

# Geotechnical Tailings Characterization from Cuiabá Mine Site to Support a Dry Stacking Disposal Design for Cuiabá Dam

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## ABSTRACT

The main advantages of Filtered Tailings (FT) are related to water reduction in tailings disposal when compared with other methods, once it allows the geomaterial to be disposed close to optimum water content, thus allowing a better tailings compaction, and consequently increasing tailings shear strength for both drained and undrained conditions. Another advantage is the significant amount of water recovery during ore beneficiation process, especially in mining projects in dry areas.

However, as the main FT disposal designs in operation worldwide are located in drier regions, this Tailings Storage Facility (TSF) method may be a challenge for tropical regions as they generally present a positive water balance. As a consequence, tailings can be saturated and present contractive behaviour if the disposal has not been made properly and compaction has not been well controlled. Thus, this paper presents the geotechnical characterization of tailings generated in Cuiabá Mine Site to support the applicability of FT technique in dry stacking design (compacted FT disposal for buttressing downstream of the dam embankment and across the tailings reservoir). It included seismic piezocone – SCPTU tests of tailings disposed in the reservoir and laboratory tests with disturbed tailings samples at different void ratios to evaluate the effect of compaction effort on the geotechnical parameters of FT to support this new TSF method.

The main results obtained from the geotechnical tests to support the design have shown: (i) tailings inside the existing TSF have presented contractive behaviour under high strain conditions and undrained strength ratio of 0.21; (ii) the denser the tailings, the higher the undrained strength ratio and the total friction angle. Besides, the contractive or quasi-steady state behaviour obtained to higher void ratios changed to quasi-steady state or strain-hardening behaviour with density increase; and (iii) the tailings critical state friction angle was closed to 32°.

## INTRODUCTION

The main factors to be evaluated before selecting a specific disposal design involving conventional disposal (slurry or pulp), use of cyclones, thickened, paste and/or filtered tailings and its suitability

are energy supply, climate, production rates, project economics, operational predictability, topographical and seismicity aspects of the area and local water supplies (Watson et al., 2010).

Due to the current scarcity of water supply, there is a strong demand for safer Tailings Storage Facilities - TSFs both from government regulations and the population, and a higher demand for minerals by the industries, the Filtered Tailings (FT) trend is increasing significantly worldwide for new TSFs and the improvement of existing facilities. As presented by Kujawa in Jewell & Fourie (2015), the main drivers that favour FT when compared with other TSFs in tropical regions are probably:

- Stacked FT are less prone to static and seismic efforts and loadings, thus reducing TSF risk of failure, mainly in regions with high seismicity activity or extreme topographic conditions;
- Deposition is made at lower moisture content, especially below the saturation point. This factor allows good compaction and low permeability to the new TSF structure, as a consequence, improves its shear strength;
- The final tailings solids content tends to increase. Therefore, water quantity released after deposition decreases significantly and the water recovery achieved during filtration is high enough that constitutes a significant cost saving. These factors are extremely important in areas that present scarcity of natural resources (borrowed materials) or expensive geomaterials for building new embankments or dams, and in areas of lower water availability;
- Reduced TSF footprint; and
- Possible progressive and continuous reclamation of the tailings and the closure of TSF over time.

However, as the geomaterial generated in FT is not saturated and presents higher solids content, the disposal process must be via trucks or conveyors instead of pumps. Hence, transportation becomes another factor that should be taken into account in its evaluation and is a key factor when the FT disposal in a TSF is the selected method. Thus, because of these aspects, the FT operational costs can be relatively high when compared with other TSFs costs usually adopted by the mining industry.

Crystal (2018) reported that the main operating FT projects around the World have production rates lower than 15,000 tons per day (tpd), but the Karara Iron Ore mine is an exception to this rule once its production rates reaches 30,000 tpd. But this author also pointed out that these projects are located in arid regions or regions whose average annual precipitation minus average annual evapotranspiration (water balance) is lower than 1,000 mm. Therefore, today, the main factors that influence a FT operation are: (i) tailings production rate; and (ii) climate conditions (drier areas or areas with lower rainfall).

