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Impoundment characterisation for hydraulic mining of tailings

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ABSTRACT

Reprocessing old tailings storage facilities (TSFs) has become increasingly common in the past ten years because of economic, environmental, and social reasons. Tailings deposited by spigots experience segregation and layering, creating deposits that are difficult to excavate due to the highly erratic geotechnical behaviour of the exposed faces. Both in-situ and laboratory testing are necessary to understand how steep, temporary tailings slopes might behave, ensuring stability through engineering analysis. This paper describes a detailed geotechnical characterization of an old TSF impoundment by in situ and laboratory testing, including sonic drilling, SCPTu soundings, geophysical field testing, and oedometric, monotonic and cyclic triaxial lab testing. Two different areas were surveyed: tailings near the dam, where coarser material is expected, and in the centre of the impoundment for the characterization of finer materials. We focused on the critical state behaviour of tailings and estimations of the state parameter, required to calibrate the numerical models employed in the analyses.

Keywords: tailings characterization, hydraulic mining, in-situ testing, tailings dams.

1. Introduction

During the mid-19th century, mining processes were notably less efficient compared to contemporary standards. Mineral bodies exhibited grades exceeding 1% (i.e., from 100 tons of rock 1 ton of ore can be obtained) often doubling the current observed grade in some copper mines. Consequently, a substantial amount of mine waste from those legacy mines still contains recoverable ore.

Most of the tailings storage facilities (TSFs) constructed by that time were built and operated following empirical methods. Many of them are upstream-raised dams located near communities, water bodies, or protected environmental settings, qualifying them as high-risk structures according to GISTM (ICMM, 2020). Chile, for instance, has more than 600 abandoned or not-in-use TSFs, some of them decades old and constructed by the upstream methodology (Sernageomin, 2020).

Reprocessing these old tailings has attracted a lot of attention in the past decade because it can reduce the risk of environmental and social impacts of dam failures while being economically attractive. Indeed, reprocessing tailings is a cheap and simple mining method for copper tailings, since no drilling, blasting, and loading equipment are required.

Nonetheless, plenty of geotechnical challenges arise when intervening in a TSF impoundment since large cuts and excavations of loose and saturated tailings are required. Understanding tailings behaviour is thus critical to ensure stability during the exploitation. The company has been mining inactive TSFs, some of them 50 years old, employing hydraulic removal by high-pressure monitors.

This paper summarizes several rounds of the comprehensive geotechnical characterization program performed to support the stability analyses of these tailings' deposits during their exploitation.

2. Site Investigation

Tailings had been disposed from the crest of the main dam by spigots. Consequently, segregation on the impoundment beach was expected to occur with coarse tailings close to the dam´s crest and slimes towards the already evaporated pond. Hence, the site investigation program focused on two zones named Zone 1 located close to the main dam and Zone 2, approximately 1 km away from the dam's crest. The objective was to identify different types of tailings along the beach extension and eventual tailings layers with complex behaviour in depth. This is schematically shown in Fig. 1.

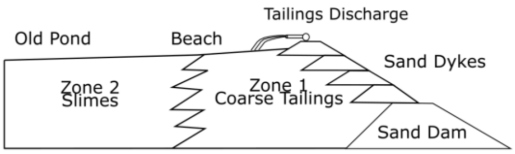

Figure 1. Tailings deposition from spigots located at the dam's crest and zones defined for their characterisation.

Among the explorations carried out, cone penetration tests equipped with a geophone on the cone's tip to measure shear wave velocity in-depth and pore pressure measurements were performed (SCPTu) on the impoundment, with a special focus on characterising Zone 1. A MOSTAP sampler was employed in twin boreholes to retrieve in-depth samples for routine soil testing.

In addition to the shear wave velocity measurements, electric resistivity tests (ERT) and test pits were carried out to study the soil fabric. Fig. 2 shows the layered deposition and different grain-sized materials in Zone 1.

Both disturbed and undisturbed samples were recovered and employed for laboratory testing (see Fig. 3) including basic soil testing, compressibility tests and monotonic and cyclic triaxial testing.

