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Evaluation of Liquefaction Susceptibility of Filtered Iron Ore Tailings from the Iron Quadrangle (Brazil)

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ABSTRACT

Over the last few years, there has been a substantial increase in the degree of complexity of requirements regarding the licensing of tailings dams in Brazil. The stacking of filtered tailings is currently proposed as an alternative solution for tailings storage facilities; however, there are numerous challenges to understand and manage these structures in regions of high rainfall and high disposal rates. In this context, the objective of this article is to evaluate the liquefaction susceptibility of filtered iron ore tailings, based on field (piezocone) and laboratory tests (characterization and triaxial compression), both performed at an experimental landfill, located in the Iron Quadrangle (Quadrilátero Ferrífero), Minas Gerais state, Brazil. Therefore, a few methodologies were used to evaluate liquefaction susceptibility by means of the critical state theory, furthermore the fragility index of the material were also evaluated. Results indicated that the constructive method used in the experimental landfill (i.e., compaction energy, moisture and layer thickness) resulted in variability in the in-situ void ratio, indicating susceptibility to liquefaction for materials on depths greater than 0.75 m from compaction surface. In addition, from laboratory tests it was possible to determine the critical state line of the filtered tailings.

INTRODUCTION

Following recent and catastrophic tailings dam flow liquefaction failure events in Brazil, an enormous public outrage has occurred leading to a great change on risk tolerance procedures and legislation. Besides, a substantial increase at the complexity level for any requirement regarding environmental permits has been made for a new tailings dam.

This scenario reinforces a trend to the use of filtered stack tailings, in view of the potential risks inherent to tailings slurry storage in conventional dams and/or the great environmental impact caused by a possible dam failure. A large capacity vacuum and pressure filter technology have recently been developed helping to increase tailings storage facilities in an unsaturated state, rather than as conventional slurry and/or paste consistency. However, there are still some limits and challenges to be overcome related to the filtered stack tailings operational and constructive aspects, mainly considering a very high production and disposal rates in heavy rainfall regions, as it happens in Brazil.

According to Crystal et al. (2018), excess pore pressure inside this type of stack usually dissipates within a few weeks or months. If the tailings become and/or remain saturated, they may be susceptible to a pore pressure increase with a consequent reduction in resistance and if they show a contractive behavior, this may lead to liquefaction phenomena.

Following the above statements, this paper aims to assess the filtered iron ore tailings liquefaction susceptibility, based on field (piezocone) and laboratory (triaxial compression) tests carried out in an experimental landfill located in the Iron Quadrangle (Quadrilátero Ferrífero) region of Minas Gerais State, Brazil.

EXPERIMENTAL LANDFILL

The experimental landfill was constructed in order to understand the filtered stack tailings behavior regarding its geotechnical, operational, and workability aspects. For this purpose, three layers were tested having different disposal thickness (0.6; 1.0 and 2.0 m). The tailings were filtered using disc filters, leading to humidity levels ranging from 10 to 15% at the filtration plant outlet, in which the Standard Proctor optimum moisture content for compaction is equal to 12%.

This landfill construction was mechanically performed and the tailings were transported from the filtration plant to the stack site by conventional trucks. Then, the tailings were spread by bulldozer D10, in order to perform the work area levelling and uniformity, in addition to allow a trafficable tailings surface. That means that the mobile equipment can move over (traffic) on the surface of the newly deposited tailings, for the subsequent layer disposal.

The landfill compaction was made only by the means of the traffic of loaded trucks and track tractor upon it. However, no compaction control was done and there was no record of the vehicle’s movements intensity. This experimental landfill construction methodology has caused, therefore, a great variability at the materials void ratio and moisture content.

TAILINGS INDEX PROPERTIES

The experimental landfill tailings are derived from the iron ore processing plant of a mine located in the Iron Quadrangle, Minas Gerais, Brazil. The results of its granulometric characterization test showed that it is a homogeneous tailing that may be classified, in general, as silt-clayey sand of brown color, being constituted by 47% of sand, 39% of silt and 14% of clay, with a specific gravity of soil particles equal to 3.09 g / cm^3. At constant load permeability tests, the tailings permeability coefficient varied from 5 x 10^{-5} to 1 x 10^{-4} cm/s, thus it can be classified as a low to very low permeability material, and besides, this material did not show plasticity.

