CPTu for assessment of flow liquefaction of tailings with similar physical characteristics

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ABSTRACT

A geotechnical assessment of mine tailings state conditions using the static cone penetration test performed at different tailings storage facilities (TSF's) will be presented in this paper. Both tailings evaluated herein are deposited as a slurry (hydraulic deposition) and have similar grain-size distribution curves.
A set of Cone Penetration Tests (CPTu) with pore pressure measurements were performed at each site to evaluate the state of the tailings. To assess the contractive-dilative behavior classical methodologies were adopted such as i) the contractive/dilative boundary suggested by Robertson (2016) ii) the approach suggested by Plewes et al. (1992) and cited by Jefferies and Been (2016) and iii) the yield stress ratio method proposed by Mayne and Sharp (2019). Partial drainage effects will be identified with classical methodologies. The results were compared to evaluate the difference and limitations of each methodology. Comments on the similarity between the two tailings evaluated herein will also be presented to explain the differences in behavior due to aspects such as mineralogy, gradation, stress history and deposition.

Keywords: CPT; tailings; material behavior; critical state, flow liquefaction.

1. Introduction

Flow liquefaction is a behavior observed in saturated or nearly saturated sand-like geomaterials that exhibit a strain softening response during undrained shear, i.e. a rapid and brittle undrained loss of strength, due to its tendency to contract under drained conditions. Very loose sands and silts are more prone to show this behavior, which can also be observed in very sensitive clays.

Tailings produced in the mining industry are normally non-valuable by-product of the ore beneficiation process, and in some cases can consist of non-plastic sand to silty-sand geomaterials. In this case, flow liquefaction becomes particularly relevant when mine tailings are hydraulically deposited, a situation where they tend to exhibit high saturation and void ratios.

Several methodologies to assess the flow liquefaction susceptibility are available and the CPTu tests can be used as a screening tool as suggested by Plewes (1992), Robertson (2016) and Mayne (2017). Viana da Fonseca et al. (2022) assessed the flow liquefaction susceptibility of the iron ore mining tailings produced at B1 (Brumadinho/MG, Brazil) and at Fundão (Mariana/MG. Brazil) using the CPTu. The cone penetration test with pore-pressure measurements (CPTu) provides high accuracy, good repeatability and low operator dependency if compared to other field tests. In addition to that, it also provides detailed information of the stratigraphy which makes it the preferred in-situ test for assessing the susceptibility for flow liquefaction.

Within this paper, the geotechnical characterization and behavior of a copper ore tailings deposited in a tailings storage facility (TSF) in Queensland, Australia, and of an iron-ore tailing disposed in a TSF located in Minas Gerais, Brazil will be presented and compared.

Two CPTus were used to evaluate the susceptibility to flow liquefaction of the tailings, using the methodologies suggested by a) Plewes et al. (1992), b) Robertson (2016) and c) Mayne (2017).

2. Susceptibility To Flow Liquefaction

As previously mentioned, three methodologies will be used in this paper to assess the susceptibility of the tailings to flow liquefaction.

2.1. Plewes et al. (1992)

Plewes et al. (1992) proposed a correlation between the slope of the critical state line (λ_{10}) and the normalized friction ratio (F or Fr), as presented in Equation 1 and Equation 2.

$$\lambda_{10} = \frac{F}{10} \tag{1}$$

$$F \ or \ F_r = \frac{f_s}{q_t - \sigma_{v0}} \tag{2}$$

where:
f_s = sleeve friction resistance
q_t = corrected cone resistance
σ_{v0} = total vertical stress

Shuttle & Cunning (2007), suggested an equation (Equation 3) that allows to calculate the state parameter (ψ) once the slope of the critical state line (λ_{10}) is determined.

$$Q_p(1 - B_q) + 1 = \bar{k}e^{-\bar{m}y} \quad (3)$$

Where Q_p (Equation 4) is the tip resistance normalized by the mean affective stress (p'_0) and B_q (Equation 5) is the pore pressure ratio, defined as shown below.

$$Q_p = \frac{(q_t - p_0)}{p'_0} \quad (4)$$

$$B_q = \frac{(u_2 - u_0)}{(q_t - \sigma_{v0})} \quad (5)$$

where:
u_2= pore pressure measured behind the cone
u_0 = *in situ* pore pressure

Jefferies & Been (2016) suggested that the effective inversion coefficients, $\bar{k}$ and $\bar{m}$, could be determined using Equation 6 and Equation 7, as a function of the slope of the critical state line.

$$\frac{\bar{k}}{M} = 3 + \frac{0.85}{\lambda_{10}} \quad (6)$$

$$\bar{m} = 11.9 - 13.3\lambda_{10} \quad (7)$$

where M is the critical friction ratio ($M=q_c/p'_c$) and λ_{10} is the slope of the critical state line (CSL) measured in $\log_{10}$ p' - e space. The M_{tc} of the copper tailings was calculated from triaxial compression tests and for the iron-ore tailings it was assumed M_{tc}=1,45 herein, adopting the average value of the range suggested by Jefferies & Been (2016).

