Cone penetration test assessment to identify fluid-like tailings to support a tailings storage facility deconstruction

Gastón Quaglia[1#], *Ignacio Adolfo* Cueto[1]

[1] *SRK Consulting (Canada) Inc.*
2600-320 Granville Street, Vancouver, BC, V6C 1S9, Canada
[#]*Corresponding author: gquaglia@srk.com*

ABSTRACT

This paper presents the implementation of a Cone Penetration Test (CPT)-based methodology to identify fluid-like tailings in the Tailings Storage Facility (TSF) pond to support a TSF deconstruction. The TSF discussed in this paper was partially raised upstream and classified as very high risk due to its location, next to a creek and a short distance to the downstream community. The owner's preferred mitigation strategy was to proceed with the TSF deconstruction. To inform the deconstruction planning, a comprehensive geotechnical site investigation was conducted, which included CPTu and boreholes with continuous thin wall tube sampling from a floating platform. The investigation identified tailings in the pond as high plasticity clays (CH) with a geotechnical fines content exceeding 95 %. The CPT results indicated low tip resistance, nearly linear pore pressure measurements, and minimal sleeve friction, suggesting the presence of fluid-like tailings in a significant portion of the TSF. The implementation of this methodology allowed to systematically confirm the presence of fluid-like tailings across the pond and define their extent. This information supported the owner's decision to employ mechanical excavation taking advantage of the tailings flowability. The observations made during the tailings excavation confirmed a good agreement between the CPT assessment and the actual material behaviour. These findings underscore the efficacy of the CPT-based method in guiding safe TSF deconstruction projects.

Keywords: fluid-like; tailings; TSF deconstruction; CPT; digital twin.

1. Introduction

Deconstruction of a TSF is often evaluated by mine owners as an alternative in their risk management strategy plan. However, the limited published successful experiences of these construction projects, plus the large uncertainties and potential risks associated with the deconstruction of loose saturated contractive tailings combined with upstream raises, makes deconstruction a less appealing choice. This work shows the application of a CPT-based methodology typically applied in Oil-Sand tailings to identify fluid-like tailings to support a TSF deconstruction project. A digital twin model of the TSF built for the project planning was used to compare the results of the CPT assessment with as-built survey data and field observations.

2. Tailing Storage Facility description

The TSF crest length was 280 m with an overall footprint of approximately 29,700 m^2. The overall embankment maximum height was 17 m, with an approximate 1.35H:1.0V downstream slope at the steepest sections. The constructed embankment volume was estimated at 109,000 m^3, and the retained tailings volume was estimated at 160,000 m^3, with a maximum depth of tailings of 10 m. The dam was close to a town, and a few farms were located immediately downstream. Because of these factors, a dam classification of "Very High" according to CDA (2019) was adopted.

There is anecdotal documentation indicating the dam was operational by 1980, but no design reports, drawings, or construction records were available. To support the deconstruction project a Digital Twin Model was built using Leapfrog (Godley & Quaglia 2023). This 3D model is a centralized geo-referenced database that improves visualization and interpretation of the available information.

2.1. Tailings characterization

In mine operations such as this project, tailings managed hydraulically are typically pumped from the mill to the storage facility as a slurry with a relatively low solids content (< 45%). At the TSF, the discharge can be subaerial or subaqueous. The freshly deposited tailings segregate and slowly consolidate under self-weight. When conducting a site investigation at the TSF in the pond area the profile could typically show these zones, a water cap, fluid-like tailings, soil-like tailings, and natural ground. In the fluid-like tailings zone the CPT results are characterized by a tip resistance (q_c) that increases with the measured dynamic pore pressure (u_2), which will be equal to the total stress of the fluid tailings (Styler 2018, Sills 1998), and increases with the increase of the solids content. The fluid-like tailings have negligible effective stress. The net tip resistance (q_{net}) and sleeve friction (f_s) show typically no changes and remain close to 0 kPa.

Several site investigation programs were completed at the site between 2019 and 2022 to characterize the

TSF pond and embankment geotechnical units, and support engineering analyses. Fig. 1, shows the location of four CPTs that were pushed in the pond area from a barge with four companion borings.

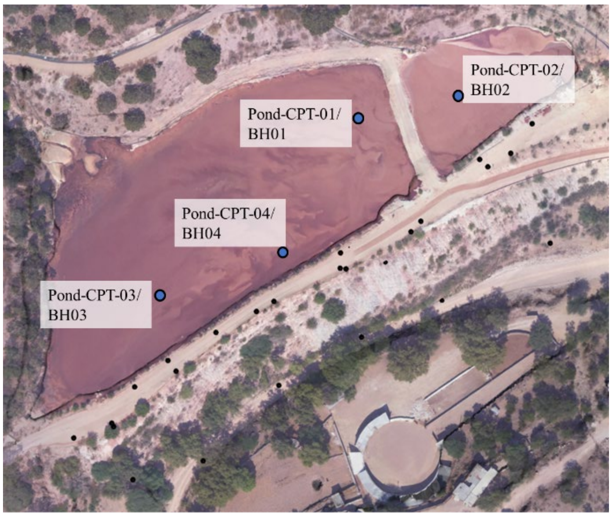

Figure 1. Dam plan view with site investigations.

