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Iron tailings reclamation: Geotechnical analysis during emerged and submerged excavations

Réutilisation des résidus de fer: Analyse géotechnique lors de fouilles émergées et immergées

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ABSTRACT: It is estimated that Brazil has around 570 Mt of iron ore stored in dams without a national reuse plan. This case study focuses on the Carajás Mine tailing dam, a reservoir with a volume of 100 Mm³ and iron ore content of 63%, located in the state of Pará. Regarding the geotechnical risk during excavations to remove the tailing, the present work identifies in depth the fine and coarse tailing through laboratory and field tests. Analyzes will be conducted to verify if the ruptures can represent a trigger that leads the tailing to liquefaction. The seismic piezocone tests (SCPTu) were reinterpreted considering perched water table, saturated specific weight equal to 30.1 kN/m³, cone factor (Nkt) equal to 15. Field seismic data were compared to laboratory seismic tests to determine the void ratio and shear modulus (G0) along the entire tailing profile, analyzing possible layers with liquefaction potential.

RÉSUMÉ: On estime que le Brésil possède environ 570 Mt de mineral de fer stocké dans des barrages sans plan national de réutilisation. Cette étude de cas concerne de la Carajás Mine résidus, un réservoir d'un volume de 100 Mm³ et d'une teneur en mineral de fer de 63%, situé dans l'État du Pará. Concernant le risque géotechnique lors des excavations pour éliminer les résidus, le présent travail identifie en profondeur les résidus fins et grossiers à travers des essais en laboratoire et sur le terrain. Des analyses seront menées pour vérifier si les ruptures peuvent représenter un déclencheur menant à la liquéfaction des résidus. Les essais sismiques au piézocône ont été (SCPTu) réinterprétés en considérant: nappe phréatique perchée, poids spécifique saturé égal à 30,1 kN/m³, facteur de cône (Nkt) égal à 15. Les données sismiques de terrain ont été comparées aux essais sismiques de laboratoire pour déterminer l'indice de vide et le module de cisaillement (G0) sur tout le profil du résidu, analyser les couches possibles ayant un potentiel de liquéfaction.

Keywords: Perched water table; iron ore tailings; seismic piezocone; bender element.

1 INTRODUCTION

In 2021, Brazil's National Mining Agency (ANM) issued Resolution No. 85, promoting and facilitating the reuse of tailings and waste generated from mining activities through innovative mineral processing techniques. The reuse of iron tailings, particularly from legacy deposits, contributes to reducing risks for society by eliminating materials with high liquefaction potential.

The best technique for recovering tailings deposited in reservoirs or dams made of this material depends on the characteristics of the deposit, composition, storage condition, transportation possibilities, handling and final use of the tailings (ENGELS et al, 2004).

Souza (2020) apud Muir et al. (2005) incorporate that topography and watercourses are preponderant in the analysis of technical and economic viability in mining and reusing the mineral asset present in the tailings. There are three primary methods for reclaiming materials from natural resources: hydraulic re-mining using high-pressure water monitor guns, mechanical reclamation, and dredging.

According to Souza (2020), it is necessary to guarantee geotechnical safety in tailings removal operations for the entrepreneur and other parties involved. In this sense, it is crucial to identify the heterogeneity of the tailings released into the reservoir, analyzing the history of disposal, resistance, deformation and pore pressures.

Becker (2022) et al, reassessing the work of Whittle et al. (2022) in dam B1 (Brumadinho), considers the presence of extensive horizontal layers of fine, clayey, plastic tailings, with a low density coefficient, which led to the formation of several perched water tables. Stability analyzes using the limit equilibrium method proved to be satisfactory and consistent with failure, provided that adequate resistance, type of sliding surface, stratigraphy and pore pressure are used.

The identification of thin soils (plastic) through piezocone tests is well debated by Aguiar (2022), identifying normalized undrained resistance (Su/σ'v) in the order of 0.11, much lower than the value of 0.22 proposed by Mesri (1975) for soft clays.