2.2. Robertson (2016)

Robertson (2016) updated the CPT-based normalized soil behavior type (SBTn) classification system proposed by Robertson (2009) to use behavior-based instead of textural-based descriptions, as presented in Figure 1.

As suggested by Schneider et al. (2012), Robertson (2016) updated the soil behavior type index, I_B, to use a hyperbolic shape in the $\log_{10} Q_{tn}$ and $\log_{10} F_r$ space as defined in Equation 8.

$$I_B = \frac{100(Q_{tn} + 10)}{(Q_{tn}F_r + 70)} \quad (8)$$

where:

$$Q_{tn} = \left[\frac{(q_t - \sigma_{v0})}{p_a}\right]\left(\frac{p_a}{\sigma'_{v0}}\right)^n \quad (9)$$

$$n = 0.381(I_c) + 0.05\left(\frac{\sigma'_{v0}}{p_a}\right) - 0.15 \quad (10)$$

where $n \leq 1.0$.

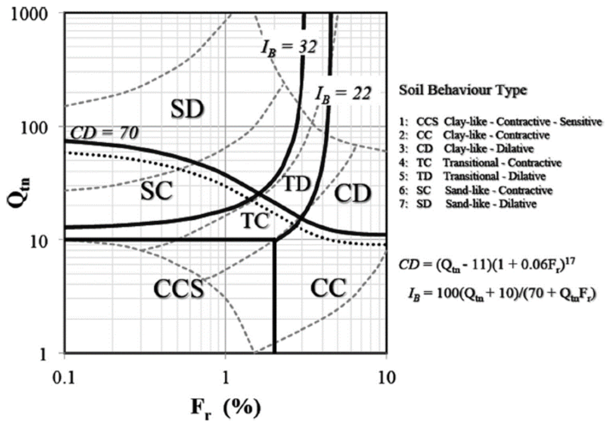

Figure 1. Updated CPT-based normalized soil behavior type chart proposed by Robertson (2016).

The soil behavior type index, I_c, was first proposed by Jefferies & Davies (1993) who recognized that the boundaries between the soil behavior type zones could be approximated by concentric circles whose radius indicates the soil behavior type index. The I_c definition was later modified by Robertson & Wride (1998) in order to apply to the Robertson (1990) chart, as defined by Equation 11.

$$I_c = [(3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2]^{0.5} \quad (11)$$

As also shown in Figure 1, the use of the contour CD=70 was suggested by Robertson (2016) to distinguish soils that are contractive and dilative at large strains. The CD=70 boundary is described by Equation 12 and combines two different criteria: i) $Q_{tn,cs}$=70 for sand-like soils and OCR=4 for transitional and clay-like soils.

$$CD = 70 = (Q_{tn} - 11)(1 + 0.06F_r)^{17} \quad (12)$$

2.3. Mayne and Sharp (2019)

Stress history is an important measurement in soils as it affects strength, stiffness, and flow characteristics. (Mayne, 2014). The preconsolidation stress (σ'_p) establish a limit between normally and over-consolidated states, i.e. indicates the boundaries between elastic and plastic behavior of soils.

The preconsolidation stress is generally described as the maximum stress that a soil has historically been subjected to, and it can be represented in the normalized form of Yield Stress Ratio (YSR) that is also called the overconsolidation ratio (OCR).

Mayne (2014) proposed a methodology derived from the cavity expansion theory and critical state soils mechanics (SCE-CSSM) to evaluate the YSR of soils from CPTu data in terms of the net cone resistance and/or the measured excess water pore pressure. A set of database from 3 case studies, including dilative and contractive materials, were analyzed by Mayne & Sharp (2019) in order to propose a method to estimate the YSR from CPTu data as a relationship of net cone tip resistance, as shown in Equations 13-14.

$$YSR = \frac{\sigma'_p}{\sigma'_v} = \frac{0.33(q_t - \sigma_{v0})^{m'}}{\sigma'_{v0}} \quad (13)$$

$$m' = 1 - \frac{0.28}{1 + (I_c/2.65)^{25}} \quad (14)$$

The proposed methodology allows to evaluate the contractive/dilative behavior of geomaterials by comparing the estimated YSR profile with the equivalent value at critical state (YSR_{CSL}) that can be calculated by Equations 15-16.

$$YSR_{CSL} = \left(\frac{2}{\cos \phi'}\right)^{\frac{1}{\Lambda}} \quad (15)$$

$$\Lambda = 1 - \frac{C_s}{C_c} \quad (16)$$

where ϕ' is the effectives stress friction angle, Λ is the plastic volumetric strain ratio, C_s is the swelling or recompression index, and C_c is the virgin compression index.