The physical characterization studies of iron ore filtered tailings, in a preliminary assessment, pointed out that, if loose, this material is susceptible to liquefaction, since it is mostly granular and, although 53% of the tailing's particles are less than 75 µm, these fines are not plastic.

GEOTECHNICAL FIELD INVESTIGATION

The quality of the experimental landfill construction and the efficiency of the compaction methodology were verified with piezocone penetration tests (CPTu). The results of these CPTu tests are presented at Figure 1, with the framework proposed by Fear and Robertson (1995), later modified by Olson and Stark (2003) and also, the relation limit to the state parameter proposed by Jefferies and Been (2016), both for assessing liquefaction susceptibility.

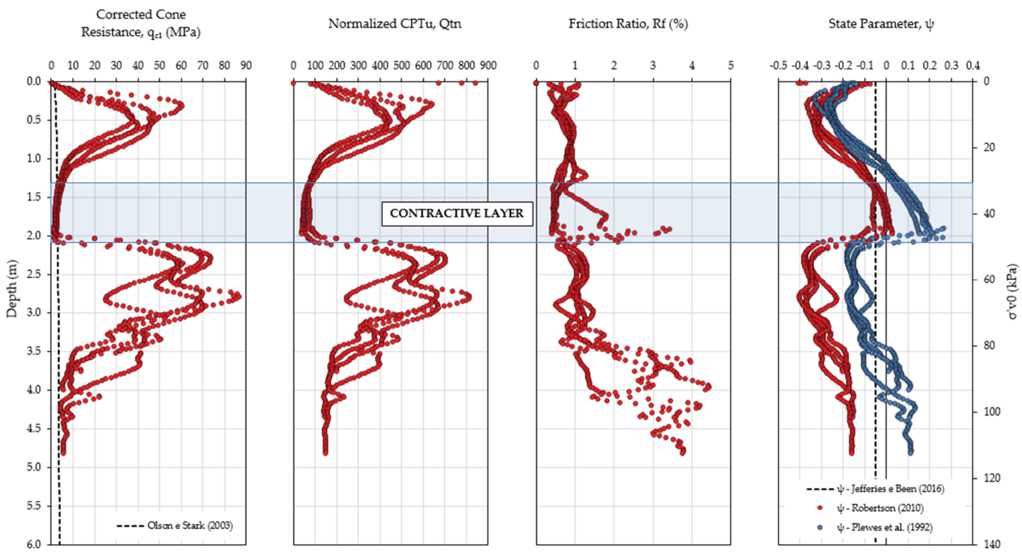

Figure 1 Summary of results for cone penetration tests (CPTu)

Overall, there is a greater influence of the compaction energy up to a depth of approximately 0.50 m, resulting in higher values of corrected tip resistance (q_{c1}). However, from 0.75 m and deeper, there is little or no compaction influence.

Regarding to the compacted regions, it was obtained peak Q_{tn} values ranging from 400 to 700 (q_{c1} from 35 to 70 MPa). However, in the non-compacted strata, Q_{tn} can be as low as 15 (q_{c1} as low as 1.5 MPa). Furthermore, by means of state parameter, it is expected dilative response on the compacted tailings, with values way below Been and Jefferies (2016) -0.05 limit, and contractive behavior on the loosen material layer, with state parameter reaching 0.25 by Plewes et al. (1992) correlation. The dilative / contractive behavior assessment by the relation between q_{c1} and σ'_v (Fear and Robertson, 1995 modified by Olson and Stark, 2003) agrees with the state parameter approach.

The CPTu tests results were plotted on a soil behavior type (SBT) graph as proposed by Robertson (2016), presented at Figure 2. Such methodology distinguishes materials with drained (sand like) from undrained (clay like) behavior. In addition, the CD line equal to 70 represents a border between contractive and dilative behavior as the piezocone penetrates the soil.