Tailings samples from the pond were obtained by pushing Shelby tube samplers. The material retrieved was observed very soft, saturated, and grey to brown. The solids content ranged between 19% and 80%. The geotechnical fines content (% Pass sieve #200) was higher than 95%, and the Atterberg limits ranged between LL=75-150 and IP=60-120. The tailings were classified per the Unified Soil Classification System (USCS) as high plasticity clays (CH).

Fig. 2 illustrates the data plots of a CPT in the pond area (Pond-CPT-02) including net tip resistance (q_{net}), sleeve friction (f_s), and dynamic pore water pressure (u_2). The data plots show areas that combine a very low net tip resistance with sleeve friction near zero and a linear trend in dynamic pore pressure suggesting the presence of fluid-like tailings.

For this analysis, the peak undrained shear strength (s_u) is calculated for soil-like tailings using Eq. (1) (Robertson 2009). In the areas where it is suspected the presence of fluid-like tailings, the total vertical stress is equal to the measured dynamic pore pressure (u_2). For fluid-like tailings, the equivalent total unit weight (γ_t) can be estimated as the variation of the total vertical stress with depth using Eq. (2) (Styler 2018), and the undrained shear strength is calculated using the modified Eq. (3):

$$su = q_{net}/N_{kt} = [(q_t - \sigma_{v0})]/N_{kt} \quad (1)$$

$$\gamma_t = \mathrm{d}u_2 \,/\, \mathrm{dz} \quad (2)$$

$$su = q_{net}/N_{kt} = [(q_t - u_2)]/N_{kt} \quad (3)$$

The cone factor (N_{kt}) value in Eq. (1) and Eq. (3) typically varies between 10 and 20, with an average of 14 (Robertson, 2009). Ideally, for a given project the undrained shear strength is also measured using vane shear tests (VST) to calibrate N_{kt}. For this TSF, VST results were not available, and a N_{kt} value of 14 was selected based on the author's experience in other TSFs at this site.

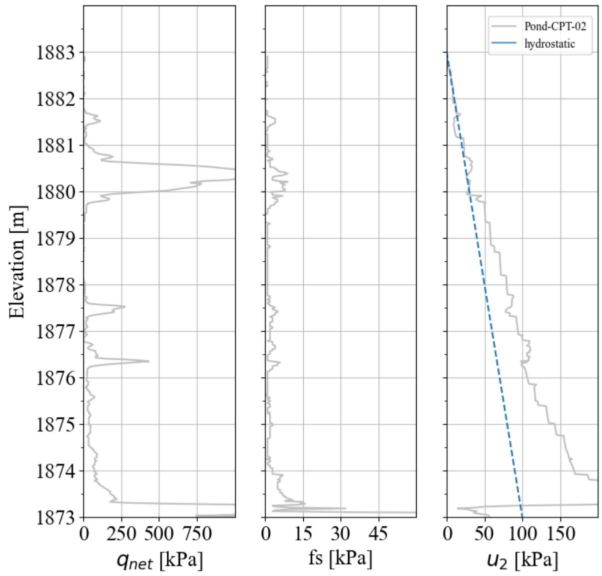

Figure 2. Pond-CPT-02 data plots.

3. Identification of fluid-like tailings

This section presents the analysis steps for the CPT-based methodology proposed by Entezari (2023) that was used in this project to identify fluid-like tailings. The authors also included a series of observations about the methodology and proposed two sensitivity analyses to evaluate the impact of these observations on the identification of fluid-like tailings.

3.1. CPT analysis methodology

The methodology establishes a series of arbitrary conditions that must be met together at any given depth of the CPT to identify the presence of fluid-like tailings:

1. The net cone tip resistance, q_{net} < 100 kPa,
2. The undrained shear strength, s_u < 3 kPa, (calculated using Eq. 3),
3. The dynamic pore pressure (u_2) must have linearity such that a linear regression results in an R-squared (R^2) > 0.95. The linearity at each point is evaluated with a moving window. The points with a q_{net} greater than 100 kPa are already considered soil-like and excluded from the linear regression calculation.

3.2. Comments on the methodology and sensitivity analyses

During the application of this methodology, the following observations were made:

- The undrained shear strength value of 3 kPa indicated by Entezari (2023) is smaller than the undrained shear strength value of 5 kPa typically used to detect fluid-like behaviour in oil-sand tailings (AER Directive 085, 2022).
- The operator has to pre-define where the profile could have fluid-like tailings to calculate the total vertical stress and the undrained shear strength using Eq. (2) and Eq. (3) before the assessment to identify the fluid-like tailings is completed.

- Entezari (2023) employs a 1 m moving window to evaluate the dynamic pore pressure linearity. This arbitrary interval has the potential to be influenced by discrete jumps in the data as a result of the fixed length of the bars used in the CPT test (e.g. 1 m).
- The method does not incorporate conditionals for sleeve friction, which are expected to be near zero (Styler, 2018).