Because of these aspects presented above, FT technology applicability in tropical regions may be a great challenge and demands a specific and careful study, once these regions generally present a positive water balance higher than 1,000 mm per year. As a consequence, tailings can be saturated and present contractive behaviour if the tailings disposal has not been made properly and its compaction has been poorly controlled or uncontrolled. Besides, as presented by Kujawa in Jewell & Fourie (2015), the label “dry” assigned to FT, which is commonly called “dry stacking”, is misleading

because FT still contain water, even in low quantities, and sometimes the tailings moisture content released by a filtration plant can be much higher than their optimum water content.

Therefore, as a way of decreasing the dependence on dams, minimising environmental impacts, improving the current tailings beneficiation process for gold recovery at the Cuiabá mine site and improving the TSF safety currently adopted (conventional dam), a “dry stacking” feasibility study was developed for the Cuiabá dam by Gomes et al. (2019). This 90m-high dam located in Sabará – MG, Brazil and operated by AngloGold Ashanti – AGA was built with conventional embankment construction and raised following the conventional downstream construction method. So, one of the main design criteria was the application of compacted Filtered Tailings – FT disposal for buttressing of the downstream embankment and across the tailings reservoir.

As Cuiabá mine has a relatively low tailings production rate, the FT method becomes attractive; however, since the mine is located in a tropical region with a high positive water balance, the new TSF at the existing TSF will require extensive geotechnical studies to make it feasible and safe to operate. Thus, this paper presents the results obtained from field and laboratory geotechnical tests performed with tailings generated by this mine site to support a “dry stacking” disposal design for Cuiabá dam.

## METHODOLOGY

FT geotechnical feasibility as a new TSF at the Cuiabá dam depends on geotechnical tailings characterization inside the reservoir (tailings beach) and specific FT geotechnical parameters. So, the methodology applied to achieve these data included field and laboratory geotechnical tests.

As Piezocone Test – CPTU is the most recommended field test for geotechnical tailings characterization disposed of a TSF, according to Schnaid (2009), seven seismic CPTU Tests (SCPTU) were performed over tailings beach of the existing Cuiabá dam; the tests were conducted as per the relevant international standards. From the SCPTU results, it was possible to evaluate and infer the following:

- liquefaction potential susceptibility (contractive-dilative behaviour): methodology proposed by Robertson (2016); and
- undrained strength ratio: methodology proposed by Olson & Stark (2003), Sadrekarimi (2014), Contreras et al. (2017) and  $N_{kt}$  theoretical method presented in Schnaid (2009).

A new methodology proposed by Robertson (2016) to evaluate tailings liquefaction potential susceptibility was adopted, because it consists of an updated chart plotted with CPTU results and combines these results with those obtained in SCPTU, as described below:

- new Soil Behaviour Type – SBTn chart: the popular SBTn chart proposed by Robertson (2010) to identify geomaterials that are potentially contractive or dilative under high strain conditions was updated to a new one that includes new boundaries to classify the geomaterial according to its behaviour, which may have, from a geomechanical point of view, a sand-like, clay-like or transitional behaviour. But this new SBTn chart has not changed old boundaries and criteria contained in the methodology formerly proposed by

Robertson (2010), given that: (i) it still uses only CPTU results; (ii) the chart still proposes a relationship between normalized cone resistance ( $Q_{tn}$ ) and normalized friction ratio ( $F_r$ ); and (iii) the contractive-dilative boundary (CD) remains equal to 70, which segregates geomaterials with potential contractive behaviour ( $CD < 70$ ) from those with potential dilative behaviour ( $CD > 70$ ). Hence, the updated SBTn chart proposed by Robertson (2016) introduces new boundaries that will support the classification of a geomaterial analysed in depth based on two geotechnical properties: its geomechanical behaviour (clay-like – C, sand-like – S or transitional – T) and its potential liquefaction susceptibility under high strain conditions (contractive – C or dilative – D); and

- $Q_{tn} - I_c$  chart: Robertson (2016) proposed a new chart to identify microstructured geomaterial, through a combination of CPTU and SCPTU results. This new chart includes a relationship between normalized cone resistance ( $Q_{tn}$ ) and small-strain rigidity index ( $I_c$ ), which is a relationship between small-strain stiffness ( $G_0$ ) and net cone resistance ( $q_n$ ) with depth, where  $q_n$  is the difference between the corrected tip soil resistance –  $q_t$  and vertical total stress –  $\sigma_v$ . So, geomaterials could be classified as “structured soils” (soils with microstructure) or “unstructured soils” (ideal soils or soils without microstructure), which can result from many factors such as secondary compression, thixotropy, cementation bonding, aging, and others. Thus, “structured soils” are geomaterials with a significant microstructure that probably present higher yield stress, peak strength, and small-strain stiffness; in contrast, “unstructured soils” are geomaterials with little or no microstructure (ideal soils) that are predominately young and uncemented.

