Lessons Learned in the Interpretation of SCPT on a Tailings Facility using the CSSM framework

Jorge León[1]* and Claudia Vallejos[1]
1. *Knight Piésold S.A., Chile*

ABSTRACT

This study presents an assessment of the application of the Seismic Cone Penetration Test with pore pressure measurements (SCPT) for evaluating a tailings storage facility with high saturation levels and low equilibrium pore pressures. The research addresses critical insights gained from a site investigation, providing practical lessons for the current industry practices. The primary findings involve the challenges related to interpreting data and characterizing the mechanical behavior of partially saturated tailings when the material is not fully saturated but contains sufficient water content to develop excess pore pressure. The study emphasizes assessing shear strength parameters, accounting for pore pressure effects in the tailings mass, the methodology adopted, and the laboratory testing carried out. The analyses performed are of a screening-level nature, enabling a straightforward and effective evaluation of tailings behavior. Furthermore, this study contributes to a more refined understanding of the geotechnical behavior of tailings with a high degree of saturation using SCPT within the Critical State Soil Mechanics (CSSM) framework to assess geotechnical behavior.

INTRODUCTION

A site investigation program was conducted on a tailings storage facility (TSF) constructed using the upstream rise method. The TSF includes a starter dam made of earthfill material that is 10 m high. It was raised in 5 m increments by placing earthfill over the tailings mass, reaching a final TSF height of approximately 50 m.

The TSF is located in a semiarid region with a low seismicity regime. There is no evidence that it has been exposed to any extreme conditions, such as an earthquake capable of triggering an undrained response. Previous stability analyses used drained strength parameters (friction angle and cohesion), neglecting undrained response. The preliminary review suggested that the tailings were highly saturated and loose, suggesting that a contractive response could occur under triggering mechanisms. This study presents data collected from SCPT soundings and laboratory tests conducted for stability assessments.

SITE INVESTIGATION AND LABORATORY TESTING

This study focuses on results from two recent site investigations that included SCPT, drilling, sampling, and instrumentation installation. Laboratory testing on relatively intact and remolded samples was carried out to estimate index properties and critical state parameters. The average particle size, D_{50}, is 0.01 mm, and 88% fine particles under sieve #200. The liquid limit is 23%, the plastic limit is 15%, and the plasticity index is 8. The specific gravity of the tailings is 2.82. Figure 1 presents typical profiles of three SCPT soundings conducted below the downstream slope of the TSF, extending to a depth of 50 m. SCPT-01 was performed at the crest of the TSF, SCPT-02 at a mid-slope location, and SCPT-03 between SCPT-02 and the starter dam. The profiles include the following normalized parameters: cone resistance (Q_{tn}), friction ratio (F_r), pore pressure (U_2), and Soil Behavior Type Index (I_c) according to Robertson (2016).

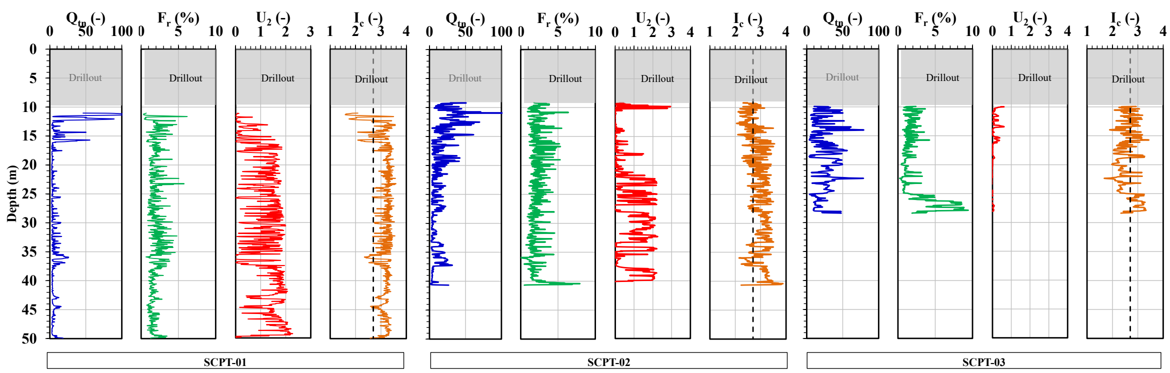

Figure 1 SCPT-01/02/03 Normalized Profiles (normalization according to Robertson, 2016)