In the case of the Fundão sandy tailings, the shear speed in the laboratory to obtain the undrained condition was estimated at 0.011 mm/min according to Coelho (2018). This makes it clear that ruptures in fine materials can be a trigger for liquefaction in thick materials, since the rupture speed in plastic materials can be greater than the dissipation time of non-plastic tailings.

Therefore, this work focuses on the importance of back-analyzing data from seismic piezocone tests in correctly determining the geotechnical profile, identifying tailings with liquefaction potential and how a good interpretation can help in decision-making when planning the removal of tailings in a dam reservoir, combining geotechnical and operational safety.

2 METHOD

2.1 Materials and testing

The tailings have iron contents of about 63%. Table 1 shows the performed geotechnical laboratory (physical characterization and bender element tests) and field studies (standart penetration, SPT, and seismic piezocone, SCPTu, tests) for the characterization and determination of geotechnical parameters of those tailings.

Table 1. Data survey.

Date	Survey	Quant	Test
2001	SPT	141	Granulometry; chemical characterization
2010	SPT	214	Granulometry; chemical characterization
2022	SCPTu	4	Physical characterization; bender element

2.2 Perched water table

Figure 1 shows layers of fine material influencing the position of the water table, generating a suspended water table (ICOLD, 2001). The term perched sheet is used in places where the pore pressures measured by tests and instruments differ from the hydrostatic pressures, this occurs when there are layers of low permeability materials and the water above this layer creates groundwater and below it may even be dry or governed by horizontal and vertical flows.

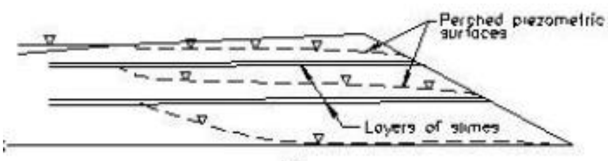

Figure 1. Perched water table around the slimes layers (ICOLD, 2001).

2.3 The problem of surface and subsurface flow

The permeability of tailings is influenced by two mechanisms during hydraulic disposal: segregation during discharge and consolidation. In this reservoir, the high rainfall in the region leads to particle transport by erosion and suspension. Submerged flow, which is complex, can initially transport coarse particles to areas occupied by fine particles. Figure 2 aims to illustrate these flow characteristics of the Carajás Mine tailings dam.

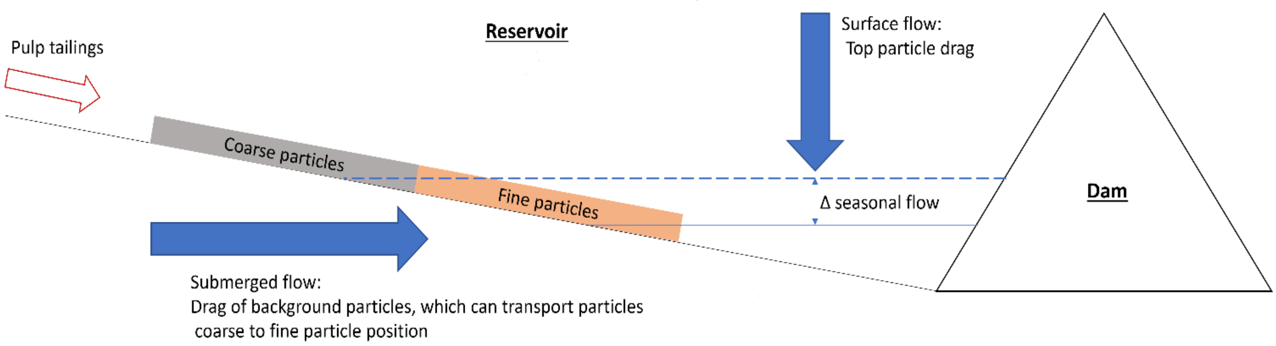

Figure 2. Hydraulic segregation of tailing over time of tailings of the Carajás Mine dam.