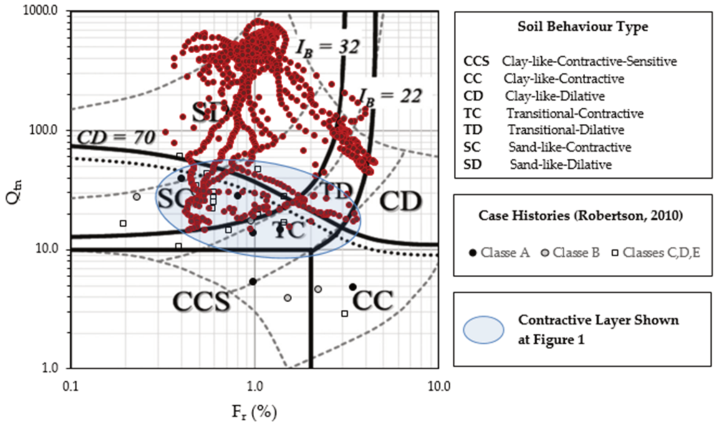

Figure 2 SBT chart based on Qtn and Fr (CPTu's results at the experimental landfill)

It is observed that, in general, the above-mentioned trend is confirmed, once the most compacted materials are located at the dilating behavior region, above the CD line equal to 70. Regarding the depths in which the compaction energy was not efficient (0.75 m below compaction surface), contractive behavior was observed, being located below the CD line equal to 70, therefore, susceptible to liquefaction. In addition, there is a good adherence of the SBT classification with the physical parameters obtained from the characterization tests (granulometry and plasticity).

GEOTECHICAL LABORATORY INVESTIGATION

Besides the characterization tests, CIU-type triaxial tests (isotropically consolidated and un-drained sheared) were performed on saturated undisturbed samples and reconstituted samples with different rates of compaction (75% and 85% of the Standard Proctor optimum moisture content - ASTM D-698) as shown in Table 1.

The tests results are presented in Figure 3, being estimated the resistance parameters and filtered tailings critical state line. It is noted that, among the analyzed tests and in general, the maximum deviator stress was obtained with axial deformations from 0.5 to 7.0%. For samples A and B, reconstituted in the laboratory with a CR of 75% and 85% and initial void ratios greater than 0.75, it was observed contractive behavior with significant positive pore pressure generation and post-peak loss of resistance (peak resistance related to less than 2% of axial deformations).

Table 1 Identification of the tested samples

Sample	Description	e_0	p'₀ (kPa)	Sample	Description	e_0	p'₀ (kPa)
A	Sample reconstituted in Laboratory (CR =75%)	1.00	100	D	Undisturbed sample collected at 1.0 m deep layer	0.60	100
		1.01	200			0.51	200
		1.00	400			0.54	400
		0.99	800			0.51	800
B	Sample reconstituted in Laboratory (CR= 85%)	0.79	100	E	Undisturbed sample collected at 2.0 m deep layer	0.54	100
		0.78	200			0.55	200
		0.78	400			0.53	400
C	Undisturbed sample collected at 0.6 m deep layer	0.51	100				
		0.51	200				
		0.50	400				
		0.49	800				