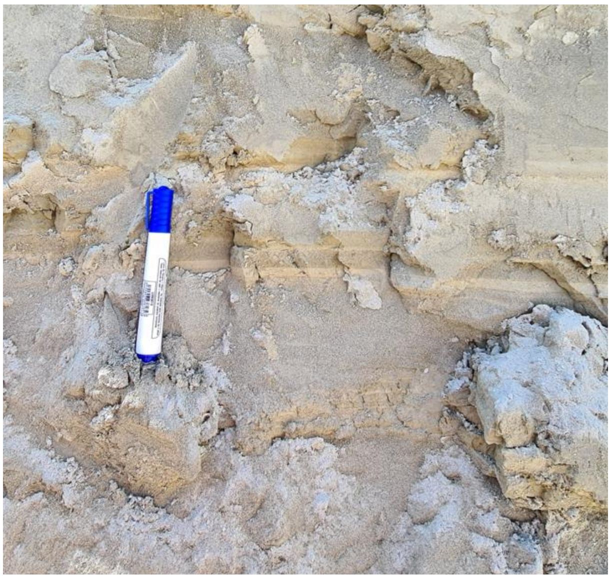

Figure 2. Layering in tailings deposition

Figure 3. Undisturbed sampling for triaxial testing.

3. In-situ Tests

3.1. CPT Results

The tip resistance (q_t), sleeve friction (f_s), and dynamic pore water pressure (u_2), are shown in Fig. 4 and Fig. 5. for tailings from Zone 1 and Zone 2, respectively. Tip resistance and sleeve friction tend to slightly increase with depth. A shallower water table is found for CPTs carried out on Zone 2, which could be explained since the pond used to be at that place when the TSF was operating more than 50 years ago. Water table depth was identified as about 33 to 40 m in Zone 1 and between 5 and 14 m in Zone 2.

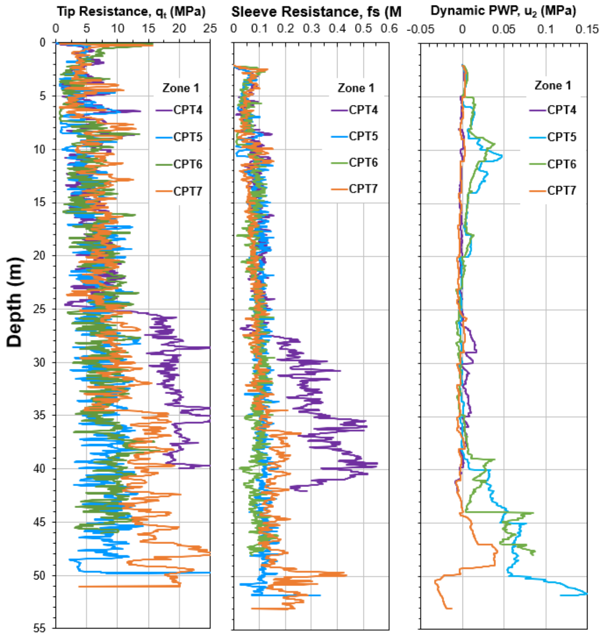

Figure 4. Tip resistance (q_t), sleeve friction (f_s), and pore pressure (u_2) for Zone 1.

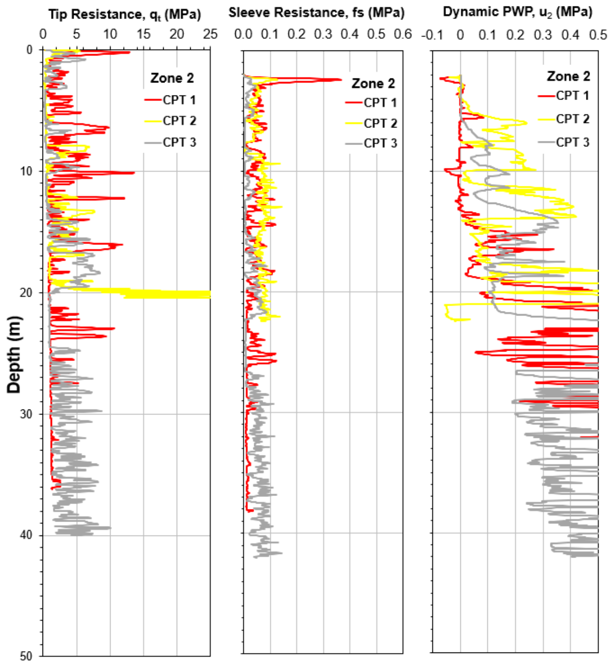

Figure 5. Tip resistance (q_t), sleeve friction (f_s), and pore pressure (u_2) for Zone 2.