Once the FT disposal can turn out a great challenge in tropical regions, geotechnical laboratory tests were run on disturbed tailings samples for purposes of geotechnical characterization and to evaluate the compaction effect on the tailings shear strength, as follows:

- Geotechnical tailings characterization: laboratory geotechnical tests were performed to determine tailings geotechnical characteristics and compaction properties. These tests – conducted as per the procedures recommended by the Brazilian standards – included: grain size distribution, specific gravity, Atterberg limits, maximum and minimum void ratios and compaction test; and
- Tailings shear strength: after geotechnical tailings characterization, key parameters such as maximum and minimum void ratios and optimum compaction parameters along with optimum water content and maximum dry density, three different void ratios, and, consequently, three different dry densities were specified as input data to the triaxial compression tests such to evaluate the compaction effect on the tailings shear strength. Once relative density and compaction degree may significantly influence the geomaterial shear strength, laboratory shear tests were conducted on tailings samples with relative density close to 2, 35 and 70% or compaction degree of 75, 80 and 90%, to evaluate the compaction degrees (loose, medium and close to dense) in the tailings shear strength.

For each void ratio or dry density measurement, seven specimens were prepared as per the recommended sample reconstitution procedure proposed by Jefferies & Been (2016). Triaxial compression tests were conducted as per the methods recommended by international standards as detailed below:

- Isotropically consolidated undrained triaxial compression test (CIU): four specimens were tested applying consolidation stress of 50, 100, 200 and 400 kPa; and

- Isotropically consolidated drained triaxial compression test (CID): three specimens were tested applying consolidation stress of 100, 200 and 400 kPa.

The tailings effective critical state friction angle was obtained from the combined CID and CIU test results. The tailings' undrained strength ratio –  $S_u/\sigma'_{v0}$  was obtained from CIU tests using two different failure criteria methods: (i) maximum peak principal stress ratio –  $(\sigma'_1/\sigma'_3)^{MAX}$  method; and (ii) maximum Skempton's pore pressure parameter –  $A^{MAX}$  method. These failure criteria methods were based on six failure criteria to determine  $S_u/\sigma'_{v0}$  of silt soils as presented by Brandon et al. (2006) using triaxial compression tests. However, these methods described above were only based on and inferred from the results and conclusions presented by this author.

Brandon et al. (2006) suggested, differently from what was addressed in this paper, that the Skempton's pore pressure parameter –  $A$  equal to zero ( $A=0$ ) should be adopted for geosystems because it is an effective procedure to determine  $S_u/\sigma'_{v0}$  of dilatant, low-plasticity silt deposits. As a consequence, if this criterion is adopted, the undrained strength is equal to the drained strength. But that author also showed that if  $A=1$  or  $A^{MAX}$  is adopted as a failure criterion to determine  $S_u/\sigma'_{v0}$ , which was the criterion adopted in this paper, the undrained strength is smaller than the drained strength. Hence, if this method is adopted, the  $S_u/\sigma'_{v0}$  of a geomaterial will decrease considerably and the soil effective friction angle ( $\phi'$ ) will not affect its value.

After the tailings undrained shear strength –  $S_u$  was determined through triaxial compression tests, Equation 1 was used to calculate the tailings undrained shear strength at failure ( $\tau_{ff}$ ), and, consequently, the undrained strength ratio at failure ( $\tau_{ff}/\sigma'_{v0}$ ). Equation 2, proposed by Budhu (2011), was applied to convert  $\tau_{ff}/\sigma'_{v0}$ , obtained from the isotropically consolidated triaxial compression test (IC) –  $[\tau_{ff}/\sigma'_{v0}]_{IC}$ , into that obtained if a Direct Simple Shear test (DSS) was used –  $[\tau_{ff}/\sigma'_{v0}]_{DSS}$ , as recommended by that author.

