

Geotechnical characterization of old tailings for use as sand stacking foundation

S. Paihua,

Knight Piésold Consultores S.A., Lima, Lima, Peru

O. Román

Knight Piésold Consultores S.A., Lima, Lima, Peru

R. Vargas

Knight Piésold Consultores S.A., Lima, Lima, Peru

ABSTRACT: Several mining projects are evaluating the use of existing tailings facilities for disposal of fresh tailings due to a trend of reducing new areas impacted by mining activities. New tailings can be placed in old tailings facilities using alternative methods such as sand stacking or filtered tailings. Placement of new tailings in an old tailings facility could lead to potential slope stability problems during and/or at the end of operations and so the understanding of the behavior of the old tailings as a foundation material for the new facility should be carefully studied.

This paper presents the results of a geotechnical site investigation program of piezocone penetration tests (CPTu) and standard penetration tests (SPT) that was carried out in an old tailings facility to evaluate its feasibility as a foundation material. The old tailings (approximately 20 to 30 years old) need to be geotechnically characterized to assess how they will behave after being loaded by the fresh tailings. The information collected during the geotechnical site investigation allowed the definition of the stratigraphic profile of the existing tailings facility. The old tailings were composed of interbedded coarse tailings (loose sand) with thicknesses between 10 and 20 meters and fine tailings (soft clay/silt) with thicknesses between 10 and 18 meters.

It was necessary to assess the behavior of the tailings during shearing, with variable pore water pressures, and with varying strength parameters in order to evaluate the feasibility of this disposal method because the physical stability of the future tailings storage facility will primarily depend on the characteristics of the existing tailings foundation. The soft fine tailings are of particular interest for the stability assessment of the new tailings facility. Geotechnical recommendations are presented for the fresh tailings disposal using the sand stacking method and for future stages of the project.

1 INTRODUCTION

Several mining projects are evaluating the use of existing tailings facilities for disposal of fresh tailings due to a trend of reducing new areas impacted by mining activities. This paper presents the results of a geotechnical site investigation program developed for a feasibility study in old tailings storage facility located in the South American Amazon Region, on top of which new tailings will be placed through sand stacking.

The sand stacking strategy has been assessed as a medium-term alternative for tailings disposal. Sand stacking basically consists of disposing the tailings using cells contained by non-structural berms within the tailings storage facility, so the tailings can be disposed as a slope above the maximum elevation of the existing dams, thus creating additional storage capacity of tailings with no need to raise the perimeter containment dams. Tailings will be hydraulically discharged into the cells until the latter are filled up; this process will be repeated after each of

the cells has been filled, drained and dried up naturally. A schematic overview of this sand stacking disposal is shown in Figure 1.

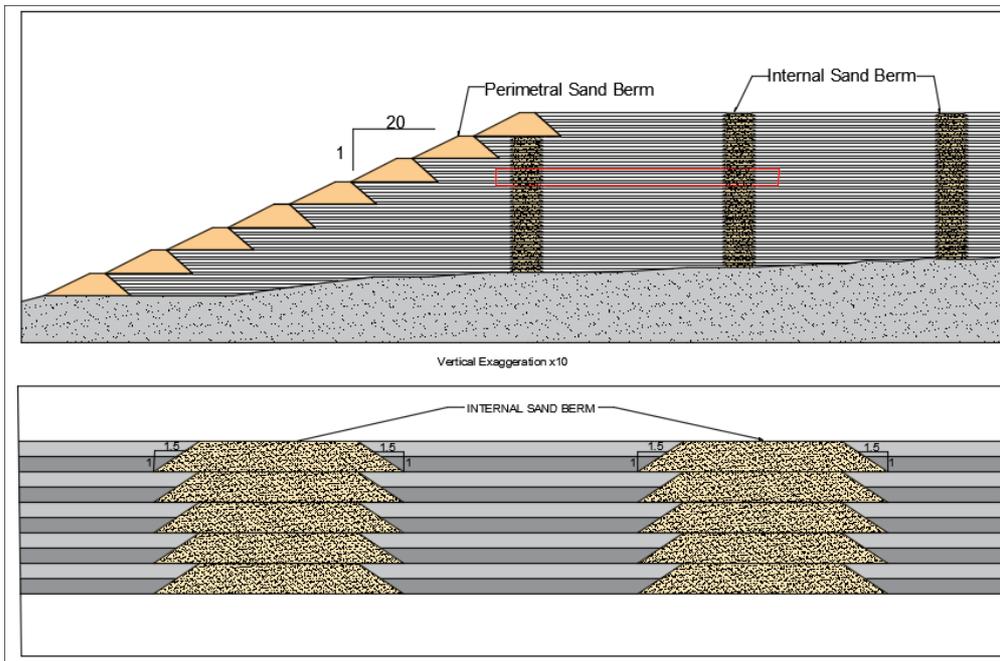


Figure 1. Tailings disposal using sand stacking

As the deposited tailings will not be compacted, it will be important to monitor the drainage conditions in order to verify whether they are adequate enough to promote the formation of stiff and drained piles to limit saturation of the sand stacking body and to prevent undrained behavior of the sands under shearing.

Based on the geotechnical investigation performed in the old tailings storage facility, it could be seen that the area where the sand stacking slope toes will be located shows highly varied foundation conditions, with zones of contractive and dilative behavior in the tailings that are composed of fine sand (coarse tailings) and variable undrained strengths in depth in the soft clay (fine tailings). As for coarse tailings, they could be susceptible areas prone to static liquefaction; whereas a certain degree of sensitivity has been estimated in fine tailings (these tailings could lose strength with excessive deformation) which could lead to a global or progressive failure in the storage facility.