Spatial variability is presented in Table 1, which shows the mean value and (in brackets) the range of tip resistance (q_t) and sleeve friction (f_s) for each CPT.

Table 1. Percentile 50 obtained for qt and fs (in brackets is shown the minimum and maximum value)

Zone	CPT #	q_t (MPa)	fs (MPa)
1: Coarse Tailings	4	7.6 [0-31]	0.11 [0.0-0.6]
	5	6.8 [0-25]	0.10 [0.0-0.3]
	6	7.1 [0-17]	0.08 [0.0-0.2]
	7	9.0 [0-31]	0.09 [0.0-0.4]
2: Slimes	1	1.4 [0-14]	0.02 [0.0-0.4]
	2	1.0 [0-31]	0.01 [0.0-0.8]
	3	1.8 [0-10]	0.03 [0.0-0.1]

3.1.1. State Parameter

Based on the Critical State framework, liquefaction susceptibility can be assessed preliminarily through the State Parameter (ψ) (Been and Jefferies, 1985).

Several authors have proposed empirical correlations between CPT results and the state parameter (e.g. Jefferies and Been, 2016). Fig. 6 shows a comparison of the results obtained using the original Plewes method (Plewes et al., 1992), Been and Jefferies method (1992), and Robertson and Wride (1998) method, applied to CPT 6 in Zone 1.

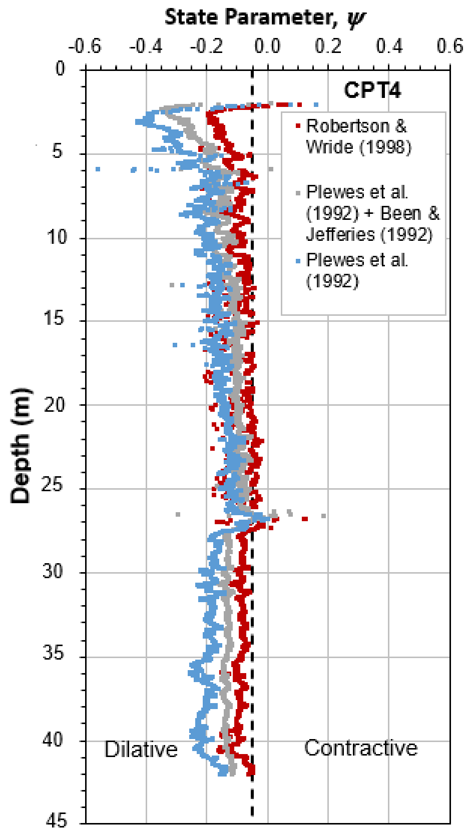

Figure 6. Comparison of three different approaches to obtain the stare parameter value (Ψ).

Fig. 6 shows that, in Zone 1, the state parameter is remarkably constant with depth, which may be indicative of parallelism between the one-dimensional compression curve and critical state lines (CSL) in $e - \ln[p']$ space and is below $\psi = -0.05$, indicative of dilative tailings. Robertson & Wride (1992) provided the lowest estimates, Plewes et al (1992) provided the highest, while Been & Jefferies (1992) fell in-between throughout the entire depth of the CPT sounding and was adopted for design.

Fig. 7 shows the histogram of the state parameter for CPT4, representative of Zone 1, while Fig. 8 shows the histogram for CPT1, representative of Zone 2. Tailings from Zone 1, which tend to be coarser, exhibit a dilative behaviour but still have about 20% of the data points above the threshold value of $\psi = -0.05$ recommended by Been & Jefferies (1992). Tailings located closer to the old pond in Zone 2, on the other hand, show a significant trend to be highly contractive, with 75% of the data points above $\psi = -0.05$.

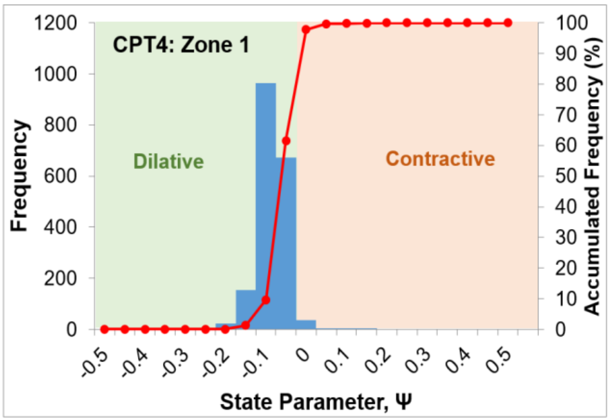

Figure 7. State parameter distribution by using Plewes et al. (1992) combined with Been & Jefferies (1992) for Zone 1.