Mayne (2014) suggest that Λ = 0.8 can be adopted as a characteristic value for soils in general, and Mayne and Sharp (2019) consider that the corresponding range of values YSR_{CSL} is typically close to 3. Thus, comparing both profiles, the YSR and its corresponding YSR_{CSL}, one can assess whether the material is in a contractive or dilative state.

3. Results

3.1. Tailings Characterization

The tailings assessed in this study are the byproduct of different ores originated from two countries. One is derived from a copper ore mining process located in the state of Queensland/Australia, and the other is generated in the state of Minas Gerais/Brazil as a result of an iron ore mining activity. The geotechnical characterization of these tailings was conducted by performing i) the grain size distribution curve, ii) the water content, iii) the specific gravity of soil solids (Gs), iv) the liquid limit (LL) and v) the plastic limit (PL).

Disturbed samples were collected near the CPTu for the iron ore tailings and undisturbed samples were collected from CPTu drilling used to characterize the copper ore tailings. The grain size distribution curves (ASTM D422) of the samples collected are shown in Figure 2 and a summary of the results of the grain size distribution curves from the samples collected in the tailings are presented in Table 1.

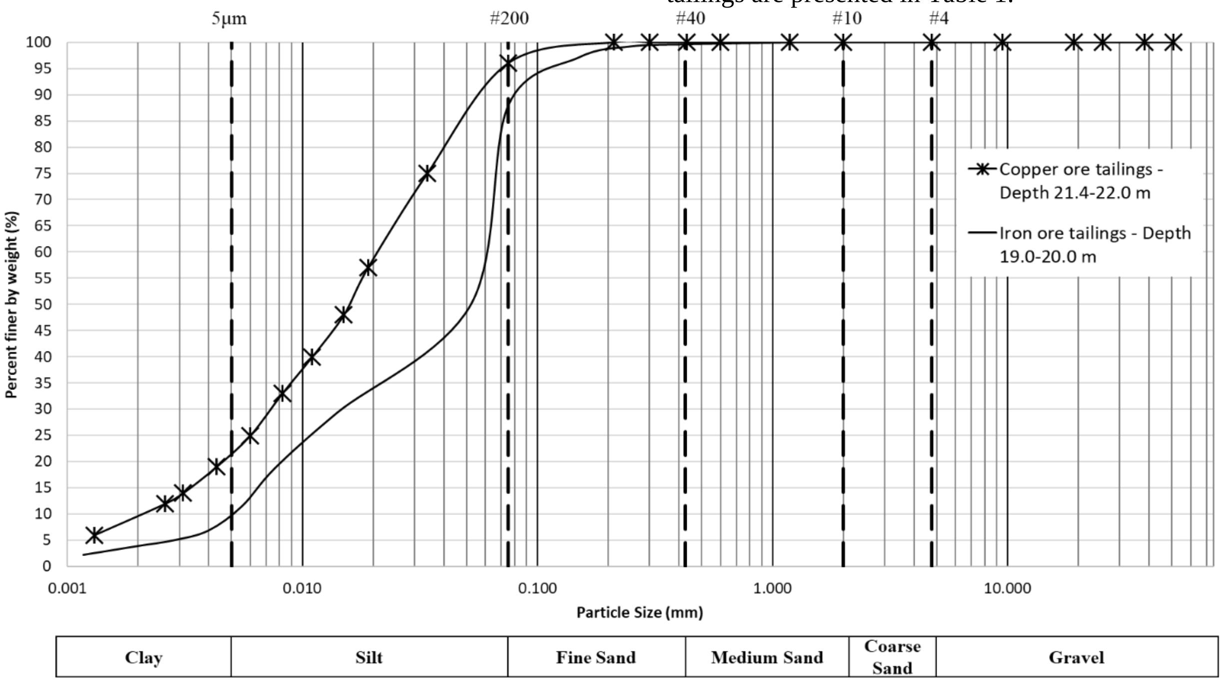

Figure 2. Grain size distribution curves of the tailings studied in this paper according to the ASTM D422-63 (2007).

The copper tailings are comprised of roughly 75% of silt-sized particles, 21% of clay-sized particles and 4% of sand whereas the iron ore tailings are comprised of roughly 78% of silt-sized particles, 10% of clay-sized particles and 12% of sand. Due to the non-controlled tailings disposal, these materials may present high variability in terms of particle size distribution leading to variable results.

