assessment process, such is the Failure Modes and Effects Analysis. The results can then be used in the dam breach analysis. However, limited guidance currently exists with respect to the selection of failures that are credible, but conservative enough, to evaluate the potential consequences of a dam breach event.

The results from the type of analysis presented in this paper, particularly the fact that each slip surface (and estimated outflow volume) is related to a specific FoS, can provide additional insight to guide the selection of reasonable failure geometries. It can also facilitate discussions in the risk assessment process or inform emergency preparedness and response planning. Future work will focus on the use of these results to guide the selection of credible and plausible failure scenarios for a reasonable assessment of potential downstream consequences.

6 SUMMARY

The outflow volume is a key parameter in the dam breach analysis and is often used to estimate various breach parameters. However, there are limitations and challenges with the current simplified methodologies that are typically used for estimating the outflow volume, the breach development time, and the breach geometry. Tailings storage facilities that impound densified tailings without a supernatant pond are likely to breach as a slump-type failure with the runout of low-flowability tailings. In these cases, slope stability analysis can provide a more reasonable approach for estimating the breach geometry and the outflow volume than the current empirical equations, which are based on failures of water-retaining dams.

The proposed methodology was applied to the Candelaria TSF where a waste rock closure cap has been designed to densify the underlying tailings. Densification will increase the tailings undrained shear strength and significantly reduce the potential for the impounded tailings to flow if a dam failure occurred. SCPT and laboratory data were used to confirm the improvements of the underlying tailings due to the construction of the test pads. The use of the 3D LEA was proposed to identify the potential breach location and estimate the outflow volume (tailings, foundation, and dam materials) that could be mobilized during a breach event. The important considerations of 3D effects can be incorporated in the analysis and include the original ground topography, the irregular geometries of the existing embankments and proposed waste rock storage, the dendritic pattern of the alluvial foundation, and the curved phreatic surface.

A review of slip surfaces with the lowest FoS was first conducted to identify the potential breach locations and guided the selection of large-scale slips to establish a range of potential outflow volumes. Additional tailings mobilization due to retrogressive failure was considered by including slip surfaces that involved larger volumes. These larger-scale slips are associated with high FoS values, which indicate a low likelihood of occurrence. The range of predicted slip geometries and their associated factors of safety provide additional insights for assessing the credibility of the failure scenario. Future work will focus on the use of these results to guide the selection of credible and plausible failure scenarios for a reasonable assessment of potential downstream consequences.

This case study highlights the importance of integrating soil mechanics concepts with dam breach analysis methodologies to provide a more meaningful approach for evaluating the potential runout impacts of a slump-type failure mode. The proposed approach can be used to facilitate risk assessments and inform emergency preparedness and response planning.

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