2.4 Criteria fine and coarse tailings

To determine the layers of fine (plastic) and sandy (non-plastic) tailings, data from the geotechnical investigation campaign and an analysis of the reservoir's history may be conducted, as follows:

- Analysis of the percussion survey campaign to identify the thickness of the tailings packages deposited in the reservoir;
- Understanding the history of tailings release based on the hydrocyclone and its underflow (sandy) and overflow (fine) discharge;
- Analysis of the SCPTu campaign and determination of the Ic behavior index (Jefferies and Been, 2006), suspended water table, vertical flow and dissipation of pore pressures;
- Analysis of the shear modulus (G_0) using the Bender element and seismic cone tests.

2.5 Criteria for evaluation of liquefaction potential in sandy tailings

The state parameter (ψ) can be obtained through correlation with the normalized cone resistance (Q_{tn}). According to Jefferies and Been (2016) ψ values below -0.05 tend to exhibit strain softening (contractile) behavior under undrained shear and indicate that the tailings may be prone to liquefaction.

Triaxial tests conducted on the Fundão dam in the fine tailings did not indicate liquefaction potential (Morgenstern, 2016).

Based on a large database of historical liquefaction cases suggested a correction factor to correct the normalized cone strength in silty sands to an equivalent value of clean sand (Qtn,cs). After the accident at the B1 dam in Brumadinho, Robertson (2021) updated Eq. 5.

$$Q_{tn} = [\frac{q_t - \sigma_v}{p_a}](p_a / \sigma'_{v0})^n \quad (1)$$

$$n = 0{,}381[I_{c(R\&W)}] + 0{,}05\left(\frac{\sigma'_{v0}}{p_a}\right) - 0{,}15 \quad (2)$$

$$Q_{tn,cs} = K_c\, Q_{tn} \quad (3)$$

$$K_c = 1{,}0 \qquad \text{if } I_c < 1{,}7 \quad (4)$$

$$K_c \approx 15 - \frac{14}{1+\left(\frac{I_c}{2{,}95}\right)^{11}} \qquad \text{if } I_c < 3{,}0 \quad (5)$$

$$\psi = 0{,}56 - 0{,}33\, log Q_{tn,cs} \quad (6)$$

where q_t is the corrected cone resistance, I_c is the soil behaviour type, K_c is the correction factor, p_a is the atmospheric pressure.

Schnaid and Yu (2007) propose the incorporation of the shear modulus (G0) to interpret the mechanical properties of sandy soils. The state parameter can be obtained through correlation (Eq. 7).

$$\psi = \alpha\left(\frac{\sigma'_{v0}}{p_a}\right)^{\beta} + \chi \ln\left(\frac{G_0}{q_c}\right) \quad (7)$$

where $\alpha = -0{,}520$, β =-0,07 and χ=0,18 average values obtained by calibration suggested by the authors.

3 RESULTS

3.1 Field investigation

Location of the piezocone tests is shown in figure 3 and results obtained from piezocone data of SCPTu-01 conducted at Carajás Mine tailing dam are presented in Figures 4 and 5. Analyses results indicated that, from the 4.5m to 12m depth, there is a layer of fine grained material, with plastic behavior.

This conclusion is based on both the direct and indirect results of the piezocone test, and is in line with historical information about the discharge of tailings into this reservoir. The SCPTu-01 piezocone is the most representative of the four tests carried out in the dam reservoir, which contains predominantly fine tailings combined with coarse tailings.

In Figure 5, the stiffness of fine soils is assessed using the rigidity index (Ir), defined as the ratio of the shear modulus (G_0) to the undrained soil strength (Su). This index is a relevant parameter for estimating the consolidation coefficient (ch) using the piezocone.

