# Evaluation of the susceptibility to flow liquefaction of a bauxite tailings

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## ABSTRACT

Recent tailings dam failures in Brazil, namely Brumadinho B-I Dam (2019) and Fundão Dam (2015), highlighted the importance of assessing the susceptibility to flow liquefaction, especially for structures constructed with hydraulically deposited sand-like materials. The phenomenon is observed in saturated or nearly saturated geomaterials that show a brittle strain softening response during undrained shear due to its tendency to contract in drained shear, typically observed in very loose sands and silts, as well as highly sensitive clays. Many field and laboratory procedures can be used to evaluate the flow liquefaction susceptibility. Of the various approaches, those based on historical case histories have been widely used in engineering practice. These methodologies consist of classifying the behavior of the soils during shear through the analysis of in situ tests, typically CPTu and SPT. Methods based on triaxial compression tests are also common, in addition to methods using Atterberg Limits and grain-size distribution curves. This paper aims to present the characterization of a bauxite tailings deposited in a Brazilian tailings dam and its flow liquefaction susceptibility analysis by the evaluation of i) grain-size distribution; ii) Atterberg Limits; iii) CPTu; iv) Vane Shear Test and v) Triaxial Compression Test. The results showed that even though the material presented a contractive behavior under shear (indicated in the CPTu tests) the laboratory test indicate that the tailings present a very ductile and clay-like behavior and, therefore, is not susceptible to flow liquefaction.

## INTRODUCTION

In the mining industry, flow liquefaction is a subject of high relevance due to the geotechnical characteristics of the tailings. In hydraulically deposited tailings facilities, the material is deposited with a high void ratio and degree of saturation. In these conditions, the tailings tend to present contractive behavior when sheared and their drained or undrained strength can be mobilized depending on the material's permeability and boundary conditions of the deposit.

When saturated, dilative soils tend to show equal or higher shear strength in an undrained condition when compared to a drained condition. On the other hand, contractive soils have lower shear strength in undrained shear when compared to drained shear. Additionally, contractive soils can show strength loss during shearing (strain-softening), although not all soils that present contractive behavior have strength loss.

Castro (1969) defines liquefaction as "a phenomenon associated with sand materials, in which the sand reduces its shear strength so that the soil mass flows until the shear stress acting within this mass becomes compatible with the liquefied shear strength of the sand".

Robertson (2010) explains that the liquefaction phenomenon is associated with abrupt strength losses of the soil due to its metastable structure. Moreover, Robertson (2017) shows that most failures due to liquefaction occur in young, low plastic or non-plastic, loose and granular soils without cementation that show brittle behavior with significative strength loss for low strain rates during undrained shear.

Many field and laboratory procedures, associated with different methodologies, have been developed to evaluate the flow liquefaction susceptibility. This paper aims to present the characterization of a bauxite tailings deposited in a Brazilian tailings dam and its flow liquefaction susceptibility analysis by the evaluation of i) grain-size distribution curves; ii) Atterberg Limits; iii) CPTu; iv) Vane Shear Test and v) Triaxial Compression Test.

## METHODOLOGY

In this paper, the first approach to evaluate the susceptibility of the tailings to flow liquefaction was the boundaries for grain-size distribution curves suggested by Ishihara et al. (1980) and Carneiro (2021). Ishihara et al. (1980) showed that the range of non-plastic fine tailings studied by them was susceptible to liquefaction just as natural deposits of more granular non-plastic soils. Carneiro (2021) presented ranges based on the grain-size distribution curves of the tailings of Fundão Dam (2015) and Brumadinho B-I Dam (2019), which collapsed by flow liquefaction.

Following the first approach using grain-size distribution curves, the evaluation of Atterberg Limits was done according to Perlea et al. (1999), Andrews & Martin (2000), Seed et al. (2003), and Bray & Sancio (2006). In these methods, the authors associate the Atterberg Limits with the fines content and moisture content to evaluate the susceptibility to cyclic liquefaction.

The CPTu test was used by applying the methodologies proposed by Robertson (2016) and Shuttle & Cunning (2008). 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. The author suggested the use of the contour CD = 70 to differentiate soils that are contractive and dilative at large strains. The CD = 70 boundary combines two criteria: i) Qtn,cs = 70 for sand-like soils, and ii) OCR = 4 for transitional and clay-like soils.