The data suggests that tailings have a relatively low resistance with interbedded layers. The I_c profiles include a vertical dashed boundary at I_c=2.7 as threshold value to classify between coarse-grained and fine-grained. It is recognized that coarse-grained and fine-grained can be misleading terms given particle size distribution of the tailings, but these terms are adopted in this study to classify the material based on material behavior rather than physical properties. The fine-grained tailings predominate in the SCPT-01 test, while the SCPT-02 and SCPT-03 tests show a greater presence of coarse-grained layers. This is consistent with lower generation of dynamic pore pressures in the sandier layers and higher cone resistance. Seismic tests indicated partially saturated conditions, with compressional wave velocity (V_p) lower than 1,500 m/s. Pore pressure dissipation tests were conducted at frequent depth intervals to estimate the equilibrium pore pressures. Dissipation times varied between 200 s up to 1,000 s. Times required to reach 50% of dissipation were estimated leading to T_{50} of approximately 30 s, suggesting partially drained conditions. Equilibrium pore pressures were significantly lower than the dynamic readings recorded during the cone penetration. Figure 2 shows the interpretation charts recommended by Robertson (2016). The $Q_{tn} - F_r$ soil behavior type plot indicates that most tailings are contractive at large strains, classified as clay-like contractive sensitive (CCS) or clay-like contractive (CC). The remaining data plot in the transitional contractive (TC), sand-like contractive (SC) and sand-like dilative (SD). The SCPT interpretation in terms of the $Q_{tn} - U_2$ plot proposed by Schneider et al (2008) shows a good correlation with the coarse-grained and fine-grained classification based on an I_c value of 2.7. The coarse-grained tailings do not have significant excess pore pressures or high U_2 values, while the fine-grained tailings show positive normalized pore pressures between 0 and 2.3 classifying as transitional contractive (TC) in the $Q_{tn} - U_2$ plot. This is consistent with the partial drainage conditions interpreted with pore pressure dissipation tests. The K_G^* values are consistent with young uncemented soils, with no significant evidence of microstructure. Some of the upper tailings near the ground surface have K_G^* values higher than 330 likely due to higher shear wave velocity affected by partially saturated conditions.

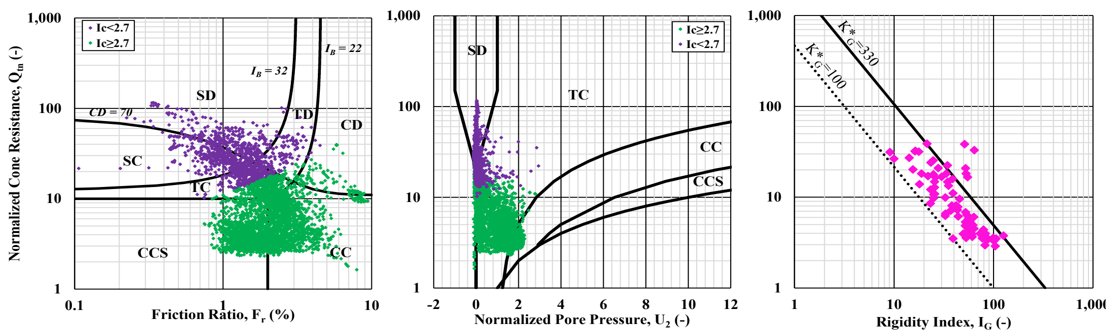

Figure 2 SCPT-01/02/03 – SBTn Plots

CRITICAL STATE LABORATORY TESTING

Laboratory testing was carried out to estimate the critical state parameters using saturated triaxial compression tests. Five drained and three undrained isotropically consolidated tests were performed on reconstituted samples prepared loose and dense using the moist tamping method. Void ratios at the end of the test were determined using the squeezing method proposed by Verdugo and Ishihara (1996). Critical state parameters λ_{10} and Γ correspond to 0.13 and 0.96, respectively.

STATE PARAMETER AND RESIDUAL STRENGTH

The assessment of the large strain behavior of tailings involved the application of the state parameter, utilizing SCPT data interpreted through two methodologies: Robertson (2010, 2022) and Plewes et al. (1992) as revised by Shuttle and Cunning (2007), described by Jefferies and Been (2016) as the screening-level method. As can be seen in Figure 3, distinctions between coarse-grained (I_c < 2.7) and fine-grained (I_c > 2.7) materials were made, producing cumulative state parameter histogram distributions. Pink dashed lines represent the contractive-dilative boundary (ψ=-0.05) and the characteristic 80th percentile following the recommendations by Jefferies and Been (2016).