Some measures considered to reduce the geotechnical risks of this disposal system applied in the tailings storage facility include an adequate drainage of the facility, a flat slope (between 20H:1V and 25H:1V) and a minimum factor of safety of 1.5 in the stability analyses. The first measure minimize the liquefaction potential of the body and the last two measures reduce the mobilized shear stresses in the foundation, thus preventing static liquefaction from developing in coarse tailings or “strength softening” in fine tailings.

As design criteria, the importance of adequate drainage of the sand stacking facility has been emphasized. The free draining nature of the future coarse tailings allow to maintain a drained body if the operational practices are adequate. For this purpose a pilot test was recommended so as to evaluate a proper rate of the tailings disposal and the natural drainage and drying of the cell. However, based on experiences collected from failures of upstream tailings facilities, the raising rate of the storage facility should be less than 9.0 meter per year, according to Vick (1990). This raising rate was preliminary recommended, because it would normally allow for pore pressures in coarse tailings to quickly dissipate. In fine tailings, the influence of the storage facility raising rate on the generation and dissipation of excessive pore pressure must be assessed through more detailed analyses and a monitoring plan during operation. Some VW pie-

zometers were installed during the site investigation in order to collect data of the pore pressure change in the foundation.

A more detailed assessment of the fine tailings could result in a lower raising rate, the need for improving their drainage conditions by applying wick drains-type engineering solutions, or by improving the shear strength of this stratum.

2 GEOTECHNICAL SITE INVESTIGATION PROGRAM

The site investigation program carried out in the area where the sand stacking strategy is suggested consisted of performing the following soundings:

- 20 drillholes with SPT testing
- 20 CPTu soundings

The location of the geotechnical investigations developed is shown in Figure 2.

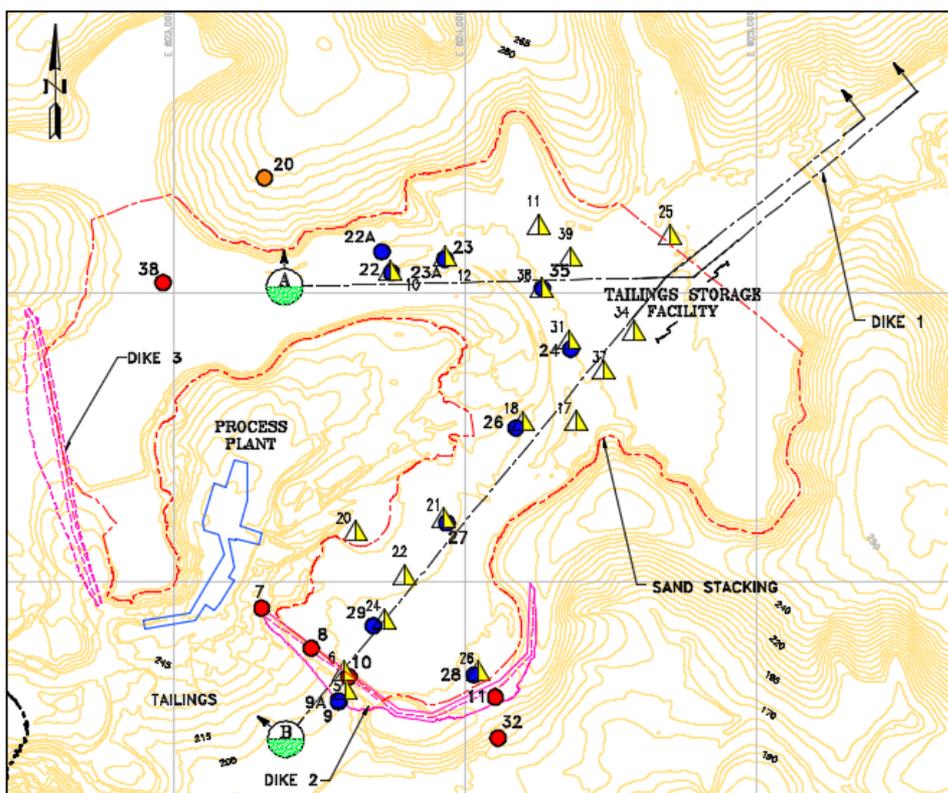


Figure 2. Geotechnical site investigation program developed in the old tailings storage facility.

Complementarily, basic laboratory tests were performed of index properties in order to classify the materials in accordance with the Unified Soil Classification System (USCS). In addition, the sample moisture content was established.

Geotechnical characterization has been performed considering the geotechnical field investigation based on the CPTu and SPT tests as a main source of information. The execution of these tests has allowed to establish the type of behavior of materials (drained or undrained) and determine the strength parameters, the same that were used in the stability analysis.

In general, the stratigraphy of the area where sand stacking will be applied will consists of the materials below:

- *Coarse tailings*, which correspond to old tailings classified as silty sand (SM), poorly graded sand with silt (SP-SM), well-graded non-plastic sand with silt (SW-SM), very loose to loose, and in some areas these tailings are medium dense grey, moist to saturated and between 7 and 23 m thick.
- *Fine tailings*, which correspond to old tailings classified as silt (ML, MH) and clay (CL, CH) with medium to high plasticity, very soft to soft, saturated, brown with traces of gray and 3 to 17 m thick. In some specific areas these tailings are firm.
- *Laterites*, which consist of clayey sand (SC), silty sand (SM), sandy silt (ML, MH) or sandy clay (CL, CH), loose/firm to dense/very stiff (N between 6 and 15, q_c between 2 and 8 MPa), moist to saturated, red or orange, with medium to high plasticity, with high iron oxide contents and thicknesses varying from 4 to 8 meters.
- *Saprolites*, which correspond to decomposed rocks at residual soil level, which consist of clayey sand (SC), silty sand (SM), sandy clay (CL, CH) and sandy silt (ML, MH) with low to high plasticity. These saprolites were divided into two types, according to their relative density /consistency; one of which is very loose/very soft to loose/firm, whereas the other type is medium dense/firm to dense/very stiff (N between 7 and 25, in general and q_c between 0.8 and 4 MPa, in general); both are moist and saturated, with different colors such as grey or red, with white and yellow, their thickness varies from 1.5 to 10 meters.
- *Bedrock*, that consists of the Madeira Granite, which is medium to coarse grain, crystalline, pink, with presence of minerals such as orthoclase, feldspar, quartz, hornblende and mica. Its geomechanical characteristics vary according to depth, such as the weathering degree, which varied from extremely weathered to fresh rock; strength varies from extremely low to very high and fracturing from extremely fractured to non-fractured.