Shuttle and Cunning (2007) conducted a detailed study using the NorSand Model and the concept of cavity expansion to evaluate the liquefaction potential of very loose silt tailings (Rose Creek silt tailings). Later, the authors (Shuttle & Cunning, 2008) presented a contour to distinguish contractive from dilative behavior using the soil behavior chart suggested by Jefferies and Davies (1991).

For clay-like tailings with low permeability, it is possible to verify the magnitude of the strength loss using the Vane Shear Tests. Two parameters can be used for that purpose: i) the sensitivity (St = Su,undisturbed / Su,remolded), where Su,undisturbed is the peak undrained strength obtained in the first rotation of the blade, and Su,remolded is the remolded shear strength of the soil, and ii) the Brittleness Index [IB = (Su,peak - Su,residual)/ Su,peak]. Skempton & Northey (1952) suggested ranges of classifications in which St > 4.0 is associated with sensitive clays. Robertson (2017) suggested that the soil exhibiting post-peak strength loss greater than 40% (IB > 0.4) can be considered highly brittle, based on an analysis of high-quality case histories where flow failure occurred.

The post-peak strength loss and brittleness can also be evaluated with triaxial tests. In this paper, a series of undrained triaxial compression tests were evaluated using the chart proposed by the ICOLD Bulletin 194 (ICOLD, 2022). Figure 1 summarizes the methodologies used to evaluate the susceptibility of the bauxite tailings to flow liquefaction.

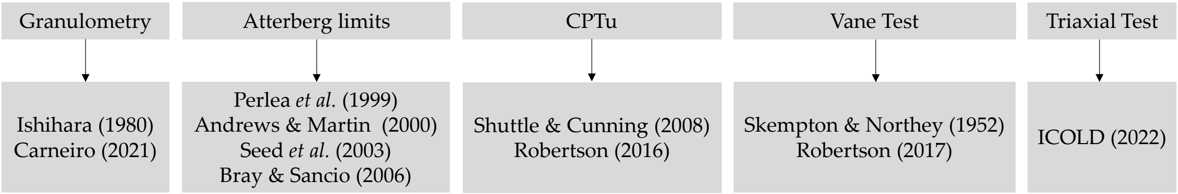


**Figure 1** Flowchart with methodologies and tests used

## RESULTS AND DISCUSSION

This section will present the results of the geotechnical characterization of the tailings studied herein and its flow liquefaction susceptibility analysis.

### Geotechnical Characterization

The grain-size distribution curves (ASTM D422) obtained from disturbed samples collected near the CPTu and Vane Shear Tests performed are indicated in Figure 2. The tailings composition is, on average, 70.0% clay-sized particles, 26.9% of silt, 2.7% of sand and 0.4% of gravel. According to ABNT NBR 6457, the tailings show an average natural moisture content of 53.1%. The Atterberg Limits were determined according to ABNT NBR 6459 and ABNT NBR 7180. On average, the samples indicated a liquid limit (LL) of 48.7% and a plastic limit (LP) of 29.9% (plasticity index of 18.8%). The average value of the specific gravity of soil solids ($G_S$) was 2.7.

Using the grain size distribution curves and the Atterberg Limits, the samples were classified according to the Unified Soil Classification System (USCS – ASTM D2487). Three samples were classified as fat clay (CH), one as lean clay (CL), and the other five as silt (ML).

## Evaluation

### *Grain Size Distribution Curves*

Regarding the liquefaction susceptibility evaluation, the grain-size distribution curves did not fit the ranges proposed by Ishihara et al. (1980) and Carneiro (2021). The samples are predominantly composed of fine soils (passing the #200 sieve) and only those with more silt-size grains partially fitted the ranges proposed by the authors.