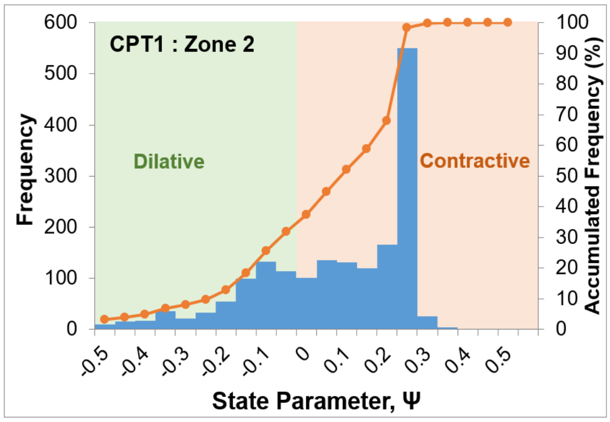

Figure 8. State parameter distribution by using Plewes et al. (1992) combined with Been & Jefferies (1992) for Zone 2.

3.1.2. Undrained Shear Strength

The undrained shear strength ratio (s_u/σ'_{v0}) was estimated from the CPT data by using Jefferies and Been (2016) and Robertson (2010) methodologies. This parameter was assessed only for layers determined either by the B_q or by being located below the water table. Only values in the range 0.03 $< s_u/\sigma'_{v0} <$ 0.5 were considered. Table 2 resumes the obtained parameters for each zone and methodology.

Table 2. Undrained shear strength over the initial vertical effective stress (s_u/σ'_{v0})

Zone	Methodology	P30	P50	Average
1	B & J (2016)	0.17	0.20	0.21
	Robertson (2010)	0.17	0.20	0.21
2	B & J (2016)	0.11	0.14	0.20
	Robertson (2010)	0.13	0.15	0.23

3.2. Shear wave velocity

The shear wave velocity (V_s) was determined by SCPTu testing and employed to compute soil stiffness ($G = \rho V_s^2$). Results are presented in Fig. 9, where an increase in V_s with depth can be observed, but with significant scatter indicating that compressible tailings layers are interbedded because of poorly controlled deposition processes that took place decades ago.

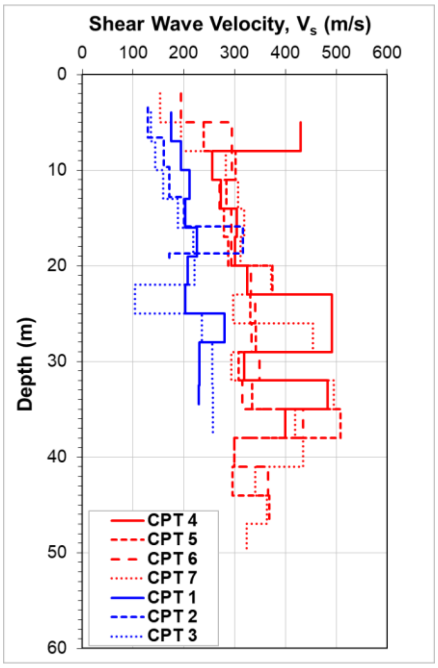

Figure 9. Shear wave velocity measured on the CPT tests.

3.3. Electrical resistivity test (ERT)

Water table in Zone 1 is located about 35 to 40 m below the surface. Therefore, the upper 35 m are partially saturated, but it is anyway important to determine if any layer has a degree of saturation that could generate excess pore pressure under undrained loading.

Fig. 10 shows two profiles of Electric Resistivity Tests (ERT) carried out in zone 1. Fig. 10 (a) shows the left abutment of the main dam, while Fig. 10 (b) shows the right abutment. ERT results were calibrated and interpreted using both gravimetric moisture content obtained from MOSTAP samples from CPT twin boreholes and with the water table reported from each CPT (obtained from dissipation tests).

Tailings in Zone 1 are in the two-phase zone (saturation between 15% and 90%, Fredlund et al. 2012). Nonetheless, there is one layer that exhibits high saturation (about 4 m to 8 m deep) and another layer is almost dry (at the center, close to the left abutment).