For this work, the methodology was modified implementing a moving window of 0.2 m to evaluate u_2 linearity. An iterative process was followed to calculate the undrained shear strength, first assuming a total unit weight corresponding to soil-like tailings, which results in a higher vertical total stress and a lower undrained shear strength, then using Eq. (3). If the s_u value was already greater than 3 kPa, the layer was identified as soil-like. If not, the process was repeated following the assumption of fluid-like tailings (Eq. 2 and Eq. 3).

Two sensitivity analyses were performed to observe the impact in the assessment of fluid-like tailings. a) the moving window used to calculate the u_2 linearity was set at 1 m, 0.2 m, and 0.08 m; and b) the N_{kt} value was set at 10, 14, and 20.

3.3. Results

Fig. 3 shows the typical results from this assessment for a CPT: dynamic pore pressure (u_2), linearity evaluation (R^2), net tip resistance (q_{net}), and undrained shear strength (s_u), at each depth where all the conditions listed above are satisfied, the layer is identified as fluid-like tailings, and the plots are coloured in red.

The q_{net} plot allows quickly identifying layers of soil-like tailings (q_{net} greater than 100 kPa), at CPT-Pond-02 for example, this is observed between 1881 m and 1880 m and below 1874 m. Layers with q_{net} smaller than 100 kPa have the potential to be identified as fluid-like tailings. The u_2 plot shows a linear trend in the upper 4 m following a hydrostatic pressure distribution. Below elevation, 1879.5 m u_2 continues to be linear with a greater slope. These general trends are analyzed in more detail with the R^2 plot, for example, the linear trend between 1879.5 m and 1878 m is supported with an R^2 greater than the threshold value in most layers of that segment. The s_u values follow a similar trend to q_{net}, with several layers below 3kPa.

This method can provide a very detailed layering due to the large amount of data in the CPTs, but an overall interpretation of the results for Pond-CPT-02, shows soil-like tailings in the upper 4 m. Between 1879.5 m and 1878 m (1.5 m layer), fluid-like tailings are identified. Below 1878 m the method predicts larger inter-mixing of fluid-like and soil-like tailings. The expected material behaviour in this zone is not conclusive.

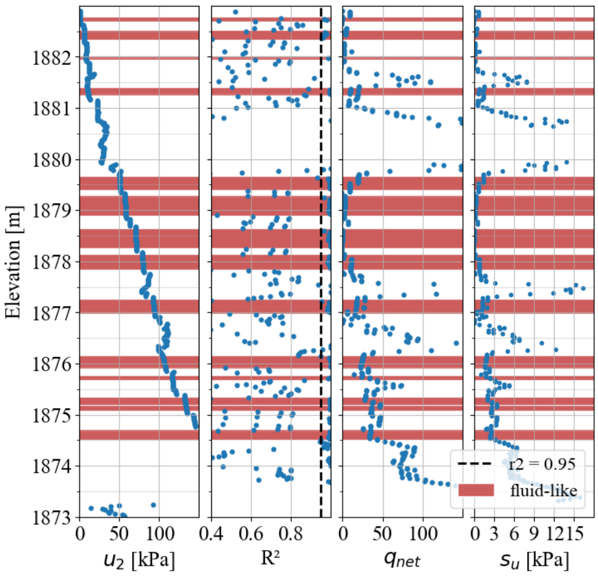

Figure 3. Fluid-like tailings assessment on Pond-CPT-02.

The CPT assessment results with the identification of fluid-like tailings for all CPTs in the pond area are presented in Fig. 4. For simplicity the results are shown only over the s_u plots, the general trends observed for Pond-CPT-01, -02, and -03 are described below.

In Pond-CPT-01 fluid-like tailings were identified almost continuously in the upper 7 m. Discontinuities in u_2 result in jumps in the R^2 values which can be observed as fine interbedded layers of soil-like tailings. However, the s_u values in this section are below the cut-off criteria supporting the interpretation of a continuous layer of fluid-like tailings. In contrast a defined soil-like layer of high s_u values between 1878 m and 1877 m. Below 1877 m a larger intermixing is observed until reaching the foundation.

In Pond-CPT-03, the results are similar to Pond-CPT-01, with several layers of fluid-like tailings and continuous s_u values smaller than 3 kPa. Both CPTs were located in the southern pond of the TSF (Fig. 1). However, the Pond-CPT-03 does not show a defined layer of soil-like tailings. The layering effect in the upper portion is mostly attributed to the loss of linearity in u_2 data.

The Pond-CPT-04 which was pushed in the southern pond but near the dam embankment (see Fig. 1) predicts a much different general behaviour from the other CPTs. It shows a linear increase of undrained shear strength with depth, and below elevation 1881.5 m the Pond-CPT-04 profile is mostly identified as soil-like, with fluid-like tailings only in the upper 1 m.