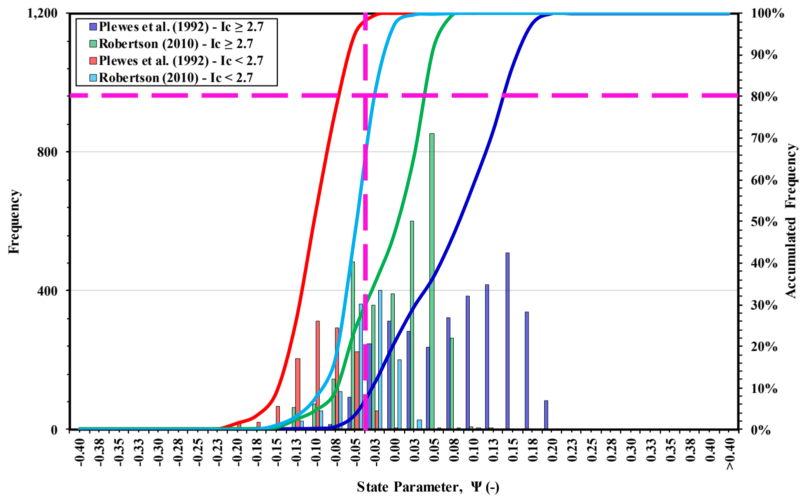

Figure 3 SCPT-01/02/03 – State Parameter Histogram

In fine-grained tailings, both methodologies indicated a significant percentage as contractive (>70%). It is noted that the difference in the characteristic state parameter between both methodologies is larger in the fine-grained tailings. Specifically, the estimated state parameter associated to the 80th percentile using the Robertson (2010) method is 0.03, whereas the Plewes et al. (1992) method suggests 0.14 for the same percentile. It is noted that Robertson's method has reduced applicability when $I_c > 3.0$ (Robertson et al. 2019; Robertson, 2022). For coarse-grained tailings, disparities between methodologies were less substantial. The residual undrained shear strength ratio ($S_{u(liq)} / \sigma_v'$) was estimated with methodologies proposed by Olson and Stark (2002), Jefferies and Been 'best-practice trend' (2016), Robertson (2022) and the revised 'best-practice trend' proposed by Robertson (2024) to assess the variability of the shear strength with different SCPT interpretation methods. The state parameters determined using the methods shown in Figure 3 were adopted as input for the 'best-practice trend' required by the Jefferies and Been (2016) and Robertson (2024) relationships. Histograms with accumulated frequencies are shown in Figure 4 for each interpretation method and SCPT probe. The graphs shown in Figure 4 include the percentages of fine-grained (I_c<2.7) and coarse-grained (I_c>2.7) materials classified for each location, providing a depiction of the material distribution across the TSF downstream slope. Analysis using the Olson and Stark (2002) method suggests lower strength values compared to other methodologies. The Robertson (2022) method and the best-practice trend, incorporating state parameters derived from the screening-level method, yield comparable results in predominantly fine-grained materials, as evidenced by the SCPT-01 distribution. This suggests a good correlation between cone sleeve resistance estimations per Robertson (2022) and the best-practice trend, particularly in materials with intermediate compressibility (e.g., λ_{10}= 0.135). The methods of Jefferies and Been (2016) and Robertson (2024) exhibit similar strength distributions, as the proportion of coarse-grained material increases ($I_c > 2.7$) from SCPT-01 to SCPT-03, irrespective of the approach used to estimate the state parameter. This consistency aligns with the understanding that both methods are typically calibrated for sands. In tests SCPT-02 and SCPT-03, where coarse-grained content is more pronounced, the Robertson (2022) method yields lower strength values compared to Jefferies and Been (2016) and Robertson (2024). This difference may stem from the Robertson (2022) correlation for sand-like materials (I_c < 3.0) being calibrated to the lower bound of well-documented historical cases, whereas the Jefferies and Been (2016) method accounts for material compressibility by calculating the slope of the critical state line, affecting residual strength estimations. The revised best-practice trend proposed by Robertson (2024) closely resembles the original formulation of Jefferies and Been (2016), with differences between the original and revised methods becoming more pronounced in coarse-grained materials.