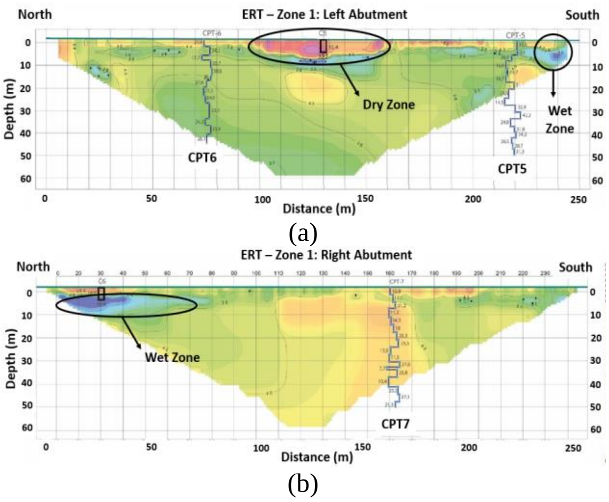

Figure 10. ERT results for the (a) left abutment and (b) right abutment of zone 1 tailings close to the main dam.

4. Laboratory tests

4.1. Basic tests

The MOSTAP sampler was employed in twin boreholes to retrieve 59 and 13 samples from Zone 1 and Zone 2, respectively. Additionally, two samples were extracted from each of the four test pits excavated in Zone 1, thus reaching 80 samples.

Particle size distribution (PSD) tests were carried out in all samples; soil classification tests were carried out only for 17 of these samples (due to material availability). Additionally, unit weight tests were carried out for the tailing's samples obtained from test pits. Table 3 summarises the unit weight results, as well as the density tests performed in the samples. Results shown prove that Zone 1 tends to have coarser tailings and higher density compared to Zone 2.

Table 3. Index properties of the tested samples

Zone	USCS	Dry unit weight, (kN/m³)	Max dry unit weight (kN/m³)	Min dry unit weight (kN/m³)
1: Coarse Tailings	SM & ML	13.9-14.8	19.4	13.0
2: Slimes	CL & CL-ML	11.0-14.4	18.0	-

Fig. 11 shows the fines content and USCS classification results in depth for (a) Zone 1 and (b) Zone 2, while Fig. 12 shows the water content and degree of saturation for both zones, including CPT, tests pits (C5 to C8) and sonic drilling results (S68, S69 and S70).

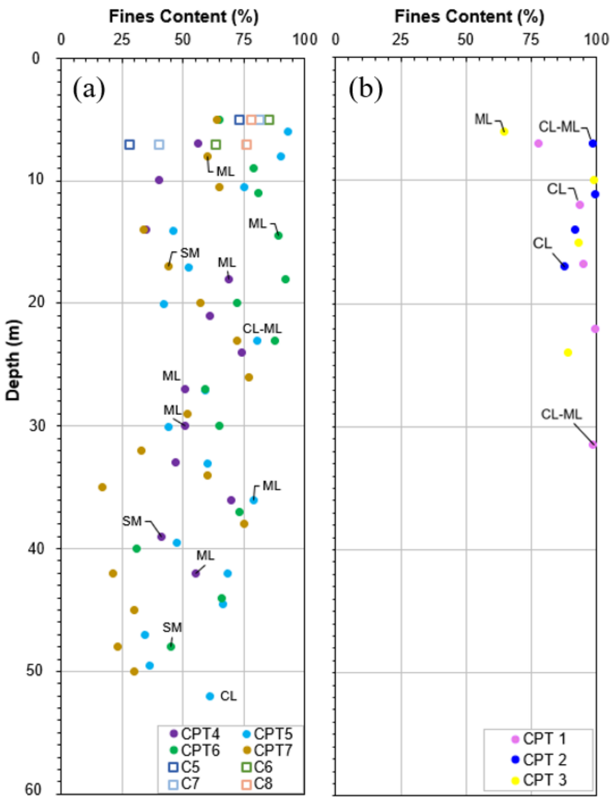

Figure 11. Soil classification (USCS) and fines content (FC) in depth for (a) Zone 1 and (b) Zone 2.

Fig. 11 shows that Zone 1 classifies mainly as SM and ML while Zone 2 is composed primarily of fines (FC over 75% in most tailings' layers) classifying as CL to CL-ML.