Table 1 - Summary: Grain size distribution of the tailings studied.

Grain Size	Copper Tailings	Iron Ore Tailings
Sand (%)	4.0	12.1
Silt (%)	74.8	78.3
Clay (%)	21.2	9.6

Although the copper ore tailings have higher clay-sized particles content, the fines were non-plastic as well as the iron ore tailings. Copper ore tailings presented unit weight γ=23.6 kN/m³ and γ_d=19.0 kN/m³, while iron ore tailings unit weight was γ=23.3 kN/m³ and γ_d=19.3 kN/m³. The water content (w) and void ratio (e) values for the copper ore tailings were 24.4% and 0.57 respectively, whereas the iron ore tailings were 25% and 0.87. The specific gravity (G_s) for the copper and iron ore tailings was 3.0 and 3.7 respectively, which is expected considering the distinct mineralogical components derived from both ores.

3.2. CPTu Test

CPTu tests were performed in both tailings with total depth of 34 m in the copper tailings and 54 m throughout iron ore tailings. The normalized parameters (Q_t, F_r and B_q) from the CPTu performed on the copper ore tailings are shown in Figure 3 and the results of tests undertaken on the iron ore tailings are depicted in Figure 4. It is possible to observe that although both materials have similar physical properties, they present distinguished properties in terms of strength and porewater pressure development.

The CPTu performed in the copper tailings had two dissipation tests performed which shows a porewater pressure profile 100% hydrostatic below 10m of elevation. In the iron ore tailings, however, it was assumed that the groundwater table was located at the elevation of 45m. The porewater pressure generation detected below 20m of depth was observed due to the fine tailings that remained saturated in this portion of the sounding. The dissipation test results from the copper tailings showed very low t_{50} values (2 and 3 seconds), which indicates a partially drained condition.

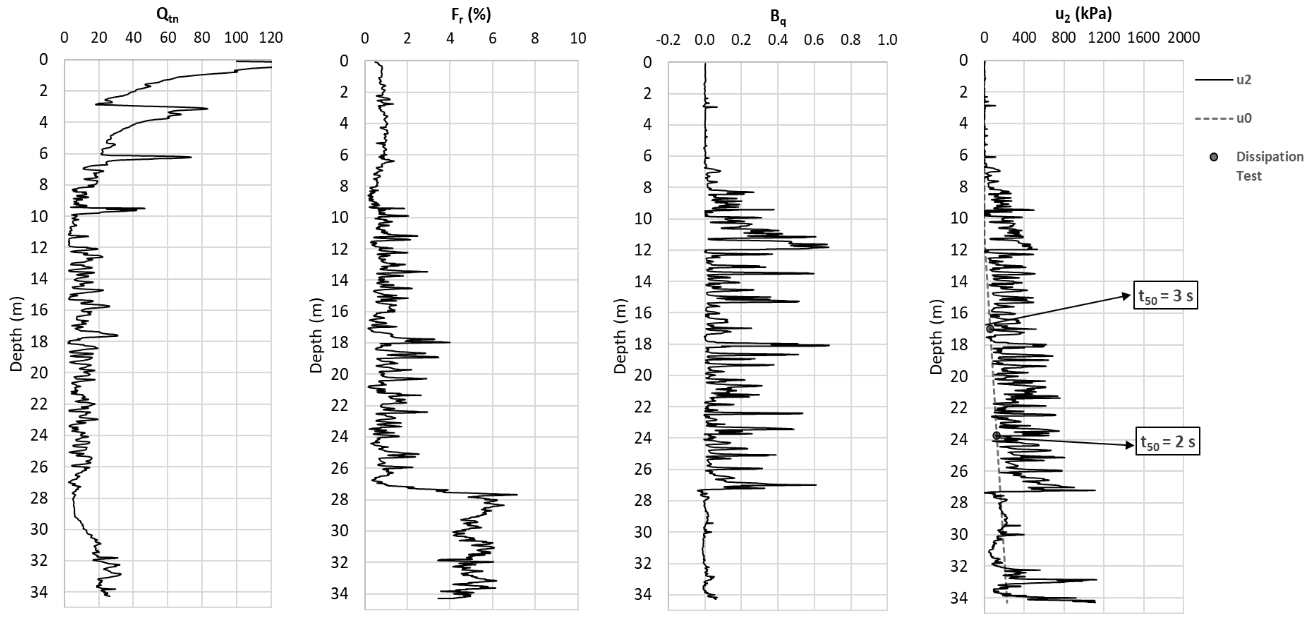

Figure 3. CPTu normalized parameters - copper ore tailings.