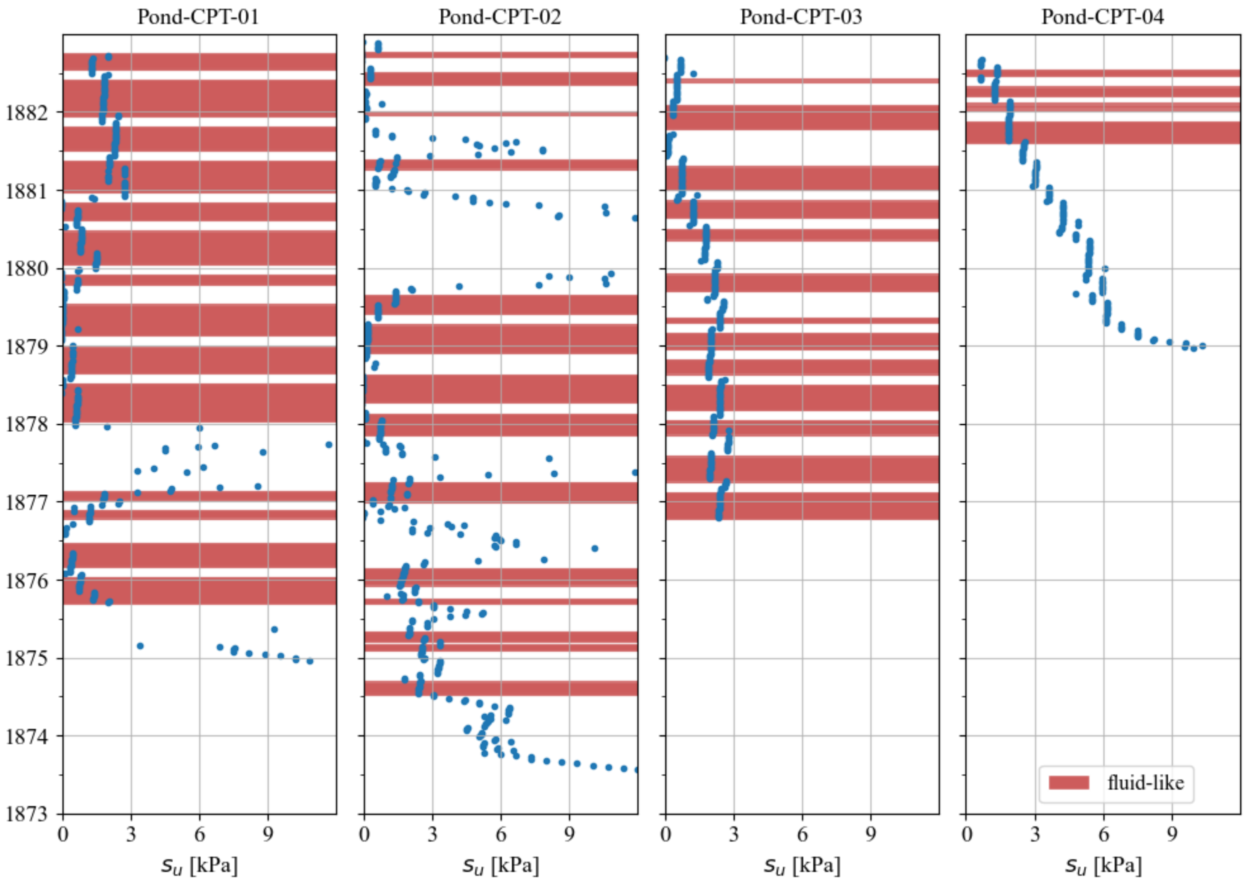

Figure 4. Results of fluid-like tailings assessment on all Pond-CPTs.

3.3.1. Sensitivity analysis results

The layered pattern of fluid-lie and soil-like tailings where the resistance is estimated to be lower than 3 kPa appears to be driven by u_2 linearity. A sensitivity was conducted to show how the analysis window size used to calculate R^2 influences the predictions. Fig. 5 compares the fluid-like tailings layers identified using a 1 m as applied by Entezari (2023), with smaller windows of 0.20 m and 0.08 m.

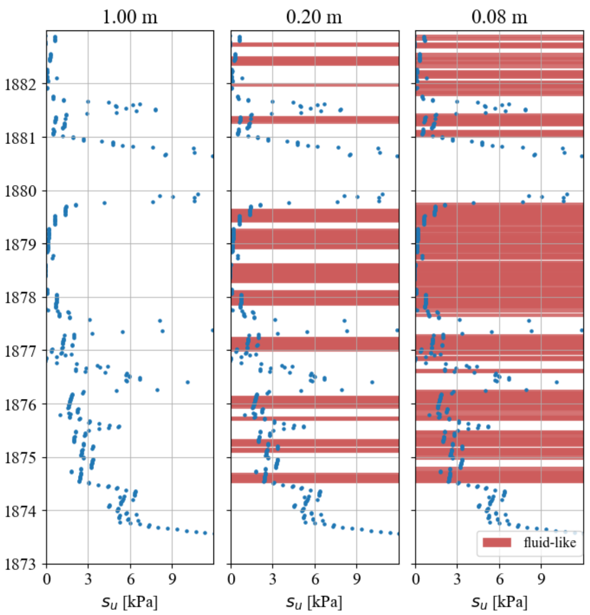

Figure 5. Fluid-like tailings assessment sensitivity to moving window used for linearity estimation.