Gravimetric water content and degree of saturation are presented in Fig. 12. In the tailings, at Zone 1, the gravimetric water content is around 15% to 20% up to 30 m deep, increasing from up to 30%-40% for depths over 30-35 m. Slimes in Zone 2 exhibit a higher water content between 25 to 45%, with most of the data being over 35% of water content.

Regarding the degree of saturation, Zone 1 tailings are saturated from 35 m deep, consistent with the data reported by the CPT soundings. In addition, the saturated layer is captured by CPT 6 which shows an $S_r \cong 100\%$ between depths of 4 and 8 m. Dato from Zone 2 confirms a shallower water table depth, which varies between 4 and 8 m deep, again consistent with the CPT data.

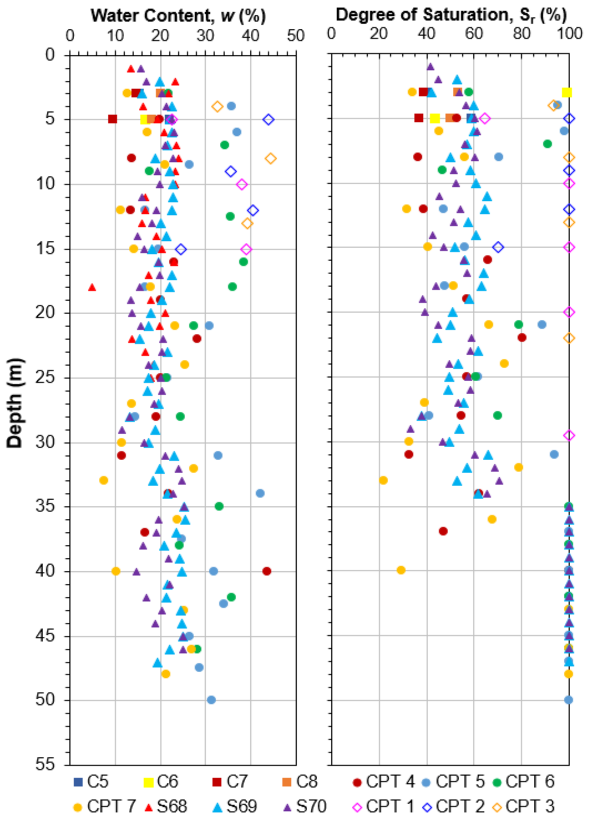

Figure 12. Gravimetric water content (w) and degree of saturation in depth for both zones

4.2. Compressibility

Fig. 13 shows the results of a single oedometer test performed in a slime sample at a dry unit weight of 11 kN/m³ (initial void ratio of e_0=1.50). The compression index is estimated as $C_c = 0.26$, while the swelling index is $C_s = 0.03$, within typical values for copper tailings.

4.3. Monotonic Triaxial Tests

All samples were remoulded using the moist tamping technique and tested for the same confining pressure ($\sigma_3' = 300\ kPa$) but at different dry densities.

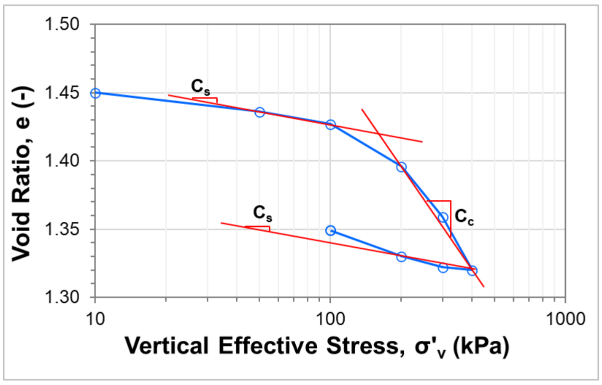

Figure 13. Oedometer test results for slimes from Zone 2.

Loose samples were tested in undrained shear to capture the phase transformation line and for an accurate determination of the critical state friction angle ϕ_{cv}, whle denser samples, at unit weights of 16.9 and 17.5 kN/m³, were tested in drained shear. See Fig. 14.

Results show that the transformation between contractive to dilative behavior occurs at a unit weight between 15.5 and 16.9 kN/m³, void ratio in the range of $0.80 < e < 0.65$, i.e., a contractive behaviour can be expected for unit weights below 15.5 kN/m³. The critical stale line has a slope of $M_{tc} = 1.35$, characterised by a friction angle of $\phi_{cv} = 34°$.