Based on the materials found in the study area, stratigraphic profiles were prepared. A representative stratigraphic profile is shown in Figure 3. This paper presents details about the characterization of the critical materials: coarse and fine tailings.

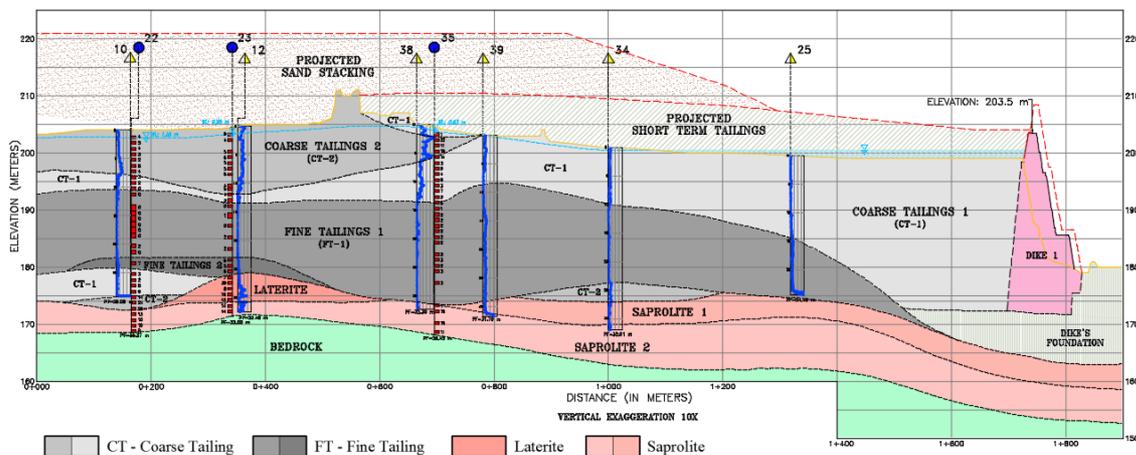


Figure 3. Typical stratigraphic profile.

3 TAILINGS CHARACTERIZATION

As described above, two types of tailings have been identified: coarse tailings and fine tailings. Coarse tailings mainly consist of very loose to loose silty sand (SM) with blow count values (N) between 0 and 7, cone tip resistance (q_c) between 1 and 3 MPa approximately, and correlated permeability with SBT classification obtained from CPTu testing between $10E-02$ and $10E-03$ cm/s, while their fines content varies from 2 to 20% and moisture from 14.7 to 34.6%. Furthermore, in some areas these tailings are medium dense, with blow count values (N) varying from 8 to 22 and cone tip resistance values (q_c) between 3 and 15 MPa, approximately. No excess pore pressure was measured above the hydrostatic level on the cone penetrations.

Fine tailings consist of silt (ML, MH) and clay (CL, CH); they are very soft to soft, with blow count values (N) between 0 and 7, cone tip resistance (q_c) between 0.1 and 1 MPa, and coefficient of permeability k_h measured between 2E-6 and 5E-6 cm/s using the correlation from Robertson (2010). In general, the fines content of these tailings is greater than 94%, their moisture content exceeds 50%, and IP varies from 20 to 62%. Table 1 shows the summary of the index properties of the tailings.

Table 1. Summary of index properties of tailings materials

Material	SUCS	Gravel %	Sand %	Silt/Clay %	LL	LP	IP	ω %
Coarse tailings	SM, SP-SM, SW-SM	0	79-98	2-21	NP	NP	NP	14-31
Fine tailings	MH, CH, ML	0	0 - 38	62 - 100	49-94	29-44	20-62	33-63

The particle size distribution of the tailings is shown in Figure 4. Also a typical CPTu sound is shown in Figure 5.

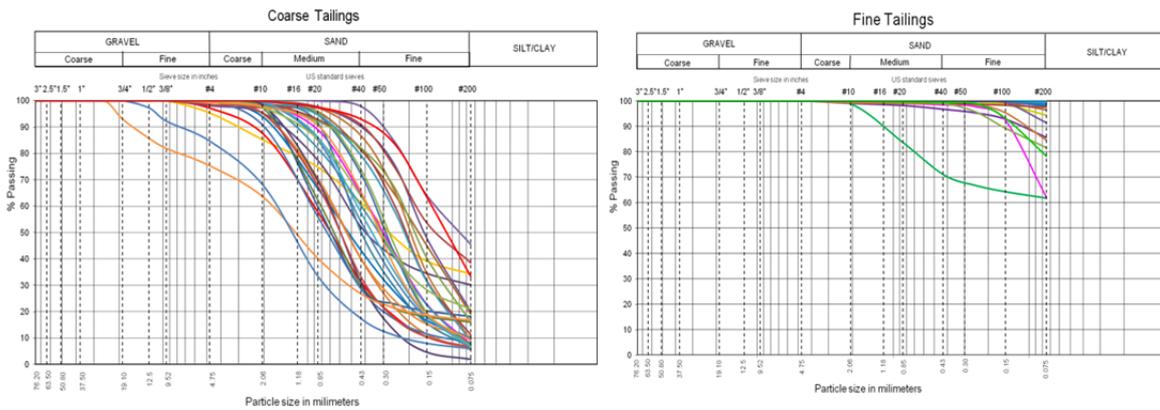


Figure 4. Particle size distributions of coarse and fine tailings.