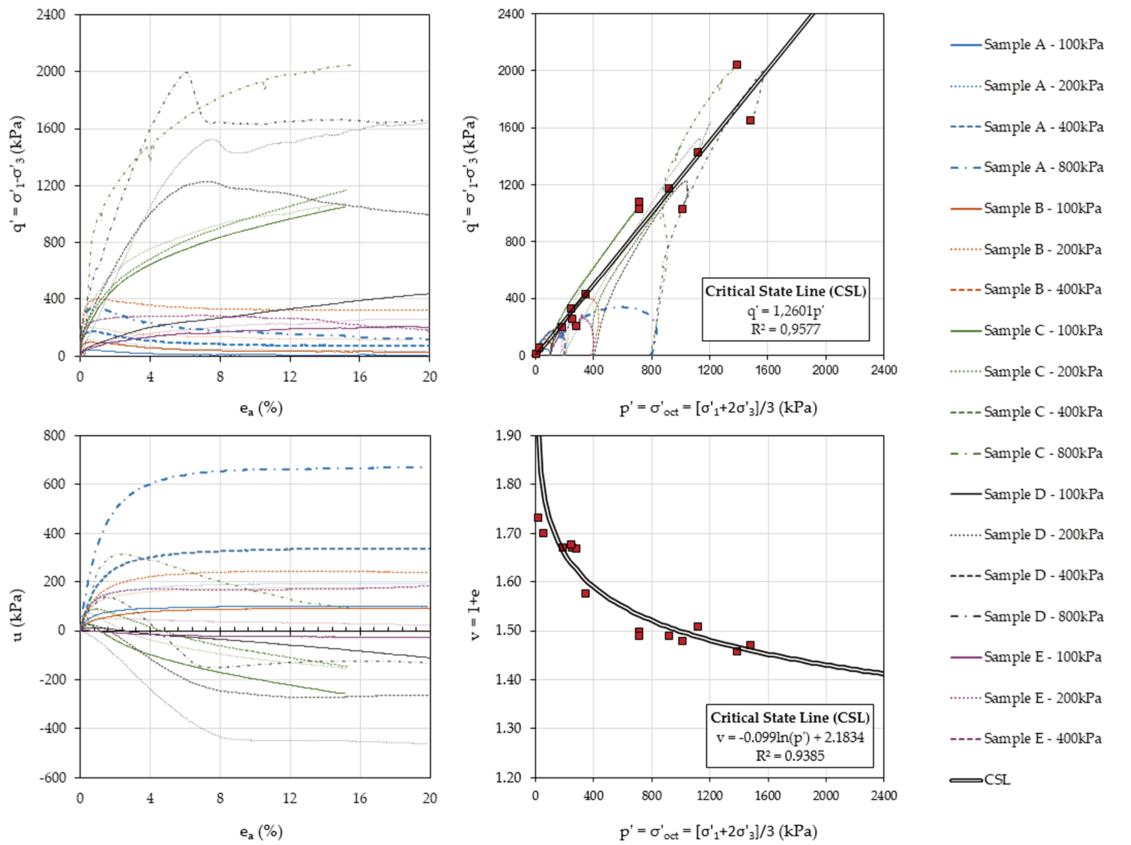

Figure 3 Undrained triaxial tests results. (a) axial deformation x deviator stress; (b) axial deformation x pore pressure; (c) mean effective stress x deviator stress; (d) mean effective stress x specific volume

The stress paths are shown in Figure 3(c). In this space, the critical state line is characterized by the parameter M equal to 1.206, in other terms a critical state friction angle of 30.1°.

The critical state line was shown in space p′ x ν at Figure 3 (d), furthermore, the same set of results, but plotted with the mean effective stress (p') on a logarithmic scale is found in Figure 4.

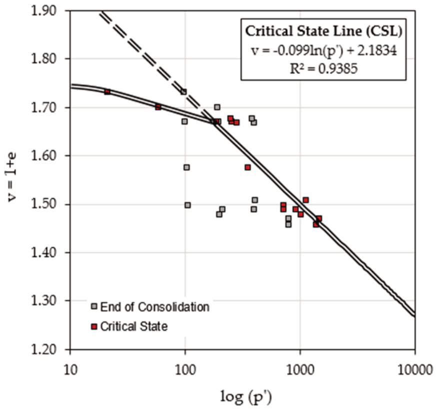

Figure 4 The filtered tailings critical state line in the space log (p') x v

Despite some scattering, the test results are consistent and allowing to define the critical state line. Generally, the line is linear for higher stresses, however, for lower mean effective stresses it is observed a break towards the vertical axe. For the linear section, the critical state parameters are λ equal to 0.099 and Γ equal to 2.18. It is worth mentioning, that for similar materials, Carrera *et al.* (2011), Viana da Fonseca *et al.* (2011), Schnaid *et al.* (2013), among others, consider that the critical state line is non-linear at low stress, presenting curvature towards the vertical axis. This condition leads to great fragility at low stresses, since shear strength decreases dramatically, leading to a pronounced strain-softening response, and eventually, complete failure by flow liquefaction with zero effective stress.