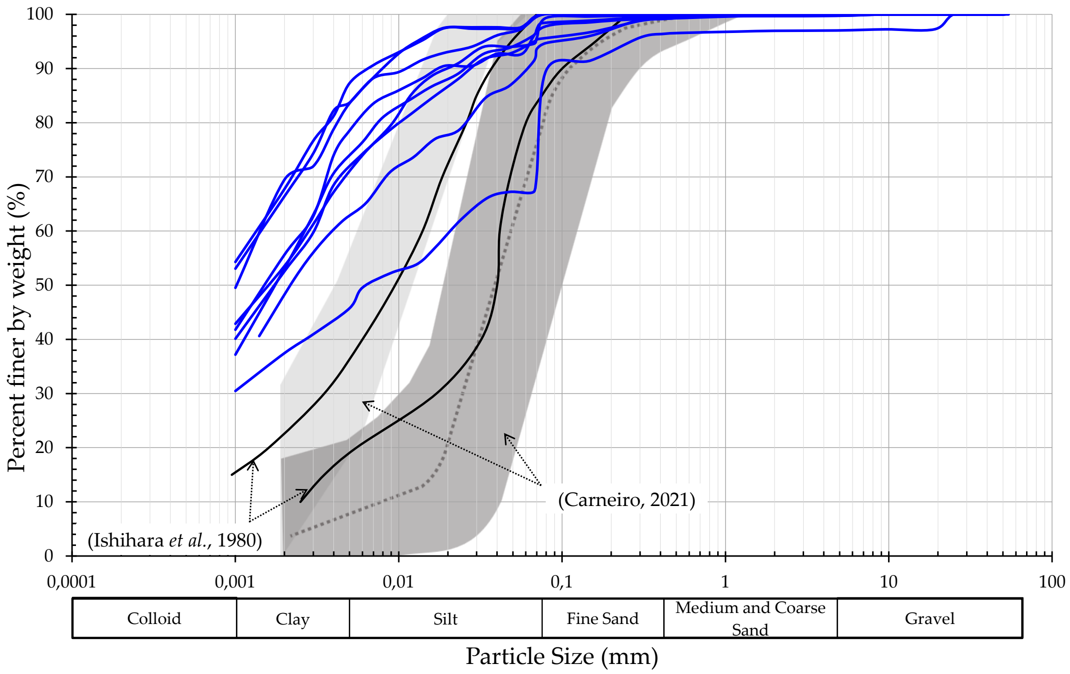


**Figure 2** Grain size distribution curves (ASTM D422)

### *Atterberg Limits*

The analyses based on Atterberg Limits, Figure 3, indicated that the samples are not susceptible to cyclic liquefaction using the charts proposed by Perlea et al. (1999), Andrews & Martin (2000) and Seed et al. (2003). Using the chart proposed by Bray & Sancio (2006), only one sample was classified as susceptible to cyclic liquefaction. It is noteworthy mentioning that these methodologies are initial screening tools to evaluate the phenomenon and they alone are not enough to determine whether the tailings under evaluation present a strain-softening behavior in undrained shear. Additionally, the authors recognize that the methodologies presented in the literature based on Atterberg Limits were developed to evaluate the susceptibility of the soils to cyclic liquefaction and, therefore, are only used as a guide in the evaluation of the susceptibility to flow liquefaction.