Changing the analysis window of the pore pressure linearity estimation from 1 m to 0.20 m creates a large difference in the identification of fluid-like tailings since it avoids more of the data jumps. Changing from 0.20 m to 0.08 m increases the cumulative thickness of fluid-like material, and results in a more continuous profile, but does not significantly influence the general trends where fluid-like tailings are identified. The raw data acquisition of the CPTs, and discontinuities during the test highly influence these results.

Fig. 6 shows the results of the sensitivity analyses with different possible N_{kt} values (Robertson 2009). The results show virtually no difference in the predictions obtained with N_{kt} 14 or 20. The observed layering is the same. This was expected since increasing the N_{kt} value reduces the calculated undrained strength. When N_{kt} is 10, the estimated undrained strength increases, affecting mainly the prediction at the bottom of the CPT changing to soil-like tailings. This sensitivity shows that, in general, most layers that are identified as fluid-like tailings remain the same despite the N_{kt} value selected. This N_{kt} value has a smaller impact on the predictions than the selection of the window size used in the moving average calculation of the pore pressure linearity

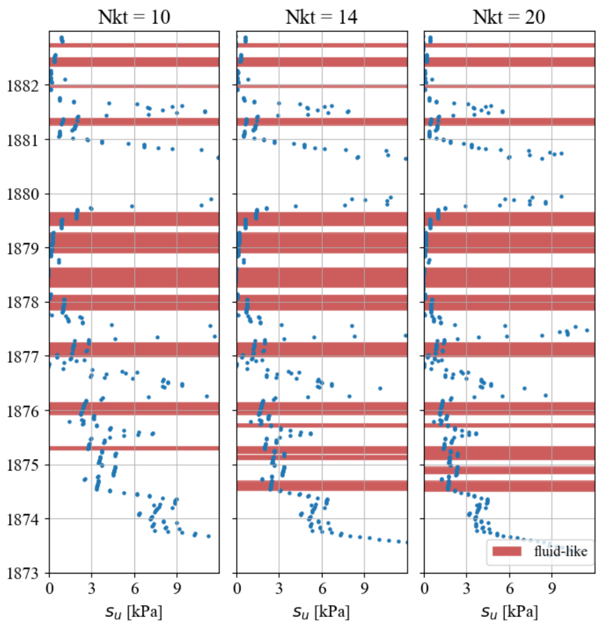

Figure 6. Fluid-like tailings assessment sensitivity to cone factor value.

4. TSF Deconstruction

The deconstruction was planned with conventional and long-reach excavators and hauling with conventional dump trucks with sealed gates. This approach provided operational flexibility with multiple working fronts in comparison to dredging or conveyor methods and avoided introducing water in the TSF as required for hydraulic mining.

The excavation was staged to maintain the safety of the operators and equipment by iterating between layers of tailings and embankment (Godley & Quaglia 2023). The planned stages of approximately 2 m depth were included in the digital twin model to support the construction supervision. Fig. 7 shows the stages in the digital twin as neat straight lines as a simplification to indicate the maximum depth of excavation.

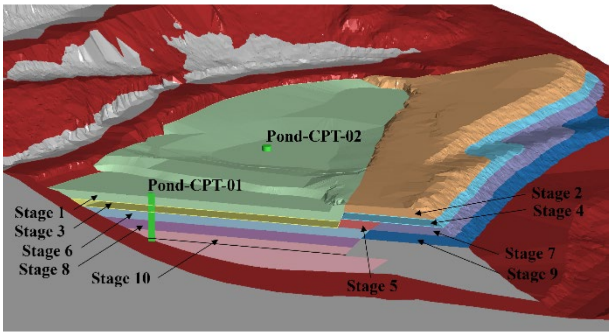

Figure 7. Deconstruction stages in the TSF digital twin.

The largest volume of tailings was excavated from the south pond. The removal of fluid-like tailings was advanced with excavators in the perimeter rear access. Aerial drone photos of the TSF are presented in Fig 8. for stages 1, 3, and 6, and the location of the excavation points, indicating the location of the excavation points. In the early stages, the excavators remained at fixed points, allowing the tailings to flow to the loading areas (Fig. 8a and 8b). As the excavation progressed, the loading points remained at the back, lowering access roads and building small access platforms ("fingers") in certain locations to reach tailings (Fig. 8c). Tailings increased in density and strength during stage 6. The excavators cut steeper slopes in the tailings that slumped into the trenches and were removed. Soil-like, soft tailings, were excavated from stage 8 (approximately 6.7 m depth) onwards until reaching the natural ground. Soil-like tailings were able to withstand much steeper temporary slopes, allowing the excavators to advance with access platforms built on the natural ground from the perimeter towards the center.

This description provides a general understanding of the works. The following sub-section presents the comparison between the predicted material behaviour and the observations during deconstruction in the area of each CPT.