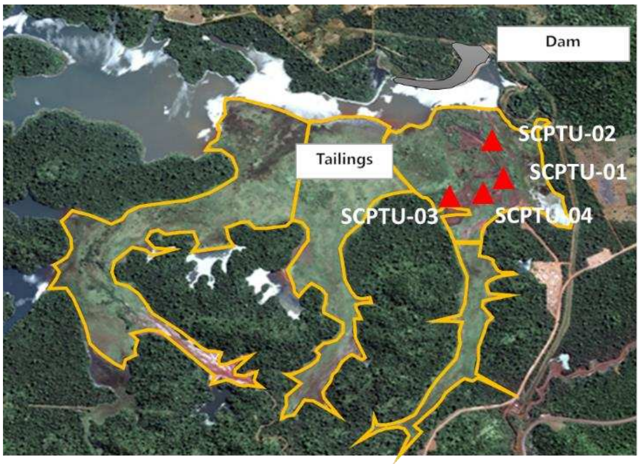

Figure 3. Site of reclamation iron tailings. Piezocone location SCPTu-01,02,03 and 4.

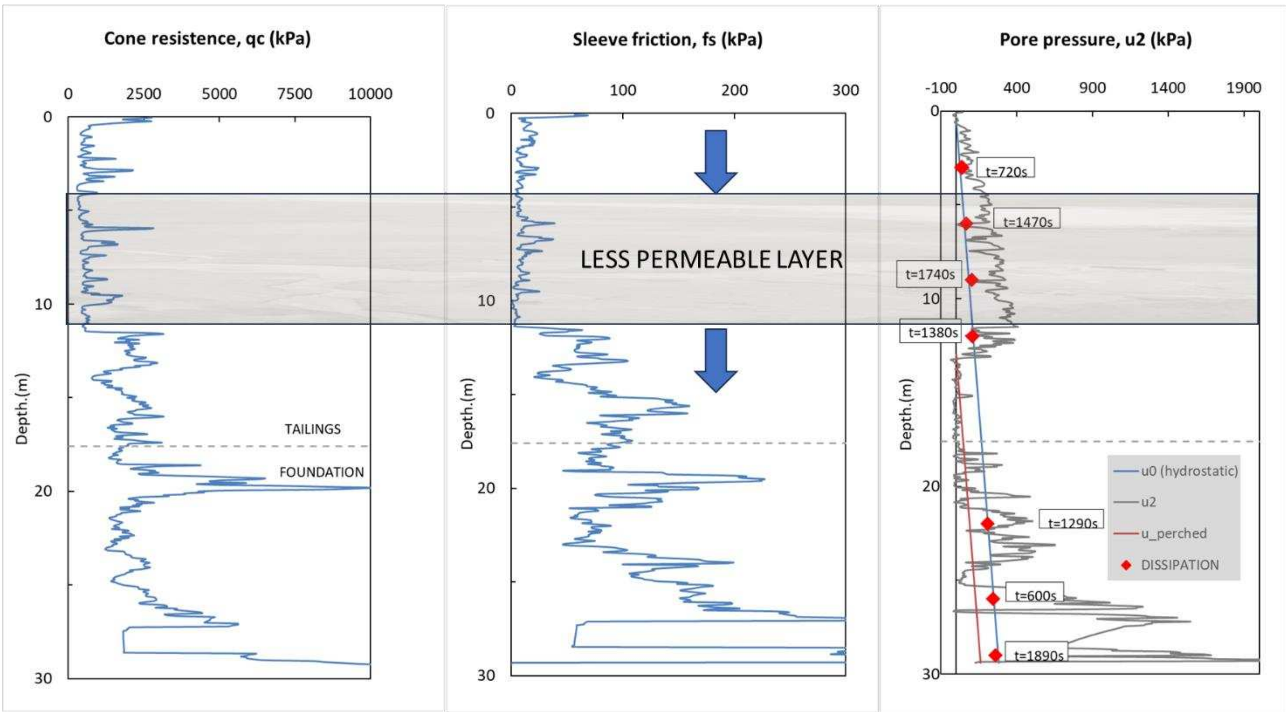

Figure 4. Direct piezocone data of SCPTu-01.