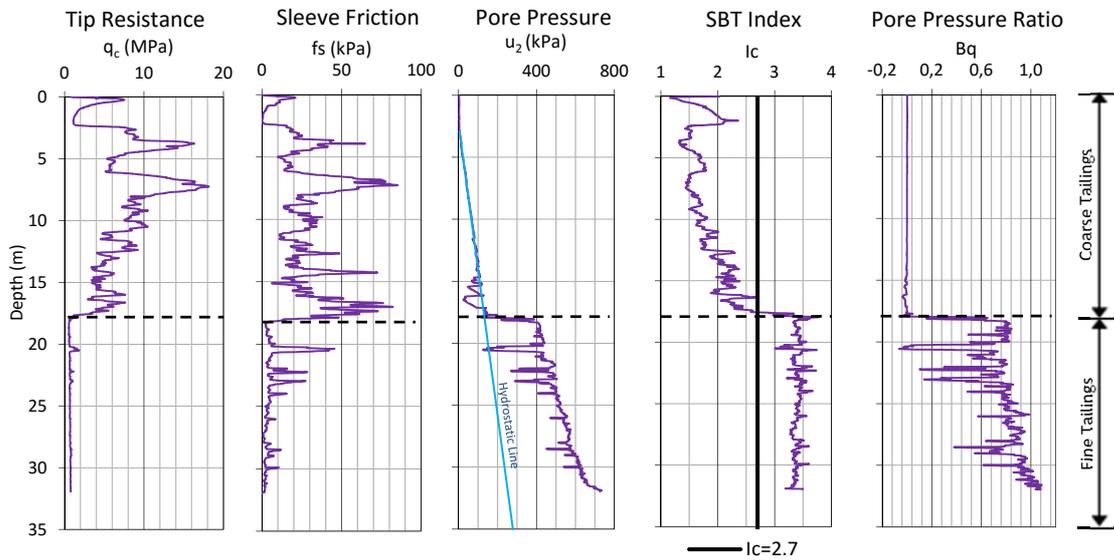


Figure 5. Typical CPTu data showing upper zone of coarse tailings and lower zone of fine tailings.

Results of SPT and CPTu tests on tailings are consistent and show similar variation in their respective locations. These results are shown in Figure 6.

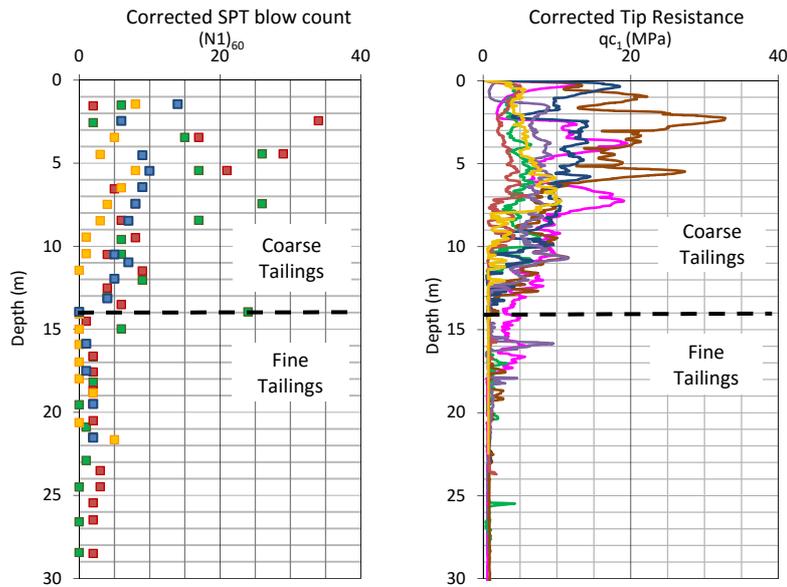


Figure 6. Similar variation in results of the SPT and CPTu tests performed on the tailings.

4 WATER PRESSURE CONDITIONS

The equilibrium water pressure in the tailings was estimated as a hydrostatic pore pressure line. This assumption was made based on pore pressure readings in the coarse tailings and dissipation tests in the fine tailings (Figure 7a).

A small drop in the water table measured in depth, from pore pressure readings (u_2), suggest a slight vertical flow (downward) along the coarse tailings profile. This flow is low enough so that we can consider a hydrostatic state without affecting significantly the estimates of the effective stress profile in the coarse tailings.