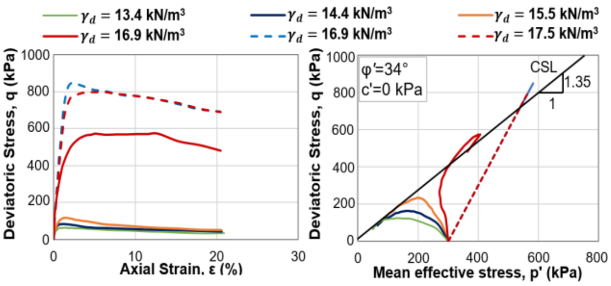

Figure 14. Triaxial test for Zone 1 tailings (adapted from Morales et al., 2021).

Three undisturbed samples of Zone 2 tailings were tested (γ_d =13.0, 13.8 and 14.4 kN/m³) and three remoulded samples were assembled using the moist tamping technique. Similar to Zone 1 tailings, four samples were tested in undrained shear, including all the undisturbed samples, and two remoulded samples were tested in drained shear.

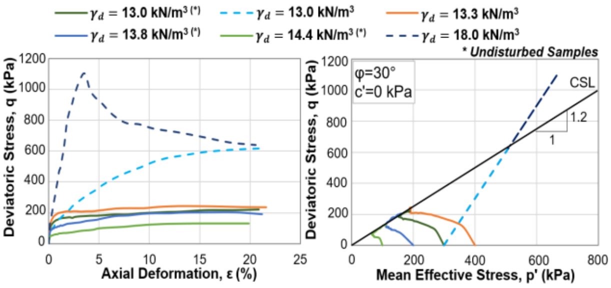

Figure 15. Triaxial test for Zone 2 tailings (adapted from Morales et al., 2021).

Unit weights below 14.4 kN/m³ ($e > 0.88$), exhibit a contractive behaviour, while the sample prepared at 18 kN/m³ ($e = 0.45$) was dilative. The critical stale line has a slope of $M_{tc} = 1.20$, characterised by a friction angle of $\phi_{cv} = 30°$.

4.4. Cyclic Triaxial Tests

Fig. 16 shows the cyclic triaxial test results obtained in remoulded samples from Zone 1 (SM) and Zone 2 (ML), considering the 5% double amplitude (DA) criteria. The dry unit weight for samples from Zone 1 and Zone 2, was 13 and 14 kN/m^3, respectively. These dry unit weights were chosen considering each zone's lowest natural dry densities obtained on site (see Table 2). All tests were performed at a confining pressure of $\sigma_3' = 100\ kPa$. In Zone 2 tailings, a $CSR = 0.15$ applied did not reach the liquefaction criteria.

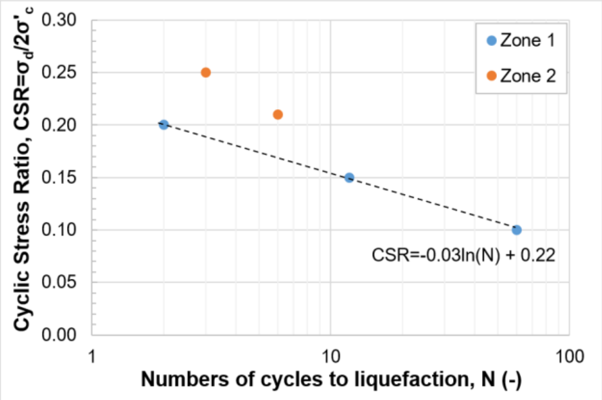

Figure 16. Cyclic triaxial test results (Morales et al., 2021)

It is observed that Zone 2 tailings exhibit a higher cyclic shear strength to liquefaction than Zone 1 tailings, which could be influenced by the higher clay content in Zone 1 tailings, increasing their CRR as some authors, have previously shown (Osipov et al., 2005; Towatha, 2008).

5. Design & expected performance of cuts and slopes

The results confirm the initial hypothesis that the tailings near their deposition point (Zone 1) are sandy, with higher effective stress strength than tailings far from the spigots (Zone 2) which are finer, mainly siltier with some clay. In addition, in Zone 1 the water table is at 35 m deep, while in Zone 2 varies from 5 to 14 m. These two aspects, combined, impact in the design of the excavation sequence, geometry, and rate.

Since the project is in a seismic area, seismic design governs the design of slopes. Based on limit equilibrium analyses and numerical models, the max slope angle has been set to 30° in Zone 1, for slopes of less than 20 m high, and 25° in Zone 2 with a maximum height of 10 m.