$$\tau_{ff} = \frac{q^{MAX}}{2} * \cos \phi'_{CS} = S_u * \cos \phi'_{CS} \quad (1)$$

$$\alpha^{DSS-IC} = \frac{\left[ \frac{\tau_{ff}}{\sigma_{z0}} \right]_{DSS}}{\left[ \frac{\tau_{ff}}{\sigma_{v0}} \right]_{IC}} = \frac{(3 - \sin \phi'_{CS})}{2 * \sqrt{3}} \quad (2)$$

## RESULTS AND DISCUSSION

### Field Tests – Tailings Beach

The SCPTU results presented in Figure 1 and Figure 2 have shown:

- After applying the methodology proposed by Robertson (2016), presented in Figure 1, and considering that the majority of the paired points  $Q_{tn} \times F_r$  obtained with depth is below the  $CD=70$  line, the tailings analysed can be classified as likely contractive under high shear strain conditions. So, tailings deposited within the Cuiabá dam reservoir are potentially susceptible to liquefaction and can be considered as a geomaterial with contractive behaviour, which means that its susceptible to suffer liquefaction when loaded;

- According to Robertson (2016), from a geomechanical point of view, microstructured geomaterials tend to be cemented or bonded and can be very stiff under low strain conditions (producing high  $Q_{tn}$  values) but can be contractive under high shear strain conditions (producing high  $U_2$  values), when the cementation is destroyed and the material becomes destructured. So, adopting the same methodology cited above, it is possible to infer from Figure 1 that the analysed tailings in question may have a significant microstructure because the majority of paired points  $Q_{tn} \times I_G$  obtained in depth showed  $K^*_G > 330$ . As a consequence, they may have higher yield stress, peak strength, and small-strain stiffness; and
- According to Figure 2, the undrained strength ratios ( $S_u/\sigma'_{v0}$ ) estimated through the methodologies proposed by Olson & Stark (2003), Sadrekarimi (2014) and Contreras (2017) were close to each other, varying from 0.21 to 0.28; however, the  $N_{kt}$  theoretical method shows that this parameter varies significantly from 0.15 to 0.88. Therefore, if  $S_u/\sigma'_{v0} = 0.21$  is assumed for tailings deposited within the Cuiabá dam reservoir, the respective “dry stacking” design may be considered conservative since this parameter was obtained by empirical correlations from CPTU results. However, it will probably result in a higher factor of safety thus ensuring the stability of the structure.

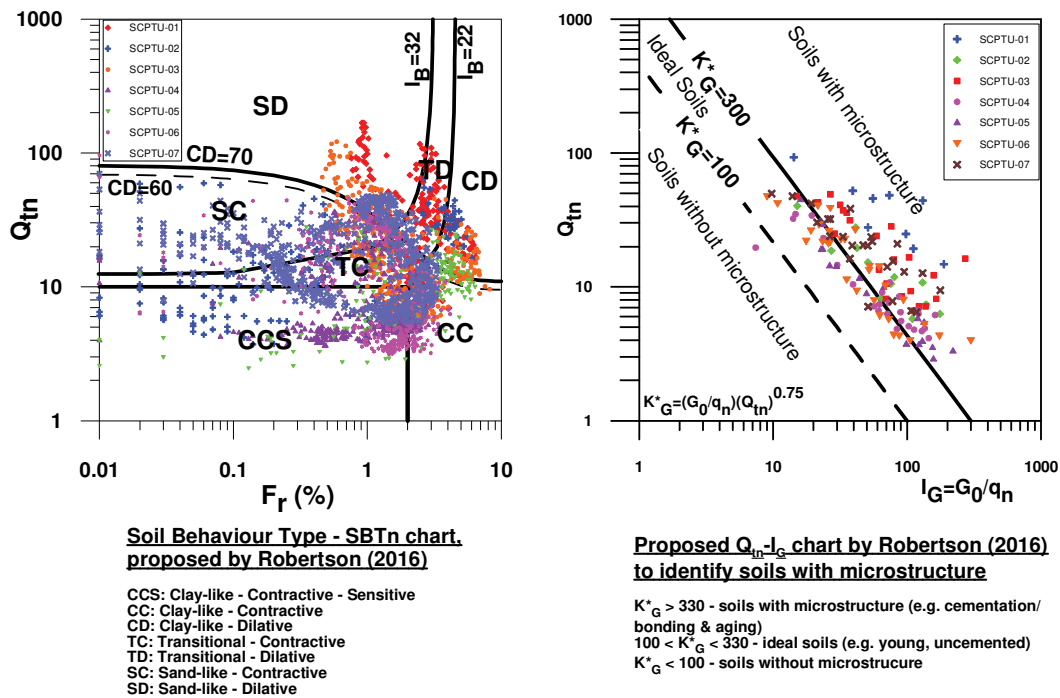


Figure 1 Tailings beach liquefaction susceptibility evaluation.