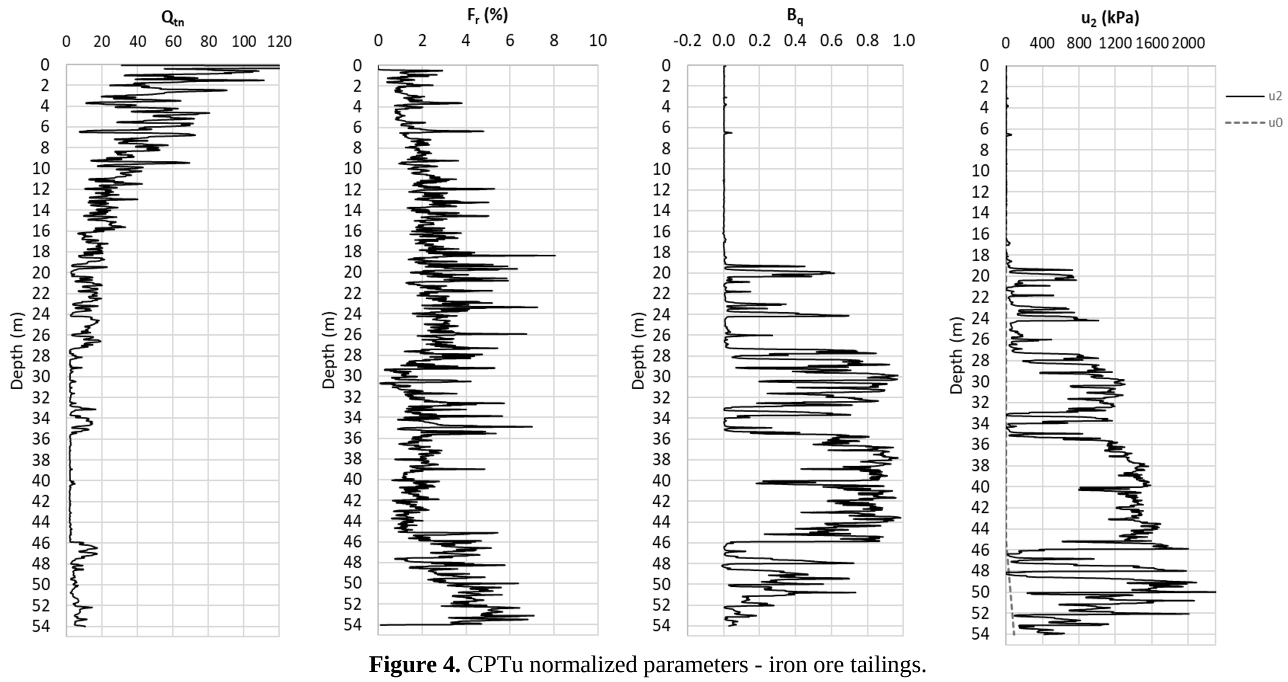

Figure 4. CPTu normalized parameters - iron ore tailings.

Figure 5 shows the soil behavior type indexes plotted for both tailings studied herein. As it is observed in Figure 5 (a), the copper ore tailings show a predominant sand-like behavior up to 8m of depth followed by a predominant transitional behavior up to 28m, below which the behavior is predominantly clay-like. The results depicted in Figure 5 (b) demonstrate that the iron ore tailings in its turn showed a very heterogenous sounding profile where it is possible to observe a predominantly sand-like layer up to 10 m followed by a predominant clay-like and transitional behavior below this elevation.