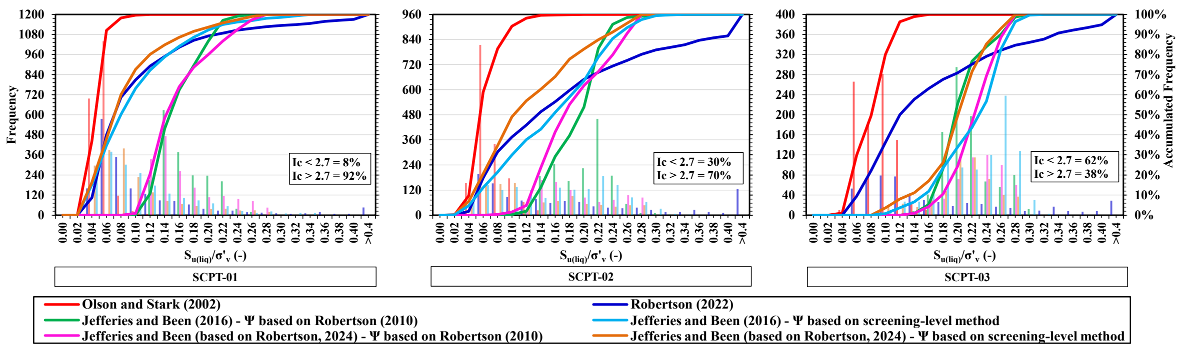

Figure 4 SCPT-01/02/03 – Residual Strength Ratio Histograms

CONCLUSIONS

Various approaches for analysing SCPT results have been compared in this study to interpret the state parameter and undrained residual strength in sandy silt tailings. Below are summarized the key results and findings:

- The study establishes a Soil Behavior Index (I_c) threshold of 2.7 to differentiate fine-grained (I_c < 2.7) and coarse-grained (I_c > 2.7) tailings, aligning with observed trends in material distribution and strength behavior across the TSF downstream slope.
- The Olson and Stark (2002) method consistently estimates the lowest strength estimates regardless of the tailings classification (fine or coarse grained)
- In fine-grained materials, the Robertson (2022) method and the best-practice trend, incorporating state parameters from the screening trend method, demonstrate good agreement with cone sleeve resistance estimations, particularly for materials with intermediate compressibility (λ_{10} = 0.13).
- In coarse-grained materials (I_c > 2.7), the Jefferies and Been (2016) and Robertson (2024) methods produce similar strength distributions, while Robertson (2022) suggests lower strength, likely due to its reliance on lower-bound historical case data for sand-like materials (I_c < 3.0).

These findings, derived from SCPT data, provide a screening-level characterization of tailings state and strength, supporting preliminary stability analyses. Ongoing research will refine these assessments with advanced models (e.g., NorSand) and considerations of partial drainage and saturation effects (e.g., Ayala et al., 2022).

ACKNOWLEDGEMENTS

The authors acknowledge the support and contributions of Javier Cousiño and Claudia Arias of Knight Piésold S.A. in preparing this article.

REFERENCES

Ayala, J., Fourie, A., and Reid, D. (2022). 'Improved cone penetration test predictions of the state parameter of loose mine tailings', Canadian Geotechnical Journal, Volume 59(11): 1969-1980.

Jefferies, M., and Been, K. 2016. 'Soil Liquefaction, a Critical State Approach', 2nd ed. Taylor & Francis Group: CRC Press.

Plewes, H., Davies, M., and Jefferies, M. (1992). 'CPT Based Screening Procedure for Evaluating Liquefaction Susceptibility', 45th Canadian geotechnical conference, Innovation conservation and renovation, Toronto, Canada, 1992.

Robertson, P.K. (2010). 'Estimating in-situ state parameter and friction angle in sandy soils from CPT', Proceedings of the 2nd International Symposium on Cone Penetration Testing, CPT'10, Huntington Beach, CA, USA.

Robertson, P. K. (2016). 'Cone penetration test (CPT)-based soil behaviour type (SBT) classification system — an update', Canadian Geotechnical Journal, Volume 53 (12): 1910-1927.

Robertson, P. K. (2022). 'Evaluation of flow liquefaction and liquefied strength using the cone penetration test: an update', Canadian Geotechnical Journal, Volume 59 (4): 620-624.

Robertson, P.K. (2024). Webinar: Understanding Piezometric Profile and more: Keys to Tailings Dam Stability using the CPT, ConeTec Group. https://youtu.be/R2nBa3MtFIY?si=44YmAkMcTUoRLixQ.

Robertson, P.K., de Melo, L., Williams, D. J. and Wilson, G. W. (2019). Report of the Expert Panel on the Technical Causes of the Failure of the Feijao Dam I.

Schneider, J., Randolph, M., Mayne P., and Ramsey, N. (2008). 'Analysis of Factors Influencing Soil Classification Using Normalized Piezocone Tip Resistance and Pore Pressure Parameters', Journal of Geotechnical and Geoenvironmental Engineering, Volume 134(11): 1569-1586, 2008.

Shuttle, D., and Cunning, J. (2007). 'Liquefaction potential of silts from CPTu', Canadian Geotechnical Journal, Volume 44(1): 1-19

Verdugo, R., and Ishihara, K. (1996). 'The steady state of sandy soils', Soils and Foundations, Japanese Geotechnical Society, Volume 36(2): 81-91, 1996.