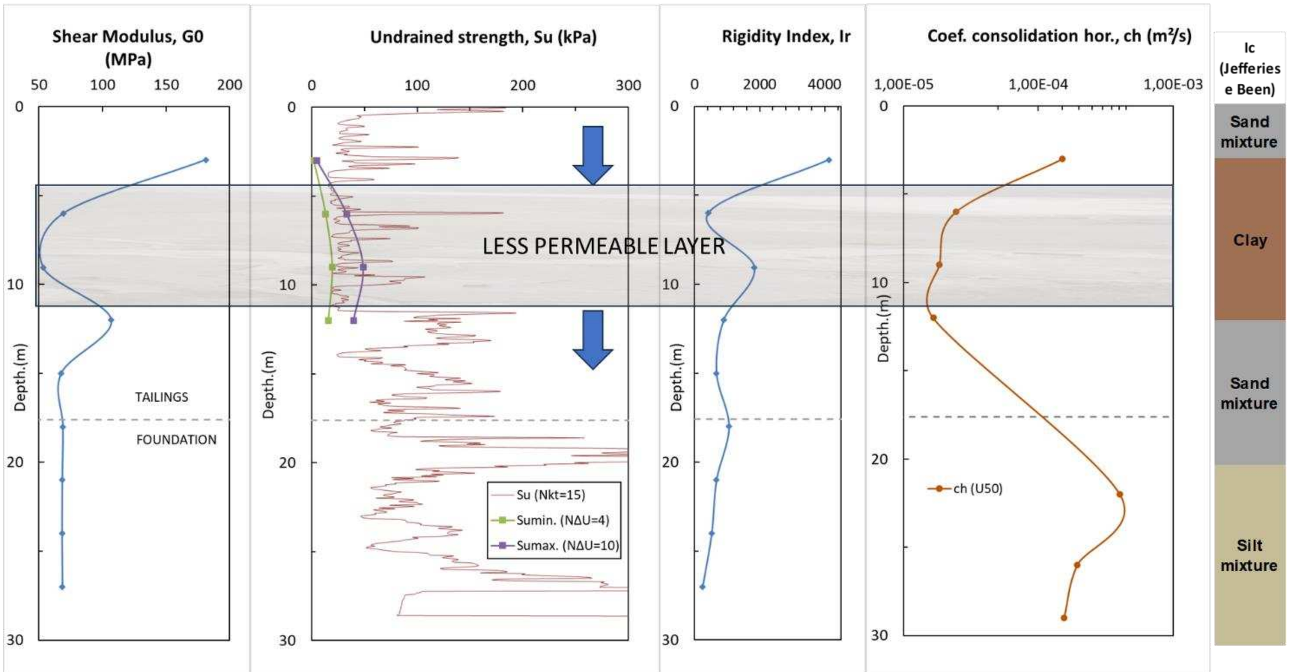

Figure 5. Indirect piezocone data of SCPTu-01.

3.2 Laboratory studies

3.2.1 Index properties

Table 2 present results of laboratory test for physical characterization of tailings from the Carajás Mine tailing dam. Figure 6 shows comparison of grain size distribution of the tailings from the Carajás Mine dam with the determined values for another iron tailings.

These laboratory tests results confirmed the geotechnical profile determined using the piezocone test, showing sandy grain size interspersed with a fine grain layer. The granulometry of the dredged tailings in the present study has a higher fines content in relation to the tailing samples from Brumadinho B1 (Viana, 2022) and Vargem Grande VG (Souza, 2020). It is essential to highlight that the percentage of iron varies depending on the granulometry of the tailings, being more concentrated in the fine grained material.

Table 2. Average values of physical characterization of the tailings from the Carajás Mine dam.