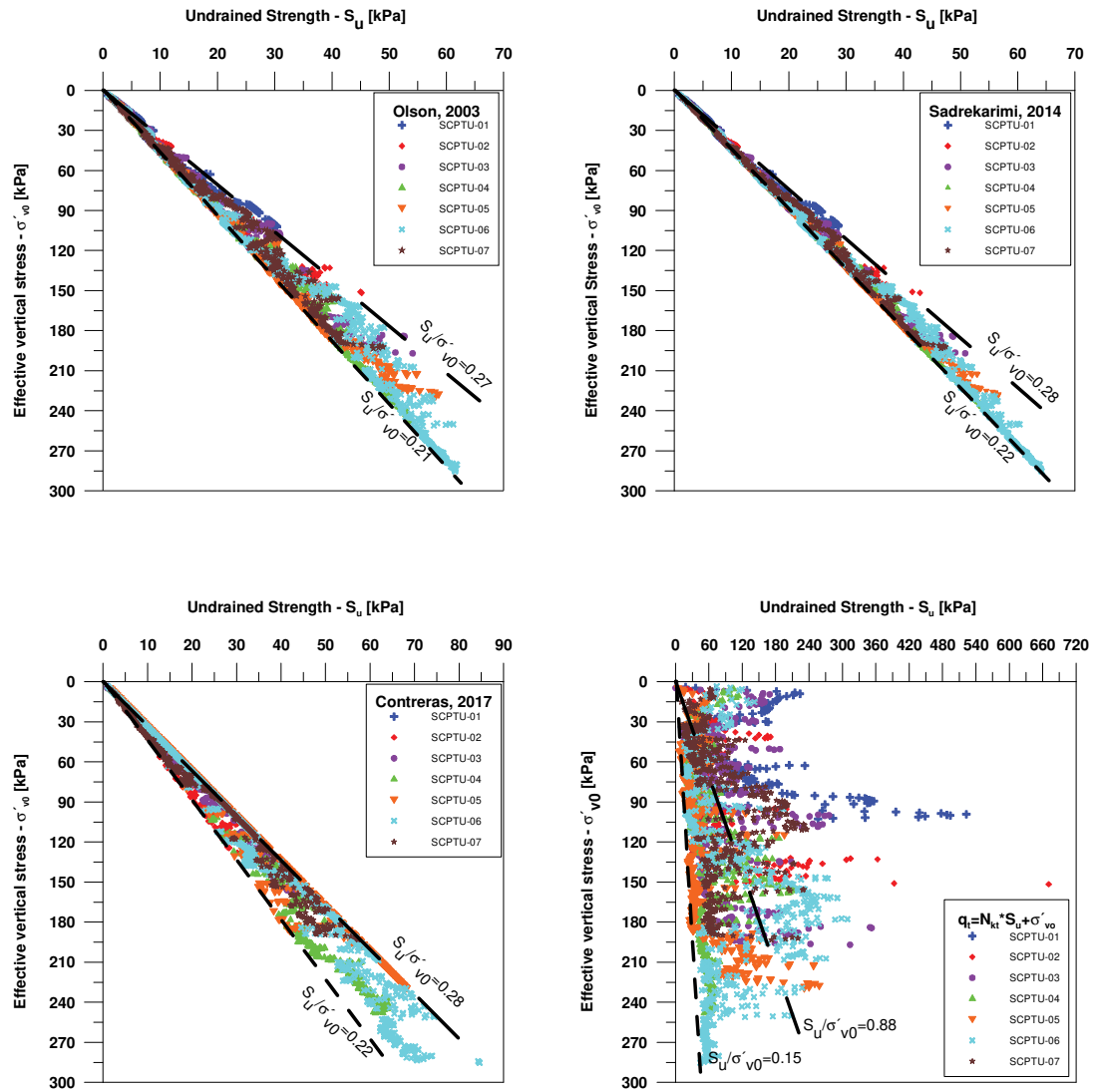


Figure 2 Undrained strength ratios ( $S_u/\sigma'_{v0}$ ) obtained from all SCPTU tests run inside the Cuiabá dam reservoir.