Although it is not discussed in this paper, suction also plays a key role in the temporary stability of slope cuts. In several tests' pits performed on the impoundment it has been observed that walls of the pits remain completely vertical for months, in excavations up to 4 m. Suction is the key factor that further compensates for the lower shear strength in Zone 2. Sequencing of the excavations and cuts can be optimized by this extra-strength provided by suction, provided that autonomous hydraulic monitors, with no human intervention, are employed in the operations.

In addition, experience throughout several years of operation has shown that the excavation itself depresses the water table 1 to 2 m per year, improving the stability of the remaining cuts through time. In attention to workers safety, it is not advised to operate hydraulic monitors where tailings show a shallow water table.

6. Conclusions

The mining company has been mining inactive TSFs, some of them 50 years old, employing hydraulic removal by high-pressure monitors. This paper summarizes the characterization program performed to support the stability analyses of these tailings' deposits during their exploitation.

Two different areas were surveyed: Zone 1, close to the deposition points, and Zone 2, at the pond. As expected, CPT results show that tailings located in Zone 2 are weaker and finer than tailings located close to the dam. Anyway, all tailings are relatively loose: 50% to 60% of the data show contractive behavior in Zone 1 and 80% in Zone 2.

The ERT proved to be a useful tool to detect interbedded tailings layers close to full saturation, more so if benchmarked with nearby drillings or CPT soundings. A MOSTAP sampler was employed to retrieve good quality samples, albeit very small, which were used to run routine tests. Results confirmed that tailings located close to the dam are coarser than those at the center of the impoundment.

Monotonic and cyclic triaxial tests were performed to determine the strength properties of tailings in both zones. A higher cyclic shear resistance to liquefaction was found in Zone 2 compared to Zone 1, although the sample density was lower in Zone 2 samples. This could be explained since Zone 2 tailings tend to have more clay content, which increases cycles to liquefaction. Furthermore, the aging effect of the 80 year's old tailings could play a key role in the field behavior during exploitation (Troncoso et al., 1988), a fact that could not be replicated in the laboratory since the samples were remoulded or somewhat disturbed during recovery.

References

Been, K. and Jefferies, M.G. 1985. A state parameter for sands. Géotechnique, 35(2), 99–112.

Been, K. and Jefferies, M.G. 1992. Towards systematic CPT interpretation. In Proceedings of the Wroth Memorial Symposium, Oxford, U.K., pp. 121–134. London, U.K.: Thomas Telford.

International Council on Mining and Metals. 2020. Global Industry Standard on Tailings Management. ICMM.

Jefferies, M., & Been, K. 2016. Soil Liquefaction a Critical State Approach. Taylor & Francis Group.

Morales, C., Castillo, E. & Posch, J. 2021. Geotechnical characterization of an old copper tailings impoundment by using the Cone Penetration Test and Laboratory Testing. Proceedings of the 7th International Conference on Tailings Management

Plewes, H.D., Davies, M.P. and Jefferies, M.G. (1992) 'CPT based screening procedure for evaluating liquefaction susceptibility '. In Proceedings of the 45th Canadian Geotechnical Conference, Toronto, Canada.

Robertson, P.K. and Wride, C.E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. Canadian Geotechnical Journal, 35(3), 442–459.

Robertson, P.K. 2010. Evaluation of flow liquefaction and liquefied strength using the cone penetration test. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 136(6), 842–853.

Sernageomin. 2020. Datos Públicos Depósito de Relaves. Catastro de Depósitos de Relaves en Chile (actualización 10-08-2020), viewed July 4th 2021- https://www.sernageomin.cl/datos-publicos-deposito-de-relaves/

Osipov, V.I., Gratchev, I.B. and Sassa, K. 2005. The mechanism of liquefaction of clayey soils (M124), Chapter 15, Landslides: risk analysis and sustainable disaster management, Springer, pp. 127–131.

Towhata, I. 2008. Geotechnical Earthquake Engineering. Springer Science & Business Media, Berlin.

Troncoso, J., Ishihara, K. & Verdugo, R. 1988, Aging effects on cyclic shear strength of tailings materials. IX World Conference on Earthquake Geotechnical Engineering. Vol 3, pp 121-126, Tokyo, Japan.

Vick, S. G. 1983. Planning, Design and Analysis of Tailings Dams. John Wiley & Sons.