Test	Value
Moisture content (w)	17%
Particle density	4.80 g/cm³
Void ratio	0.83
Saturated density	3.03 g/cm³

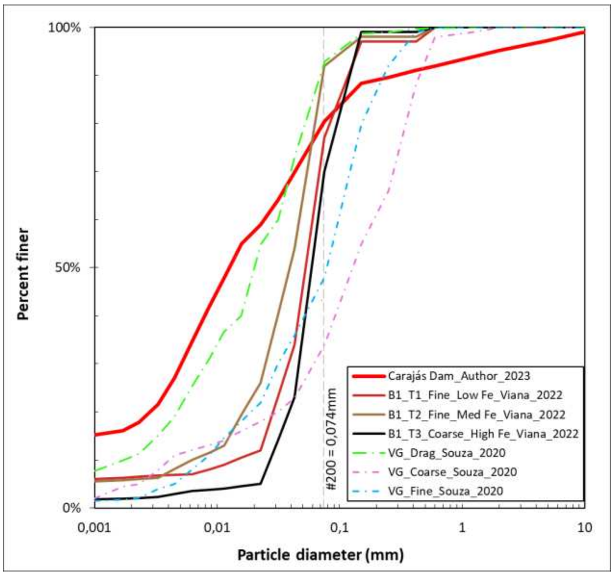

Figure 6. Comparison of grain size distribution of the tailings from the Carajás Mine dam with another iron tailings.

3.2.2 Bender element

For the Bender Element test, samples of the tailings of Carajás Mine dam was collected at 6 m depth from the top. In the laboratory, this sample was conditioned in a triaxial chamber, connected to end-to-end electrodes to measure the speed of the S wave (V_s) at each variation in effective stress consolidation (Fig. 7). The tests were conducted on the same sample, which initially had a relative density of 30%, and was subsequently tested at 50% and 75%. The samples were isotropically consolided for effective stresses of 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa and 600 kPa. The shear modulus (G_0) can be obtained through correlation (Eq. 8).

$$G_0 = \rho . V_s^{\,2} \qquad (8)$$

where ρ is a specific gravity (kg/m³)

Figure 8 show results of correlation between the shear modulus (G_0) and S wave velocity in the Bender Element test. With the results obtained in the field (V_s), it is possible to obtain the depth profile of the shear modulus (G_0). Notice that Silva (2022) carried out Bender element tests on fine and sandy tailings and the results were similar to the present work.

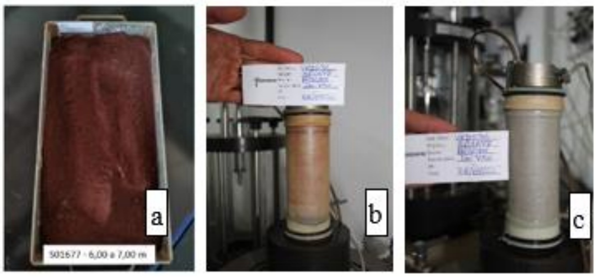

Figure 7. a) Sample; b) Bender element initial condition; c) Final condition.

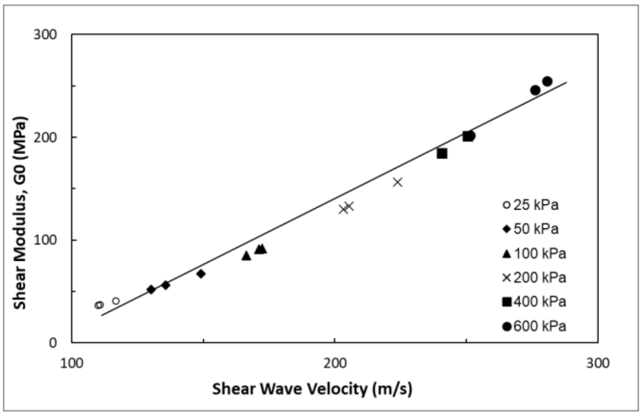

Figure 8. Correlation of shear modulus (G_0) and S wave velocity in the Bender Element test.

3.2.3 Comparison of determined results from Bender element and seismic piezocone tests

Figure 9 presents a comparison of the shear modulus of tailings from the Carajás Mine dam, determined using results from the Bender Element and seismic piezocone tests. These results validate the findings obtained from laboratory tests.