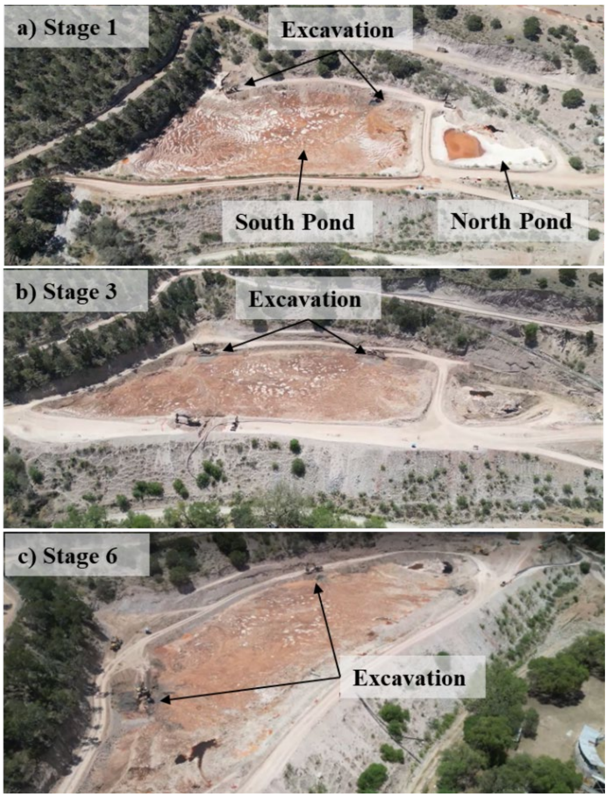

Figure 8. Deconstruction progression in the south pond area.

4.1. Comparison of deconstruction observations with CPT assessment

The TSF digital twin model was used to track the advance of construction. Fig. 9 shows a cross-section in the same position as Fig. 7 that illustrates the results from the CPT assessment (e.g., identification of fluid-like tailings and the calculated undrained shear strength) together with the as-built survey at the end of each excavation stage. It can be observed that the excavation surfaces were initially horizontal due to the presence of fluid-like tailings (e.g., stage 1 and stage 3), and their slope increases with the change in material behaviour. The Pond-CPTs were advanced in 2020 from a barge, for this reason, the data collected starts from a collar elevation higher than the initial excavation surface surveyed in 2023. This elevation change is due to a combination of evaporation of water in the pond, seepage, and settlement of the tailings.

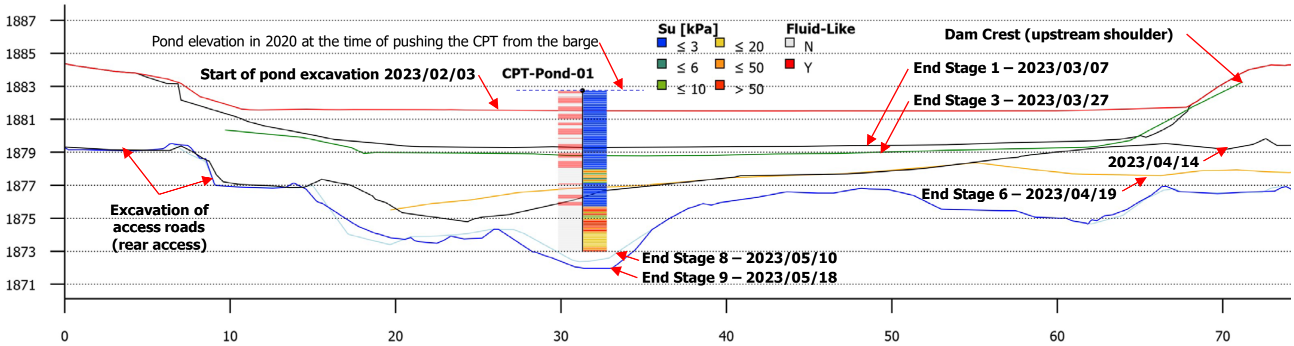

Figure 9. TSF digital twin cross-section with as-built excavation stages, and Pond-CPT-01 assessment results.

While the south pond area followed a similar trend during the excavation some differences were observed between CPT locations. Fig. 10 shows the results from the CPT assessment and the excavation stages near CPT-Pond-01, where a good agreement was observed between the analysis and construction observations. The assessment results indicated fluid-like tailings almost continuously along the first 7 m until reaching a sudden change in the tailings' undrained shear strength.

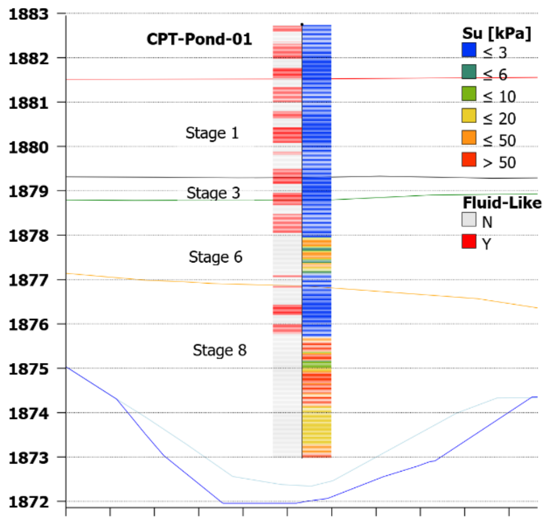

Figure 10. CPT-Pond-01 in digital twin: fluid-like assessment (left), undrained shear strength (right), and as-built excavation.