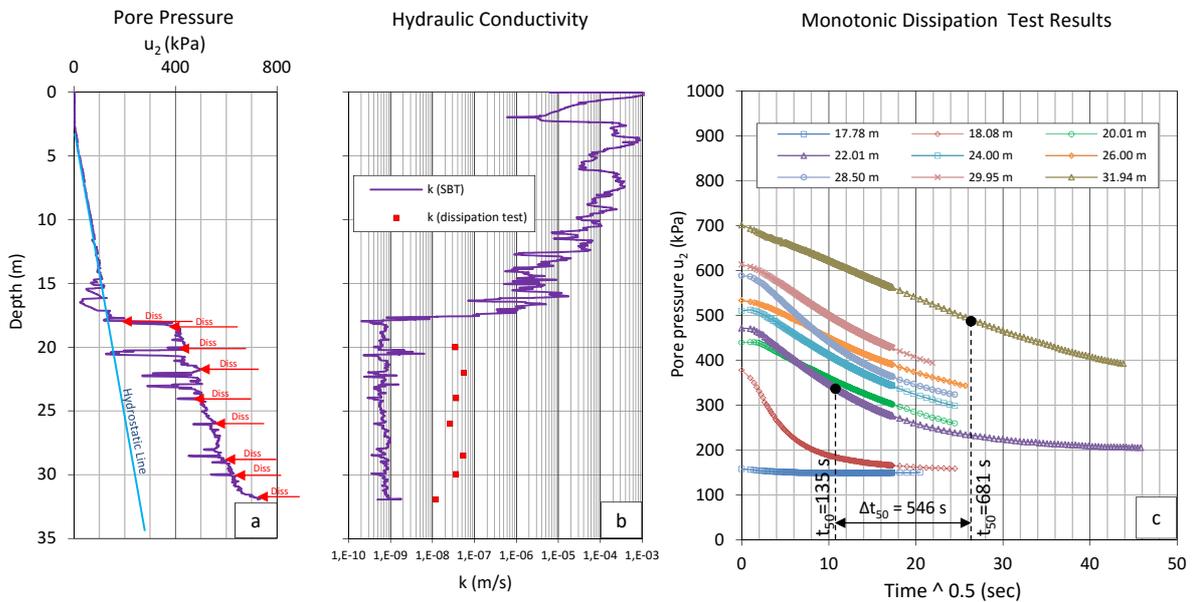


Figure 7. Pore-water pressure conditions and results of dissipation tests.

In the fine tailings, due to their low permeability (Figure 7b), the flow through them was not an issue. However, it was necessary to assess whether there were excess pore pressures in this layer due to an unconsolidated state. Therefore, some dissipation tests (all monotonic) in fine

tailings were performed, which showed that there is not an excess pore pressure in this material, so a hydrostatic level was assumed.

Cone penetrations in this fine tailings were considered fully undrained based on the time required to dissipate the 50% of the excess pore pressure (t_{50}) measured in the dissipation tests (Figure 7c). The t_{50} value was >100 sec in all the tests (DeJong et al., 2013).

5 TAILINGS BEHAVIOR DURING SHEAR

In order to describe the strength of the tailings, the first step was determining whether tailings are contractive or dilative during shearing. Contractive materials present undrained behavior with positive pore pressures during shearing, whereas dilative materials develop negative pore pressures during shearing. As for materials presenting contractive behaviors, the undrained shear strength parameters used in the stability analyses are appropriate, as well as the drained or effective strength parameters for dilative materials are adequate.

Drained or undrained behavior of the tailings during shearing was evaluated using correlations between the CPTu penetration tip resistance (corrected for stress conditions) and the effective stress conditions within the tailings (Fear and Robertson, 1995). In addition, the behavior of the tailings during shearing was also assessed using correlations of the $(N_1)_{60}$ values obtained from SPT testing and the effective stress conditions with the depth inside the tailings (Fear and Robertson, 1995).

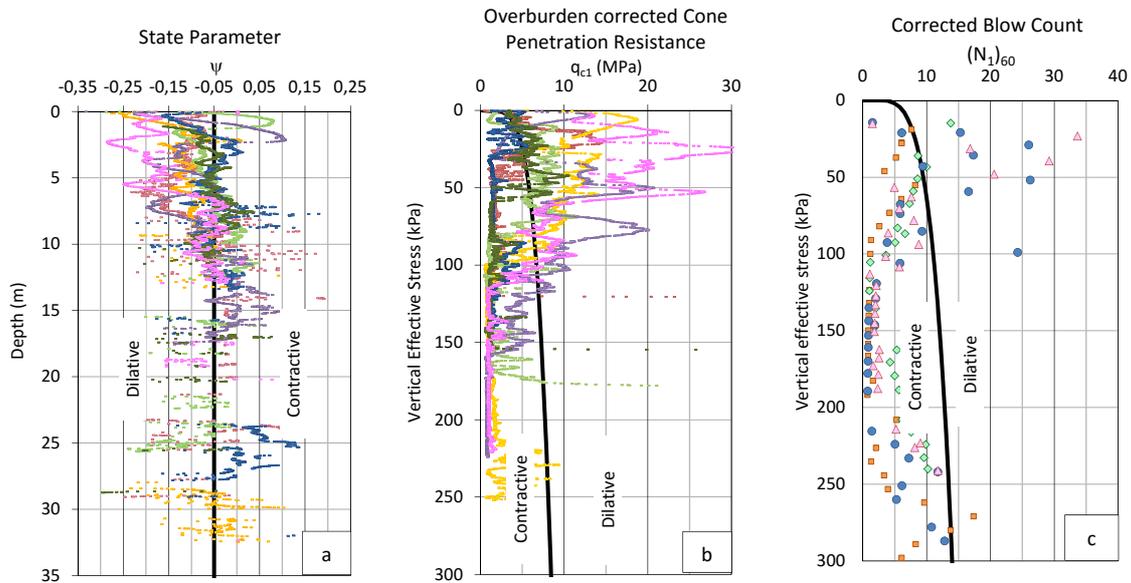


Figure 8. Coarse and fine tailings behavior during shear.

Figure 8a shows the state parameter Ψ , which is defined as the difference between the relationship existing voids (voids volume / solids volume) of a soil and the critical void ratio (which defines the boundary between the contractive and dilative behavior). Positive values of Ψ and even negative values greater than $-0,05$ indicates a contractive behavior while less than $-0,05$ negative values indicate dilative behavior (Jefferies and Been, 2006). The state parameter was estimated using data from CPTu tests and the correlation of Robertson (2010) from $Q_{in,cs}$ parameter. Figure 8b and 8c also shows the CPTu penetration tip resistance profiles (q_{c1}) and the SPT $(N_1)_{60}$ values versus the estimated effective strength at a specific depth, respectively. The curve included in those figures defines the boundary between the materials that may present contractive behavior and the materials that may present dilative behavior during shearing (Fear and Robertson, 1995). The profiles shown in Figure 8 suggest that coarse tailings could develop contractive and dilative behavior, whereas fine tailings will develop variable undrained strength values varying in depth.