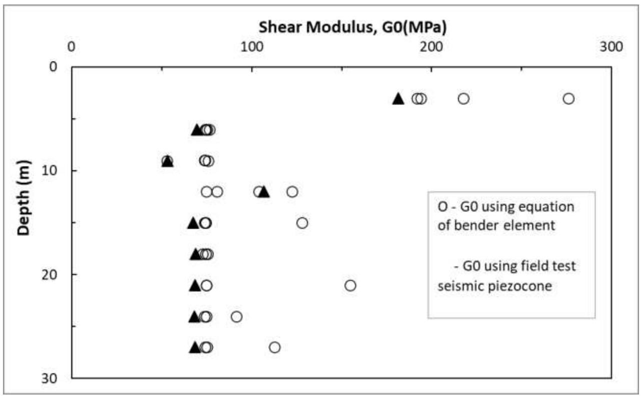

Figure 9. Comparison of results of shear modulus profile (G_0) with depth determined from the Bender Element and seismic piezocone tests.

3.2.4 Potential liquefaction

Figure 10 shows the profile of the state parameter obtained by the methodology of Robertson (2010/2021) and Schnaid and Yu (2007). Notice that the procedure for evaluation of the state parameter by

Schnaid and Yu (2007) is valid for sands and the determine values for the fine tailings using this methodology may not be representative. The results suggest that the sandy tailings near the surface do not exhibit liquefaction potential. However, the sandy tailings situated beyond the fine tailings show liquefaction potential, as indicated by positive state parameter values (ψ). According to Jefferies and Been (2016), materials exhibit contractive behavior when ψ exceeds -0.05.

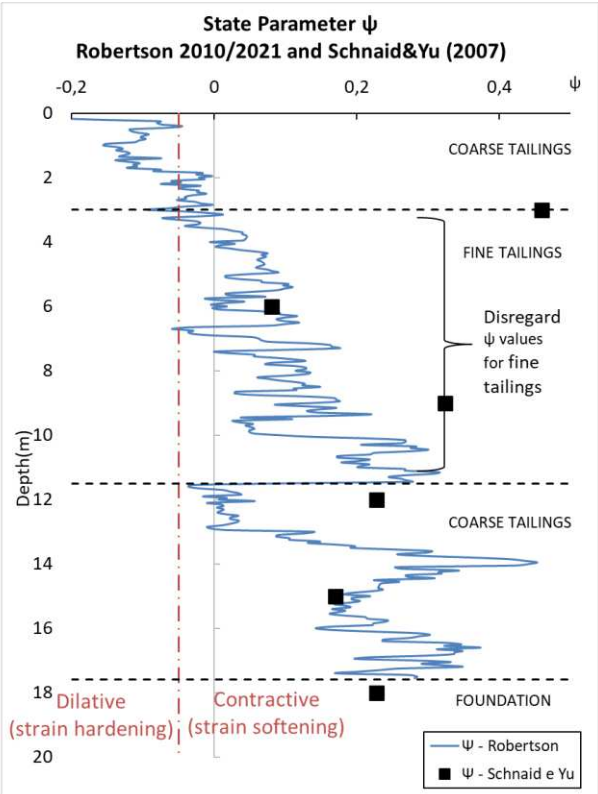

Figure 10. Profile of the state parameter obtained by the methodology of Robertson (2010/2021) and Schnaid and Yu (2007).

4 CONCLUSIONS

The performed geotechnical study indicate that certain tailings from the Carajás Mine dam may have liquefaction potential. It is noteworthy that the excavation process and potential ruptures in the fine tailings could trigger liquefaction. Based on these findings, both submerged and surface excavations were planned to commence from upstream to downstream of the dam reservoir. This approach aims to minimize the liquefied volume in the event of temporary instabilities, ensuring that it remains small enough to prevent overtopping of the structure. As coarse and fine tailings may undergo changes over time due to surface and subsurface flow, it is crucial to conduct investigation campaigns regularly to support stability analyses and potential geometry revisions for stabilizing the tailings. This is particularly important in regions with liquefaction potential.

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