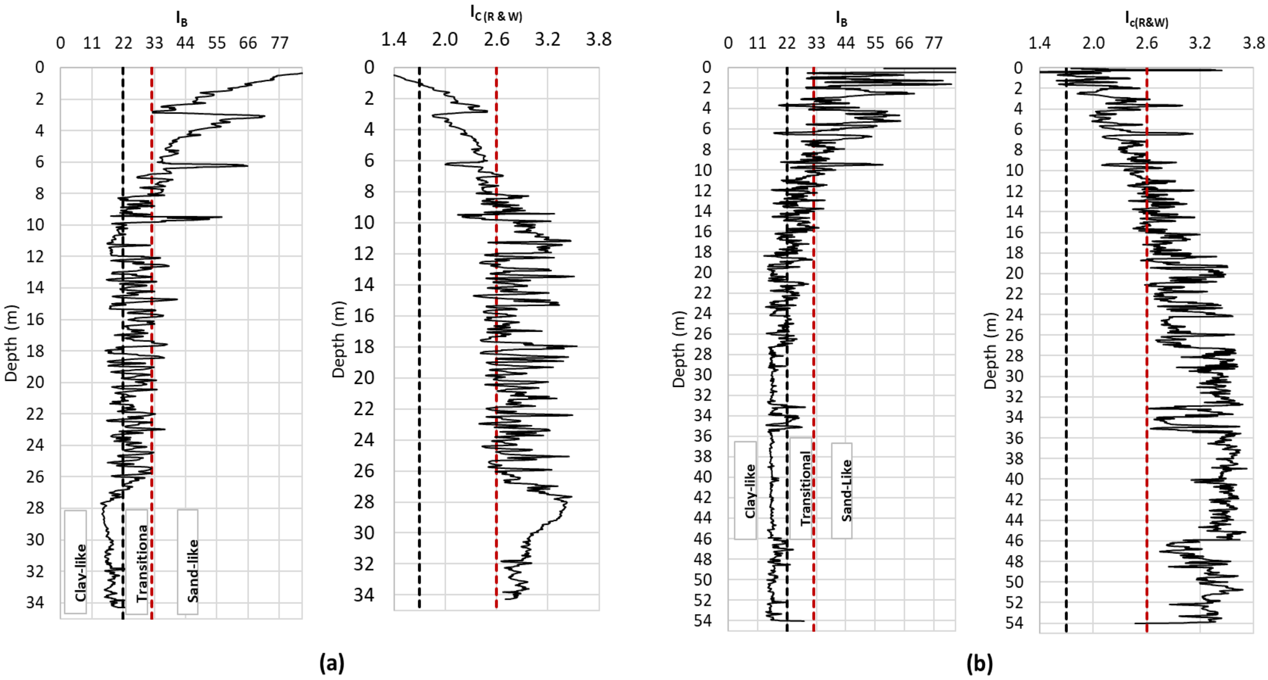

Figure 5. - Modified soil behavior type index (I_B) suggested by Robertson (2016) and soil behavior type suggested by Robertson and Wride (1998) for (a) copper ore tailings and (b) iron ore tailings.

3.3. Susceptibility to Flow Liquefaction

As can be seen in Figure 6, triaxial tests were performed in the copper ore tailings, and the results obtained from a set of three drained and undrained tests with different confining stress levels were used to define M_{tc} and λ_{10} for the purpose of better calibrating the method proposed by Plewes et al. (1992). For the iron ore tailings, it was assumed M_{tc}=1,45 herein, using the average value of the range suggested by Jefferies and Been (2016) for sand and silt tailings

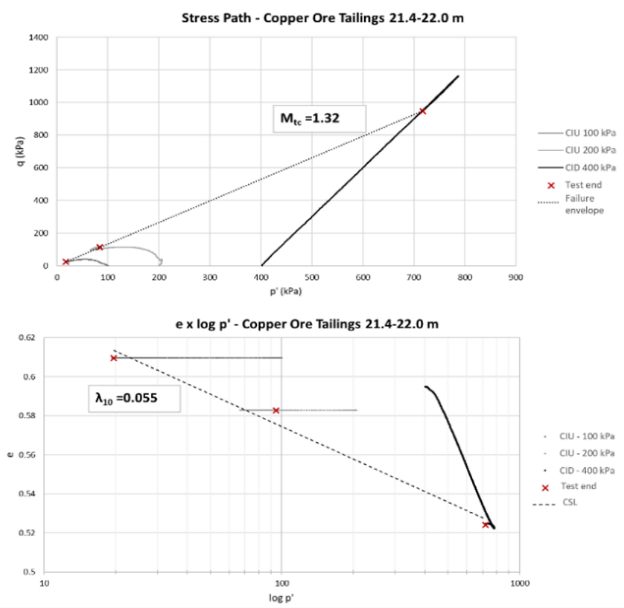

Figure 6. Critical State Line – copper ore tailings

Figure 7 and Figure 8 show the results of the evaluation of the susceptibility of the copper and iron tailings to flow liquefaction respectively. The results of the applied methodologies are represented in (a) Robertson (2016), (b) Plewes et al. (1992) and (c) Mayne and Sharp (2019).

As can be seen in Figure 7, most of the copper ore tailings showed a contractive behavior for all three methodologies used, with exception of the last 4 m of the sounding that has presented a dilative behavior according to Roberston (2016) and Mayne and Sharp (2019) approaches. The dilative behavior observed in the first 2 m of the test can be due to a possible drier layer near the tailings surface.

The iron ore tailings results can be seen in Figure 8 and have shown interbedded layers of contractive and dilative tailings, as expected for a very heterogeneous material. The first 16 m of the sounding showed a predominantly dilative behavior assessing the CD=70 boundary proposed by Roberston (2016), and the ψ= -0.05 limit incorporated into Plewes et al. (1992) by Jefferies and Been (2016). However, the opposite behavior is observed if Mayne and Sharp (2019) methodology is used to assess the first 11 m depth of the test, indicating a predominantly contractive layer. Mayne (2017) suggests an interbedded contractive/dilative layer from 11 m to 27 m depth, what is also indicated by Robertson (2016) and Plewes et al. (1992) from 16 m to 27 m depth. All three methodologies show a mostly contractive behavior below 27 m depth.