Furthermore, the behavior type of these materials was evaluated according to the SBT classification developed by Robertson (2010), normalized strength (Q_{tn}) versus the normalized friction rate (F_r) shown in Figure 9.

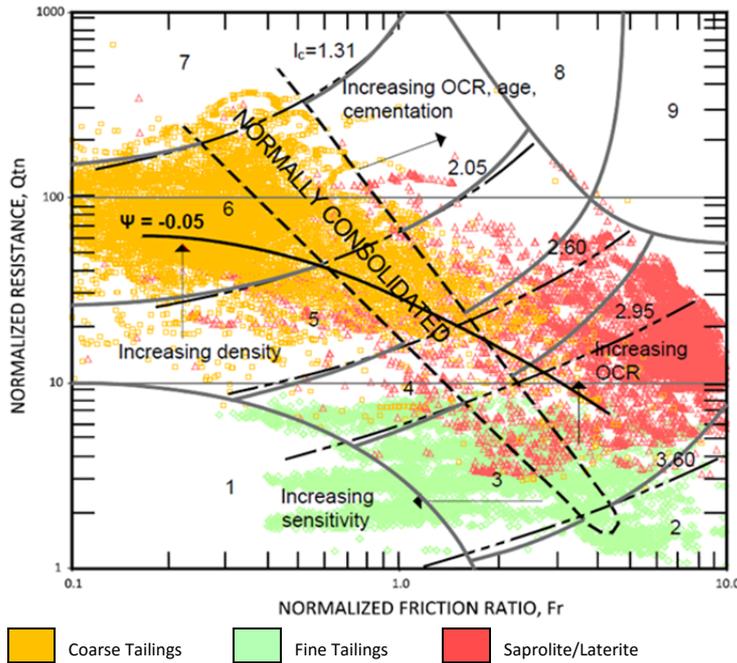


Figure 9. Normalized CPT Soil Behavior Type (SBT_N) of tailings.

Foundation conditions of the area where the sand stacking slope toes will be located are complex and show great variability; however, the study performed allowed for a reasonable estimated model and the strength characteristics of these materials in order to separate them into geotechnical units.

6 TAILINGS STRENGTH PARAMETERS

6.1 Fine tailings

Since penetration tests in the fine tailings were fully undrained ($t_{50} > 100$ sec in the dissipation tests), therefore we can estimate a high quality undrained shear strength (S_u) profile with the CPTu soundings.

A first approach is an empirical correlation between the cone tip resistance q_c and S_u , using the cone factor N_{kt} as follows:

$$Su \times N_{kt} = q_t - \sigma_0$$

The value of the cone factor N_{kt} often falls in the range from 10 to 20 and is influenced by several factors such as overconsolidation ratio, plasticity of the soil, sensitivity, etc. However, this method could lead to a low precision profile because the very low values of q_c parameter and the poor accuracy of the cone tip for these soft materials.

A second method, based on theoretical approaches with cavity expansion theory (Battaglio 1986, Vesic 1972) is preferred on these soft clays: estimating the undrained shear strength from the pore pressure readings u_2 using the $N_{\Delta u}$ factor:

$$Su \times N_{\Delta u} = u_2 - u_0$$

This method is preferred on soft clays because it has better accuracy in the S_u estimation because the very large values of excess pore pressure ($u_2 - u_0$) in these tailings. The $N_{\Delta u}$ factor usually falls in the range from 7 to 10 (Lunne, 1997).

Figure 10a shows the S_u profiles from a representative CPTu sounding on fine tailings estimated by both methods, using a $N_{kt}=14$ and a $N_{\Delta u}=10$. It also shows the residual shear strength profile (S_u residual).

An evaluation of fine tailings is usually complex due to their intermediate nature (cohesive/frictional). A low residual shear strength profile was estimated using the friction sleeve (f_s) readings of the CPTu, which in mine tailings may be characteristic of contractive soils that are prone to flow liquefaction problems. However, in this case, the high plasticity index ($PI>20$) of the fine tailings limit their liquefaction potential (Bray and Sancio, 2006).

Also, low f_s readings could be indicative of sensitive or strain softening soils (exhibit reduction in shear strength beyond the peak with increasing strain) and the B_q parameter near to 1.0 is also indicative of such characteristic. The strain softening behavior of sensitive soils could lead to a progressive failure due to local disturbances, expected large deformations or shear stresses near to the peak shear strength. Therefore it was important to recommend some measures with the purpose of reduce the mobilized strength in the fine tailings and therefore minimize the possibility of the strain softening behavior. These measures are: a facility geometry with a flat slope (between 20H:1V and 25H:1V) and a minimum factor of safety of 1.5 in the stability analyses. Also a raising rate of the storage facility less than 9.0 meter per year (Vick, 1990) was recommended in order to allow the dissipation of pore pressures on the foundation. Further studies, laboratory tests and pilot tests are need to confirm the pore pressure response of the fine tailings under loading.

Because of the uncertainty about the effect of the raising rate on the consolidation and pore pressure development in fine tailings, for the stability analysis it was preferred a total stress approach with a variable S_u profile (lower boundary) varying between 10 and 40 kPa (Figure 10b and 10c). An increment of the effective stresses due to the raising of the facility could improve the shear strength of the fine tailings if the pore pressures are dissipated.