FRAGILITY INDEX

The undrained fragility index (IB) was evaluated, as proposed by Bishop (1967) (Equation 1), for those contractive behavior samples (samples A and B). The index represents the reduction of the undrained strength through shearing, so in the case of values near zero, it would represent no loss of resistance, however, values close to the unity means a total loss of resistance.

$$I_B = \frac{q'_{(yield)} - q'_{(critical)}}{q'_{(yield)}} \tag{1}$$

According to Robertson (2017), this parameter can express the material's liquefaction potential when IB values are found above 0.40. The sample fragility results are summarized in Table 2.

Robertson (2017) presented IB greater than 0.4 from data on the historical cases of flow liquefaction failure, samples A and B showed this fragile behavior, resulting in IB above 0.4 (except the sample B with $p'_{consolidation}$ equal 400 kPa). As expected, for samples that showed fragility, it was observed that the fragility indexes are directly proportional to the relationship between the consolidation mean effective stress and the mean effective stress in the critical state ($p_{consolidation}'/p'_{cs}$). It is worth mentioning that, due to the CSL non-linearity at low stresses and loosen conditions, the $p'_{consolidation}/p'_{cs}$ abruptly increased, thus justifying an even more significant loss of strength.

Table 2 Fragility index at CIU triaxial tests performed on the experimental landfill filtered tailings

Sample	e_0	$p'_{consolid}$ (kPa)	$p'_{consolid}/p'_{cs}$	IB
A (Reconstituted CR=75%)	1.00	100	14.29	0,8
	1.01	200	6.90	0,6
	1.00	400	4.30	0,5
	0.99	800	4.21	0,5
B (Reconstituted CR=85%)	0.79	100	4.62	0,6
	0.78	200	3.25	0,4
	0.79	400	1.52	0,2

CONCLUSION

By the means of the physical characterization studies of iron ore filtered tailings, in a preliminary assessment, pointed out that, whenever it is loose, this material is susceptible to liquefaction (non-plastic granular material). The geotechnical investigation, both field and laboratory, confirmed this assessment by various tests and methods.

Piezocone penetration tests results showed no influence of compaction on depths greater than 0.75 m, leading to loosen tailings with contractive behavior and susceptibility to liquefaction if saturated. Besides that, triaxial tests performed on loosen reconstituted specimens ($e_0 > 0.75$), showed strain-softening and then liquefaction behavior, with almost complete strength loss for low confinement stresses.

Regarding the critical state line, it was observed non-linearity for low confinement stresses, furthermore, for higher mean effective stresses, CSL is straight on a log p' x ν plot. As pointed out, other authors have also showed this trend and it contributes to the strength loss and strain-softening response, thus leading to liquefaction.

As known, in order to occur liquefaction of a given tailing storage facility, at least three elements are needed: a contractive material, saturation or near full saturation of the deposit and a trigger event to start the process. If any one of these elements are eliminated, this type of failure does not occur. Considering that the trigger event has a non-controlled aspect, we may approach this problem with two perspectives. One would be to control saturation and the other would be to compact the disposable materials so it dilates when sheared.

Whenever the tailing's compaction is considered as a solution to the liquefaction flow failure, regarding a very high production and disposal rates of tailings in heavy rainfall regions, the tailings disposal must be controlled in order to obtain dense materials with dilative behavior, at least in the regions where may occur the critical slip surfaces into the tailings stack.

From the design point of view, some aspects needs further research, it worth mention the behavior of compacted filtered tailings when sheared at very high confinement stresses, as it is not known as if in these stress state could change a dilative characteristic to a contractive one. Furthermore, studies on the susceptibility liquefaction of non-saturated materials are essential to guarantee safety on filtered iron ore tailings.

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