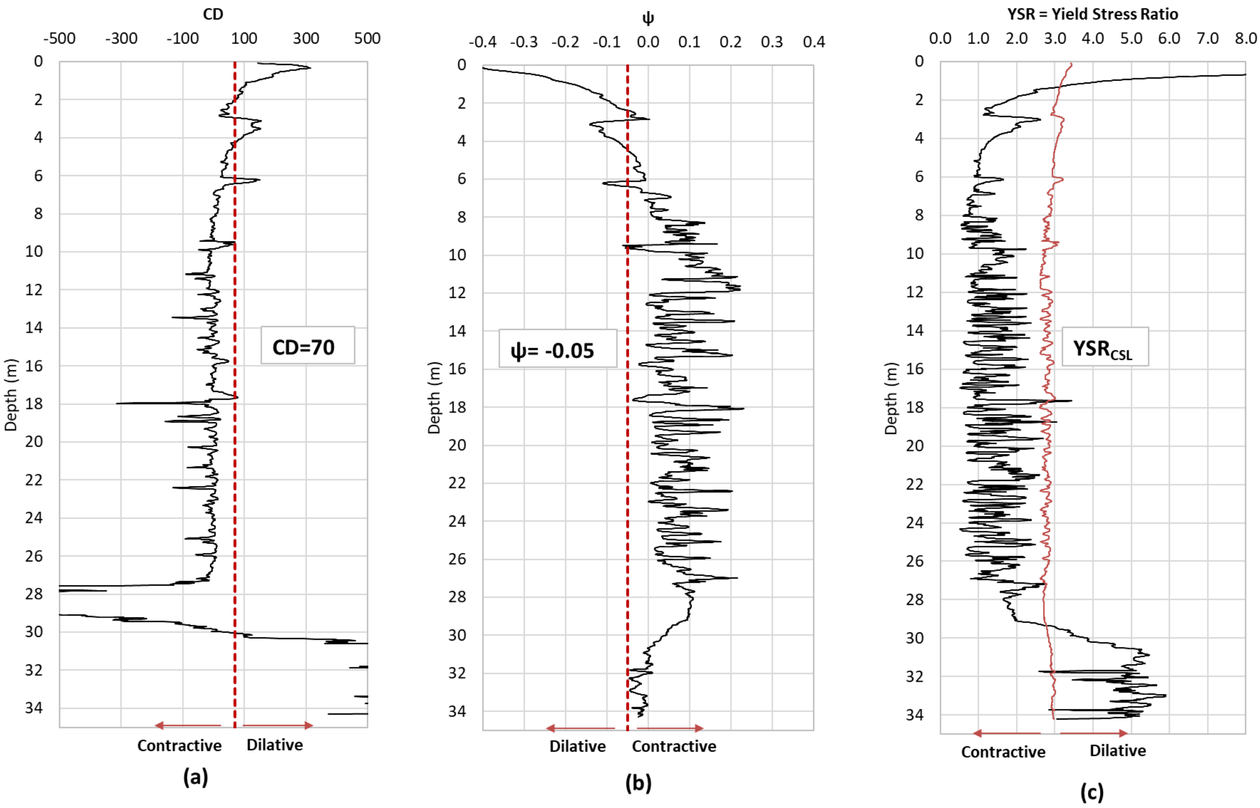

Figure 7. Evaluation of flow liquefaction susceptibility based on (a) Robertson (2016), (b) Plewes et al. (1992) and (c) Mayne and Sharp (2019) – copper ore tailings.