## Laboratory Tests – Disturbed Tailings Samples

### Geotechnical Characterization

Table 1 presents the geotechnical characterization results obtained from disturbed tailings samples collected at Cuiabá mine site. Based mainly on the maximum and minimum void ratios and the optimum compaction parameters, it was determined that the triaxial compression tests should be

conducted to disturbed tailings samples prepared to void ratios of 1.25, 1.03 and 0.83 such to obtain samples with relative density close to 2, 35 and 70% or compaction degree of 75, 80 and 90%.

**Table 1** Tailings generated in Cuiabá Mine geotechnical characterization

Sample Type	Specific gravity – $G_s$	Atterberg Limit	$e^{MAX}$	$e^{MIN}$	Sand [%]	Silt [%]	Clay [%]	$w^{ót}$ [%]	$\gamma_d$ [kN/m <sup>3</sup> ]
Disturbed	2.811	Non-plastic	1.25	0.70	29	68	3	18.75	16.79

### *Triaxial Compression Tests*

Table 2 and Figure 3 present the results extracted from the triaxial compression tests conducted on disturbed tailings samples molded under loose, medium and almost dense conditions, which were specified after the geotechnical characterization results. They have shown:

- After analysing the effective stress path – ESP for all the void ratios studied, all of them showed that tailings in general presented a contractive behaviour to higher consolidation stresses and quasi-steady state behaviour for lower consolidation stresses. Moreover, for all the consolidation stresses adopted, the results showed that the contractive behaviour of tailings samples with higher void ratios changed to quasi-steady state behaviour as the densities increases. So, this geomaterial may suffer liquefaction when submitted to undrained stresses or rapid loading if compaction is poorly controlled or uncontrolled. On the other hand, if this geomaterial is subjected to denser conditions (compaction degree higher than 90%), it may present strain-hardening response and, consequently, will reach an ultimate state under high strain conditions, as reported by Robertson et al. (1998);
- The denser the tailings, the higher the undrained strength ratio, and the DSS undrained strength ratio at failure ( $[\tau_{tf}/\sigma'_{v0}]_{DSS}$ ) obtained for a void ratio of 1.03 (compaction degree of 80%) was close to that obtained through the theoretical method. It was also observed that the tailings undrained strength ratio obtained from triaxial compression tests was higher than that obtained from empirical correlations adopted for the CPTU results. This behaviour was expected because tailings inside the Cuiabá dam reservoir were hydraulically disposed and present lower densities; consequently, with void ratios higher than those adopted for the triaxial compression tests. Additionally, triaxial compression tests were conducted to three different dry densities to evaluate the effect of controlled compaction on a “dry stacking” design. However, the  $[\tau_{tf}/\sigma'_{v0}]_{DSS}$  parameter obtained for loose samples (higher void ratio) was close to that obtained through empirical CPTU correlations for the same geomaterial;
- The total shear strength also increased with density mainly when the void ratio changed from 1.03 to 0.83. But when tailings void ratio varied from 1.25 to 1.03, the tailings undrained strength ratio and total friction angle did not increase significantly. It was also observed that the total friction angle obtained for tailings samples with a void ratio of 0.83 (denser compaction degree – close to 90%) was slightly below the effective critical state friction angle;



- When a geomaterial presents contractive behaviour under high strain conditions, the maximum  $(\sigma'_1/\sigma'_3)$  method should be applied to peak undrained strength ratio at failure. However, as the tailings studied presented, under certain conditions, a quasi-steady state behaviour and, sometimes, strain-hardening response, it may be suggested and proposed that the  $[\tau_{ti}/\sigma'_{v0}]_{DSS}$  parameter obtained from  $A^{MAX}$  method and the undrained stability analysis should be adopted for the Cuiabá dam “dry stacking” design; and
- Effective critical state friction angle  $(\phi'_{cs})$  obtained to these tailings was closed to  $32^\circ$ .