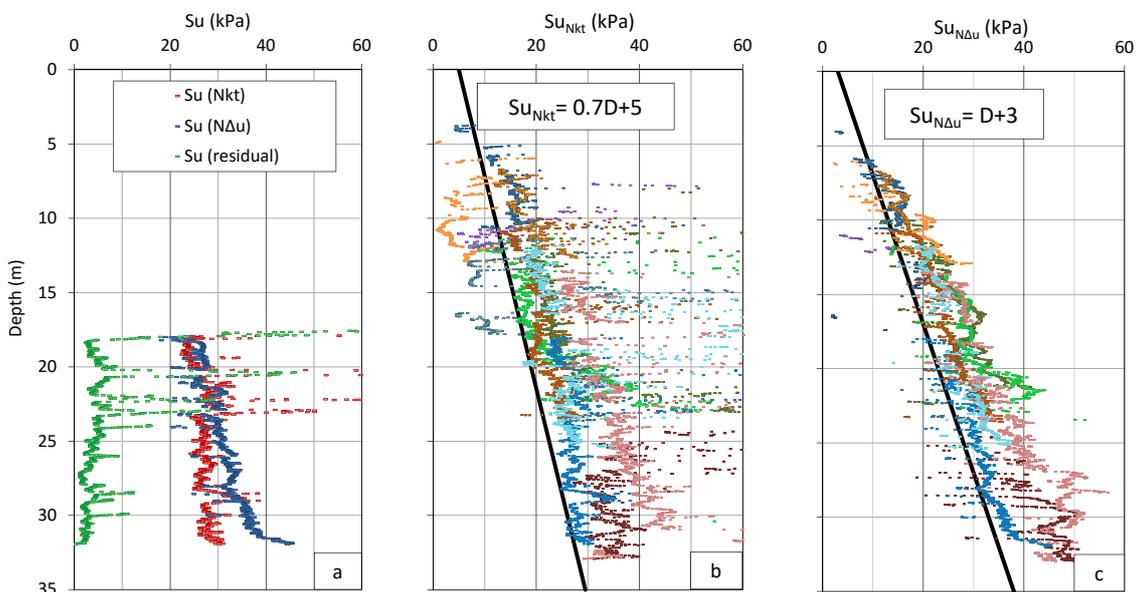


Figure 10. Undrained shear strength “ S_u ” of fine tailings.

6.2 Coarse tailings

As mentioned previously, the coarse tailings were characterized based on contractive and dilative behaviors during shearing, using CPTu and SPT tests from the field investigation.

The peak undrained strength ratio (S_u/p' , where p' is the vertical effective stress) and effective strength parameters (drained) of tailings was estimated from the results of CPTu tests fol-

lowing established correlations between the tip resistance measured and strength parameters. Typical values of peak undrained strength ratio are in the range of 0.2 and 0.3 (Martin, 1999). The peak undrained strength ratio was estimated using the measured tip resistance from CPTu soundings together with correlations presented by Olson and Stark (2003) for loose materials. These correlations are based on back analysis of actual flow failures to evaluate the shear strength mobilized at triggering of a failure. The correlations have been used with the CPTu data to calculate profiles of peak undrained strength ratio for the coarse tailings.

Calculated S_u/p' values are shown in Figure 11a using average and lower bound relationships presented by Olson and Stark. Values are presented for the looser (weaker) tailings layers only (tip resistance < 6.5 MPa and values $(N_f)_{60} < 12$) for which the correlations are valid. Based on these findings, an average S_u/p' value of 0.22 has been adopted to define the peak undrained shear strength of the potentially contractant coarse tailings in the pool area.

Effective shear strength parameters have been defined for the sands and sandy tailings materials consistent with materials exhibiting dilative behavior. Effective friction angles estimated from the SPT data give a similar range of values (typically 28 to 35 degrees), with the higher values generally corresponding to tailings at lower stresses (near surface). For stability analyses the shear strength of coarse sandy tailings (cycloned sands) has been defined using with an effective friction angle of 30 degrees. Effective friction angles were estimated from the SPT N_{60} values of the correlation tests by Kulhawy and Mayne (1990). The calculated values of effective friction angle are shown in Figure 11b.

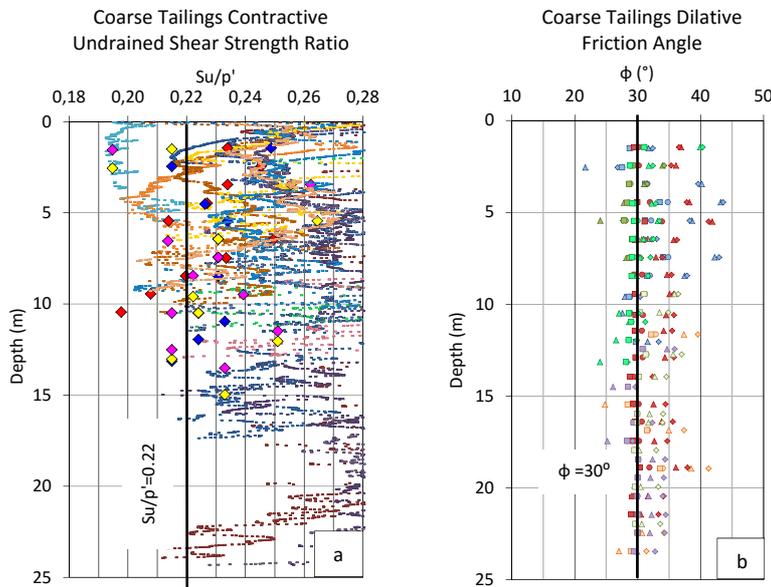


Figure 11. Shear strength parameters of coarse tailings.

7 STABILITY ASSESSMENT

Stability analyses were performed by means of the limit equilibrium method using the GeoStudio Slope/W Program in static conditions for the analysis section shown in Figure 2. The groundwater table (GT) was estimated, under an adequate drainage condition, at the base of the sand stacking storage facility. Material properties used for the stability analyses are shown in Table 2. A minimum factor of safety of 1.5 has been established for sand stacking due to the sensitive clay types in the foundation.