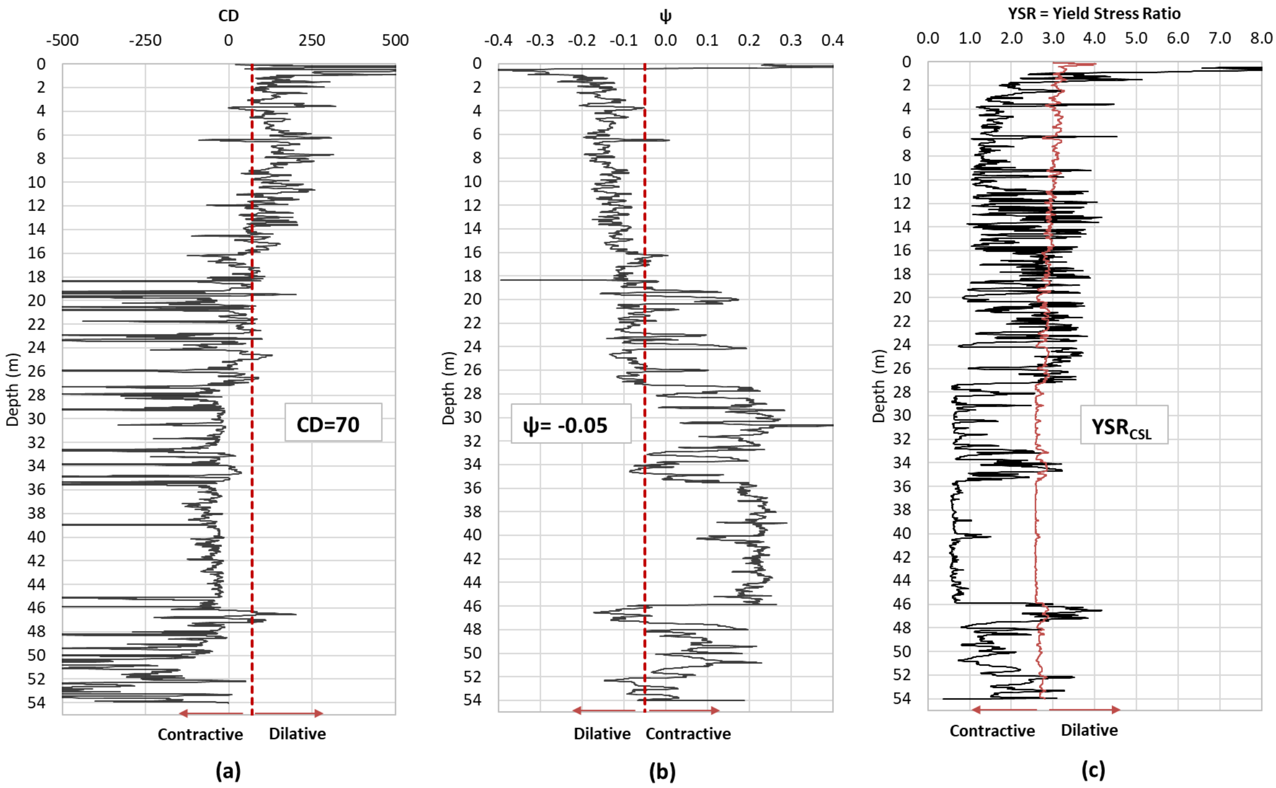

Figure 8. Evaluation of flow liquefaction susceptibility based on (a) Robertson (2016), (b) Plewes et al. (1992) and (c) Mayne and Sharp (2019) – iron ore tailings.

4. Conclusions

This paper presented an evaluation of the susceptibility to flow liquefaction of two different tailings originated of different ores and locations using the following methodologies: i) Plewes et al. (1992), ii) Robertson (2016), and iii) Mayne and Sharp (2019). Both geomaterials are deposited as slurry and are composed predominantly of silt-sized particles, with different percentages of sand and clay-size particles. Both materials presented similar unit weight and moisture content, but slightly different void ratios and specific gravity as expected considering the distinct mineralogical components derived from both ores.

The results discussed in the study showed that for both tailings assessed herein the approaches suggested by Plewes et al. (1992) and Robertson (2016) yielded similar results. Nevertheless, to some extent these methodologies diverged from the one proposed by Mayne and Sharp (2019), especially within the initial depth of the soundings.

Considering that for the copper ore tailings the Plewes et al. (1992) and the Mayne (2017) approaches were calibrated from triaxial test results, the authors recommend these methods to be preferred for this particular geomaterial. The results presented for the iron ore tailings were observed to be more divergent when it comes to Mayne (2017) methodology compared to Plewes et al. (1992) and Robertson (2016) methodologies, requiring further studies in the laboratory to better characterize the material in terms of the necessary parameters to calibrate the methodologies herein assessed. In general, most of the sounding presented a contractive behavior throughout the profile.

It is also important to emphasize that all these methods should be used as a screening-level assessment and the relations adopted are based on calibration chamber tests results or empirical studies in natural soil. As observed in this study, there are instances where the methodologies discussed can yield to different conclusions regarding the state of the geomaterials and further investigations (including laboratory tests) will contribute to better understand the behavior of the tailings, being an effective tool to guide towards the liquefaction susceptibility assessment.

Acknowledgments

The third author acknowledges the financial support by UIDB/04708/2020 and UIDP/04708/2020 of CONSTRUCT – Institute of R&D in Structures and Construction, Portugal funded by the national funds through the FCT/MCTES (PIDDAC).

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