Excavation of fluid-like tailings near CPT-Pond-01 was completed from the rear of the pond during stages 1, 3, and part of stage 6. A transition from fluid-like to soil-like tailings was observed on consecutive days within stage 6, approximately between elevations 1879 m (Fig. 11a) and 1877 m (Fig. 11b) similar to the predictions obtained from the CPT assessment. The fluid-like tailings identified in the upper portion of stage 8 did not match the field observations. At this depth, the tailings were able to hold temporary slopes. This difference could be supported by an increase in the undrained shear strength due to unloading. This effect was not considered in the CPT assessment performed only with the initial vertical stresses.

Figure 11. a) Excavation of fluid-like tailings during stage 6, b) Excavation of soil-like tailings during stage 6.

Fig. 12 shows the results from the CPT assessment and the excavation stages near CPT-Pond-03. The presence of fluid-like tailings layers interbedded with soil-like tailings layers, but with continuous s_u values smaller than 3 kPa suggested the presence of fluid-like tailings down to elevation 1877 m. At the CPT-Pond-03 location, the excavation surveys show an approximately horizontal slope until the end of stage 6 supporting the prediction of fluid-like tailings.

In the field, the closest excavation point was located in the south abutment (Fig 13.). Here fluid-like tailings were observed during stage 1 and part of stage 3. During the advance of stage 3, the tailings were able to maintain a temporary slope. This field observation could be supported by the presence of more and thicker soil-like tailings layers within stage 3 in comparison to the CPT assessment results within stage 1.

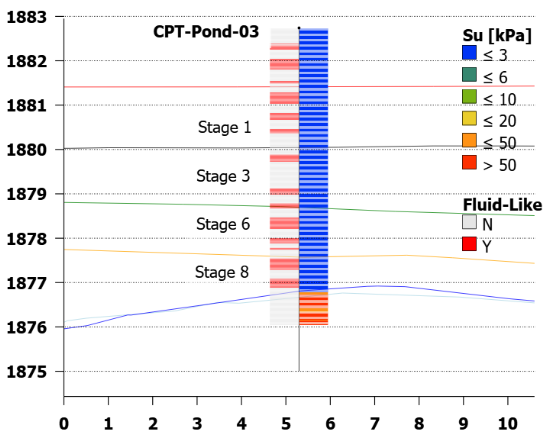

Figure 12. CPT-Pond-03 in digital twin: fluid-like assessment (left), undrained shear strength (right), and as-built excavation.

Figure 13. Excavation point in the south margin (stage 3).

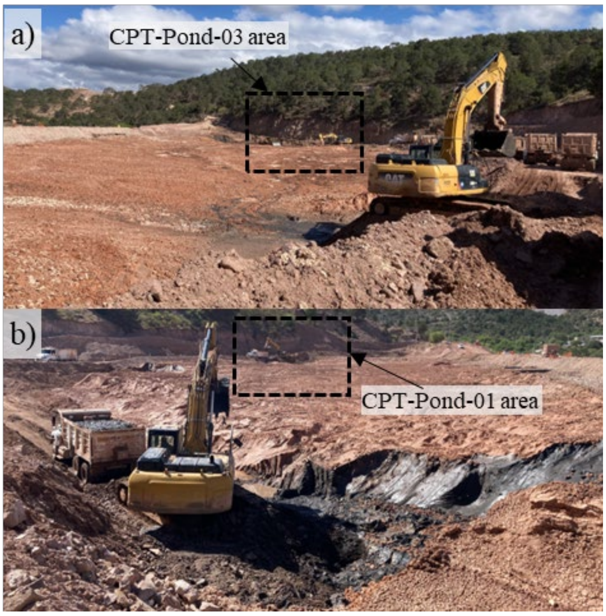

Figure 14. a) CPT-Pond-01 excavation area, b) CPT-Pond-03 excavation area (stage 6).

To further illustrate the material variability within the south pond images of the two excavation points on the same date and at approximately the same elevation of ~1878.5 m are shown in Fig 14.. While fluid-like tailings were still being excavated near the CPT-Pond-01 area (Fig. 14a), more soil-like tailings were removed at the south end closer to the CPT-Pond-03 area (Fig. 14b). The authors note that in the second example, the excavation point in the south abutment (Fig 13.) was closer to the dam embankment which can support the presence of more soil-like material. On the other hand, the excavation was far enough from the location of Pond-CPT-03 which can also influence the comparison between the CPT assessment and the field observations.

In the area of the CPT-Pond-04 near the embankment, the tailings were observed moving towards the center during stage 1 forming a gentle slope as the pond was lowered (Fig. 15). The slope remained during stage 3. During stage 6 already embankment material was being excavated at this position, matching the assessment of soil-like material with an increase of undrained shear strength with depth (Fig. 4).