It is worth mentioning that these analyses have been performed assuming that the tailings storage facility will have adequate drainage, maintaining a groundwater table near the sand stacking base. Stability analysis result is shown in Figure 12. For this assumption to be met, the following conditions are required: 1) discharged material must allow a free drainage and/or an efficient drainage system must be designed, and 2) the storage facility must be adequately monitored and operated. The first condition will need to be confirmed at later stages of the study,

through laboratory studies and/or by performing pilot tests in order to check the feasibility of discharge into the cells, drying through evaporation and free drainage. The second condition must be evaluated periodically by a trained professional in accordance with the operations manual, who must collect all storage facility recommendations and design assumptions.

Table 2. Material properties used for the stability analyses

Material	Unit Weight kN/m ³	Cohesion, <i>c</i> kPa	Friction Angle (degrees)	Undrained Strength, <i>Su</i> kPa	Peak Undrained Strength Ratio, <i>Su/p'</i>
Coarse Tailings 1	17	-	-	-	0.22
Coarse Tailings 2	18	0	30	-	-
Fine Tailings	14	-	-	(*)	-
Saprolite/Laterite	18	5	30	-	-
Bedrock					
Short Term Tailings	17	-	-	-	0.20
Sand Stacking	15-17	0	30	-	0.20(**)

* Undrained shear strength function estimated based on CPTu tests, see Figure 10

** Assumed value for critical operation conditions

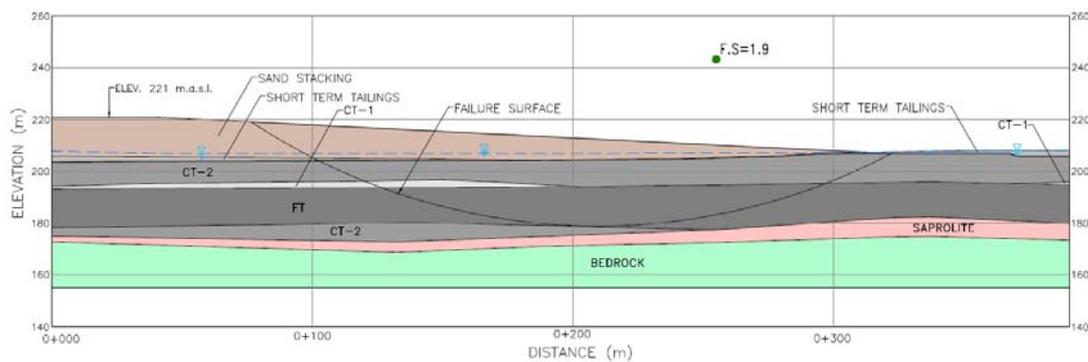


Figure 12. Stability analysis considering adequate operation.

In addition, the stability analysis has been performed considering critical operation conditions, i.e. with inadequate drainage of the storage facility, as a result of which the groundwater level is located near the surface. Stability analysis result is shown in Figure 13. In this case, and since tailings will be disposed of without compaction (loose), this saturated storage facility could present undrained behavior during shearing and was therefore modeled under this critical assumption with $Su/p' = 0.20$. A Factor of Safety of 1.40 was obtained, which means that stability of the sand stacking would be precarious under inadequate drainage conditions.

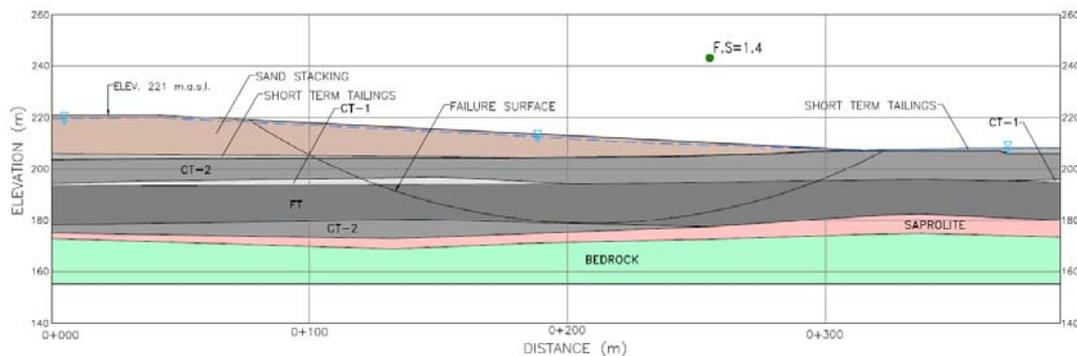


Figure 13. Stability analysis considering critical operation.

8 CONCLUSION

The likelihood of the sensitive soft clays found in the foundation poses risks for the feasibility of the Project when using the Sand Stacking System, due to the loss of strength that those clays could suffer in the event of deformation, as well as due to their vulnerability to the progressive failure mode. Therefore, the design and operation of the structures founded on this material must follow the geotechnical analysis recommendations, and an adequate monitoring plan must be established during the early years of operation.

A more detailed assessment of the fine tailings could result in the need to improve their drainage conditions by applying engineering solutions, such as wick drains, or by improving the shear strength of this stratum. The foundation conditions of the areas where the sand stacking slope toes will be located are extremely diverse, that is why it is possible to distinguish two types of coarse tailings, one that presents contractive behavior and one that presents dilative behavior. Also, the sensitive soft clay (fine tailings) presents an undrained strength that varies with depth. These materials will need to be assessed in a more detailed manner in future stages of the study using laboratory tests and monitored during pilot tests.

The sand stacking body must be maintained with adequate drainage as a high level of saturation could result in undrained behavior and, therefore, in precarious stability of the storage facility.

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