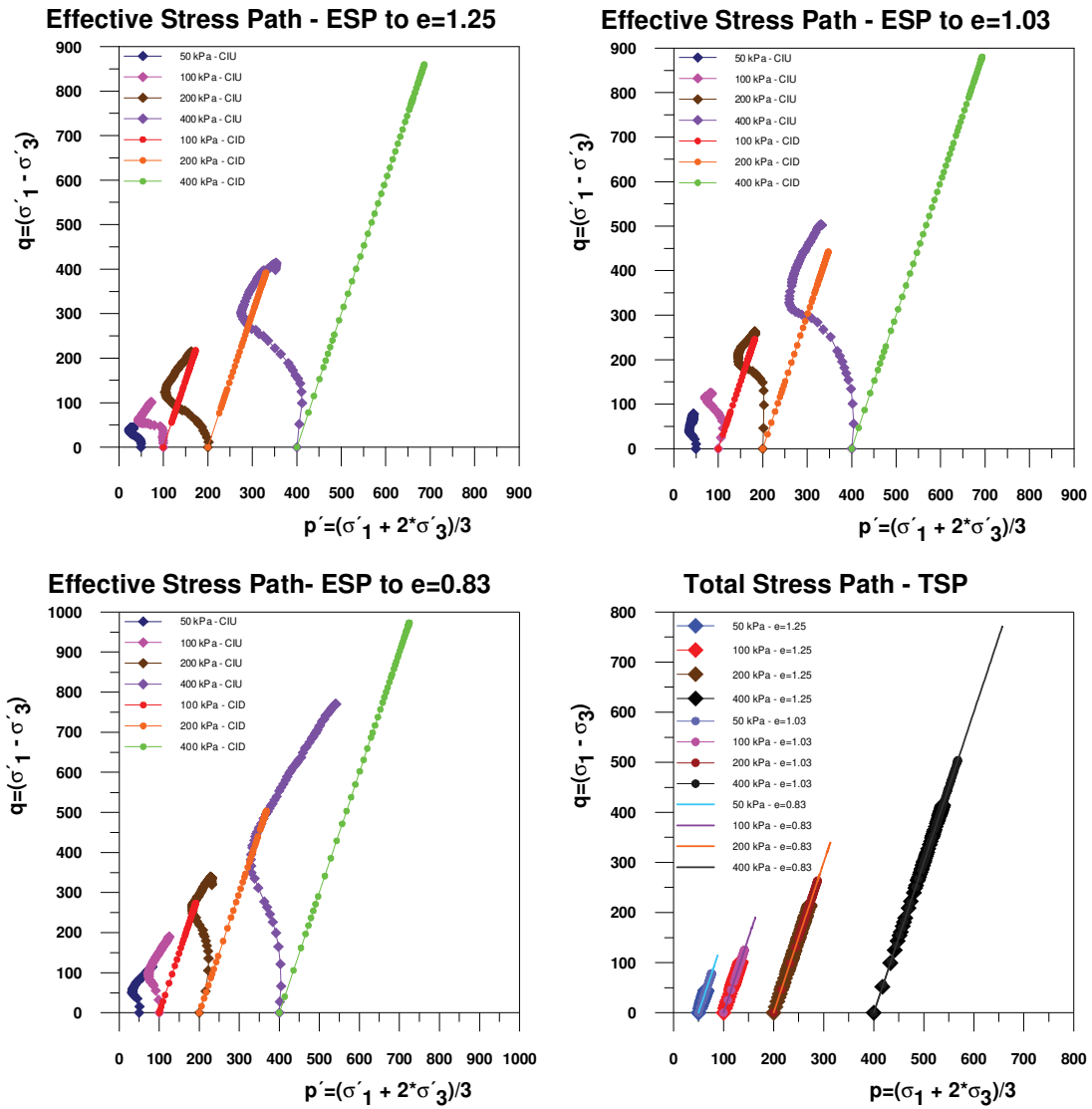


Figure 3 Effective and Total Stress Path (ESP and TSP) obtained from CIU and CID tests, using CSSM.