Figure 15. CPT-Pond-04 excavation area near the dam embankment.

In the north pond, a different layering was observed during deconstruction, and the field observations were in relatively good agreement with the CPT assessment results. Fig. 16 shows the results from the CPT-Pond-02 assessment and the excavation stages. The north pond had a higher elevation (1882.3 m) and at the time of the deconstruction the upper tailings were relatively dry (Fig. 8a) which allowed the contractor to advance stages 1 and 3 until over a dry working platform at an approximate average elevation of 1880 m (Fig. 17a). This selected plane matches the soil-like layer identified with larger s_u values between elevations 1881 m and 1879.7 m.

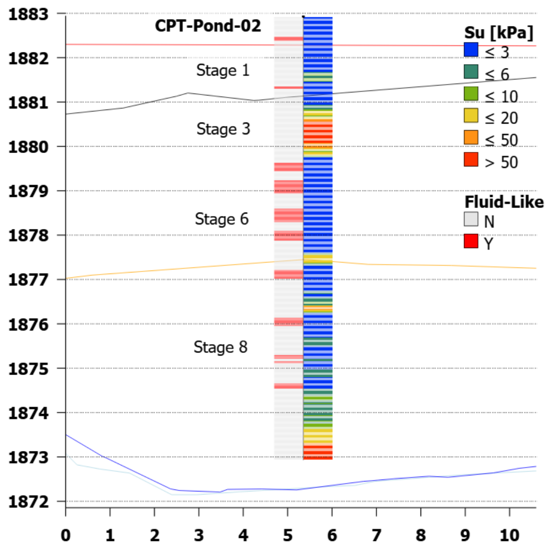

Figure 16. CPT-Pond-02 in digital twin: fluid-like assessment (left), undrained shear strength (right), and as-built excavation.

The deconstruction was then resumed with the excavator positioned at the embankment and fluid-like tailings were removed from a portion of the north pond (Fig. 17b) during the advance of stage 6. The thickness of fluid-like material was not recorded but estimated to be less than 2.5m since below the elevation 1877.5 m (end of stage 6) no more fluid-like tailings were observed.

Figure 17. a) Excavation stopped at ~1880 m, b) Excavation during stage 6 below 1879 m.

5. Conclusions

This work presented the implementation of a CPT-based methodology to identify fluid-like tailings to support a TSF deconstruction planning and the comparison with the observations made in the field during the deconstruction process. The main conclusions of this work are:

- The CPT assessment methodology with the proposed modifications for the dynamic pore-pressure (u_2) linearity evaluation was useful in identifying the extent of fluid-like tailings in the pond area.
- The predicted layered pattern of fluid-like and soil-like tailings, was highly influenced by the linearity measurement in the dynamic pore pressure. The results from a sensitivity analysis showed that reducing the moving window from 1.0m to 0.20 m had a great impact on the prediction results.
- The results from a sensitivity analysis with the N_{kt} value varying between 10 and 20, show that this value has a small impact on the prediction results.
- In general. the observations made during the tailing's excavation near CPT-Pond-01, CPT-Pond-02, and CPT-Pond-03 confirmed a good agreement between the materials identified and the field observations.
- These results from the CPT assessment supported the decision to employ mechanical excavation taking advantage of the tailings flowability. The agreement with the field observations confirmed the value of the information provided by the CPTs to support a risk management decision.

References

Canadian Dam Association (CDA). "Technical Bulletin: Application of Dam Safety Guidelines to Mining Dams", Canada, 2019.

Entezari, I., McGowan, D., Glavina, J., & Sharp, J., "A comparison between in situ techniques to measure undrained shear strength of oil sands tailings", In: GW Wilson, NA Beier, DC Sego, AB Fourie & D Reid (eds), Paste 2023: Proceedings of the 25th International Conference on Paste, Thickened and Filtered Tailings, University of Alberta, Edmonton, and Australian Centre for Geomechanics, Perth, pp. 787-797.

Godley, D. & Quaglia, G. "Deconstruction of an Upstream Raised Tailings Storage Facility: Project Design and Execution", In: Tailings and Mine Waste, Vancouver, Canada, 2023, pp. 1155-1166

Robertson P. K. 2009. Interpretation of cone penetration tests — a unified approach. Canadian Geotechnical Journal. 46(11): 1337-1355. https://doi.org/10.1139/T09-065

Robertson P. K. 2010. Estimating in-situ state parameter and friction angle in sandy soils from CPT. 2nd International symposium on cone penetration testing, Huntington Beach, CA, USA 2010 May

Robertson, P. K. (2016). Cone penetration test (CPT)-based soil behaviour type (SBT) classification system — an update. Canadian Geotechnical Journal, 53(12), 1910-1920

Styler M. A., McGowan D. & Sharp J., "Characterizing soft oil sand tailings by gamma cone penetration testing" IOSTC 2018: Proceedings of the International Oil and Sand Tailings Conference, Edmonton, pp 112-120.