**Table 2** Shear strength parameters obtained from triaxial compression tests

Parameters		Disturbed Tailings Samples		
		e=1.25	e=1.03	e=0.83
Total Shear Strength	Cohesion – c (kPa)	0	0	0
	Friction angle – $\phi$	21°	23°	30°
Effective Shear Strength	Cohesion – c' (kPa)	0	0	0
	Peak Friction angle – $\phi'$	32°	34°	34°
Critical state friction angle – $\phi'_{cs}$		32°	32°	32°
Undrained Strength Ratio for Isotropically Consolidated Triaxial Compression Tests (IC) – $[S_u/\sigma'_{v0}]_{IC}$	$(\sigma'_1/\sigma'_3)^{MAX}$ Method	0.48	0.61	0.90
	A <sup>MAX</sup> Method	0.35	0.42	0.48
Undrained Strength Ratio at failure for Isotropically Consolidation Triaxial Compression Tests (IC) – $[\tau_{ff}/\sigma'_{v0}]_{IC}$	$(\sigma'_1/\sigma'_3)^{MAX}$ Method	0.41	0.48	0.73
	A <sup>MAX</sup> Method	0.31	0.36	0.42
Conversion Factor ( $\alpha_{DSS-IC}$ ): IC tests to DSS tests			0.713	
Undrained Strength Ratio at failure for Direct Simple Shear Tests (DSS) – $[\tau_{ff}/\sigma'_{v0}]_{DSS}$	$(\sigma'_1/\sigma'_3)^{MAX}$ Method	0.29	0.35	0.52
	A <sup>MAX</sup> Method	0.22	0.25	0.29
	Theoretical Method for normally consolidated fine-grained soils – $[\tau_{ff}/\sigma'_{v0}]_{DSS} \approx 0.50 \sin \phi'_{cs}$		0.26	

## CONCLUSION

Geotechnical field and laboratory characterization tests were performed with tailings from the Cuiabá mine site to support a “dry stacking” disposal design for Cuiabá dam. According to the test results obtained, it can be concluded that:

- Tailings inside the current TSF presented a contractive behaviour under high strain conditions and an undrained strength ratio close to 0.21. However, according to a new methodology proposed by Robertson (2016) to evaluate the geomaterials liquefaction potential susceptibility, tailings disposed in the Cuiabá dam presented microstructure, which means that their yield stress, peak strength, and small-strain stiffness parameters are probably higher. Thus, any extra loading over the tailings inside the Cuiabá dam reservoir must be carefully and slowly applied. So, it is recommended that these loads should be applied after a buttress is constructed at the downstream slope embankment of the current TSF;
- Undrained strength ratios obtained from the triaxial compression tests run on disturbed tailings samples were, in general, higher than those obtained from field tests run on tailings deposited within the dam reservoir. Once the tailings inside dam reservoir were disposed hydraulically and presented lower densities (higher void ratios) than those tested in the laboratory, i.e., higher void ratios, hydraulically-disposed tailings may have semi-horizontal strata of different textures and geotechnical behaviour as a result of the sedimentation process, and the tailings undrained strength ratios from field tests were obtained through empirical correlations. This behaviour was expected and confirmed because the laboratory tests were run on homogeneous tailings samples under controlled compaction conditions, while the field tests were conducted under in situ compaction conditions;
- The denser the tailings, the higher the geotechnical strength parameters, especially the total friction angle, peak effective friction angle and undrained strength ratios. Considering CSSM, the tailings effective critical state friction angle was closed to  $32^\circ$ , which shows that FT disposal, mainly for the buttress, can be done at a denser void ratio, which must be equivalent to a compaction degree higher than 95%. Such higher density is required and has been proposed, but was not studied in this paper, because prior geotechnical tests performed by AGA on the same tailings, considering a compaction degree of 95%, have shown that this geomaterial presents dilative behaviour under high and low strain conditions; and
- The “dry stacking” design at the Cuiabá dam must include a well-controlled compaction and a dedicated, suitable and qualified team for the management of the Quality Assurance and Quality Control (QA/QC) thus ensuring the operational methodology is adhered to, similar to that proposed by Lara et al. (2011) for the Cerro Lindo FT disposal project:
  - Thickness control of the compacted layer; each layer must be 30-35 cm thick for compaction;
  - Onsite moisture and density control of the compacted layer;

- Compaction has to be executed at a moisture content close to the optimum water content or slightly dryer;
- Grain size (gradation) distribution, void ratios and specific gravity control of FT deposited each 5.0 metres in high;
- Shear strength and moisture control of FT deposit in depth through SCPTU and laboratory tests once a year; and
- Control of the overall slope angle of the FT deposit.

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