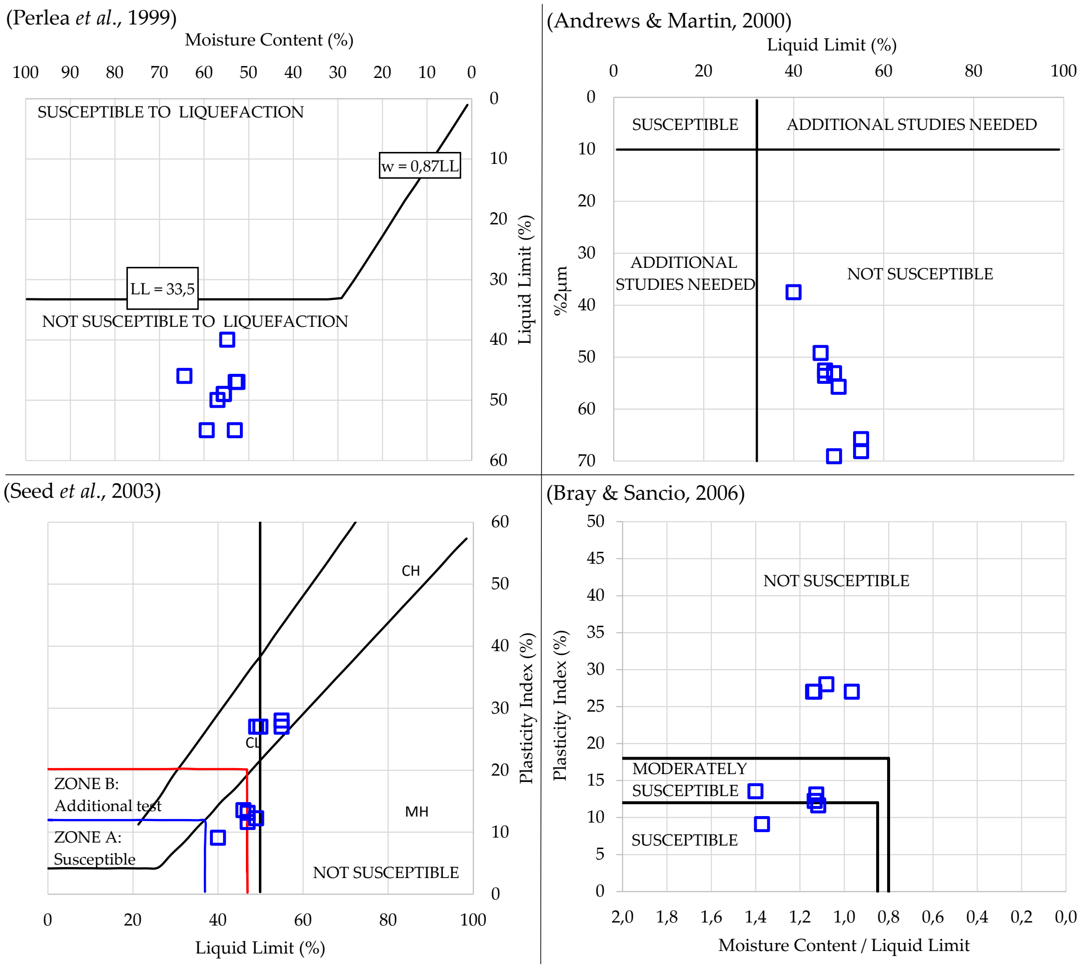


**Figure 3** Atterberg Limits based methods

## *CPTu*

The CPTu test results plotted on the charts proposed by Robertson (2016) and Shuttle & Cunning (2008), Figure 4, indicated a predominant contractive clay-like behavior for both methodologies. Some data points were in the region of sensitive clay-like behavior due to the small values of sleeve friction resistance (fs). However, according to McConnell & Wassenaar (2022), these tiny values of sleeve friction generate errors in the classification chats due to the precision of the CPTu to measure the sleeve friction in very soft soils.

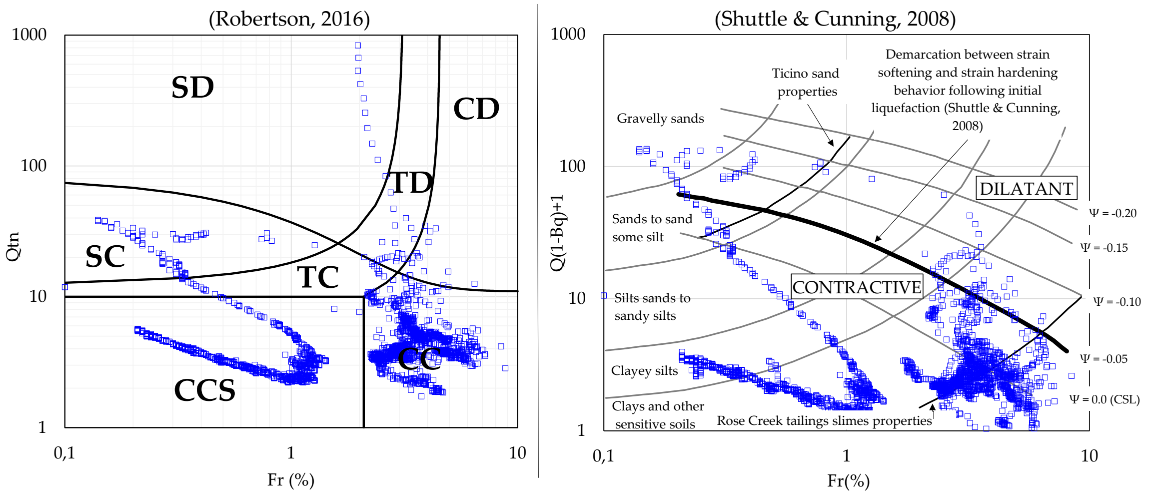
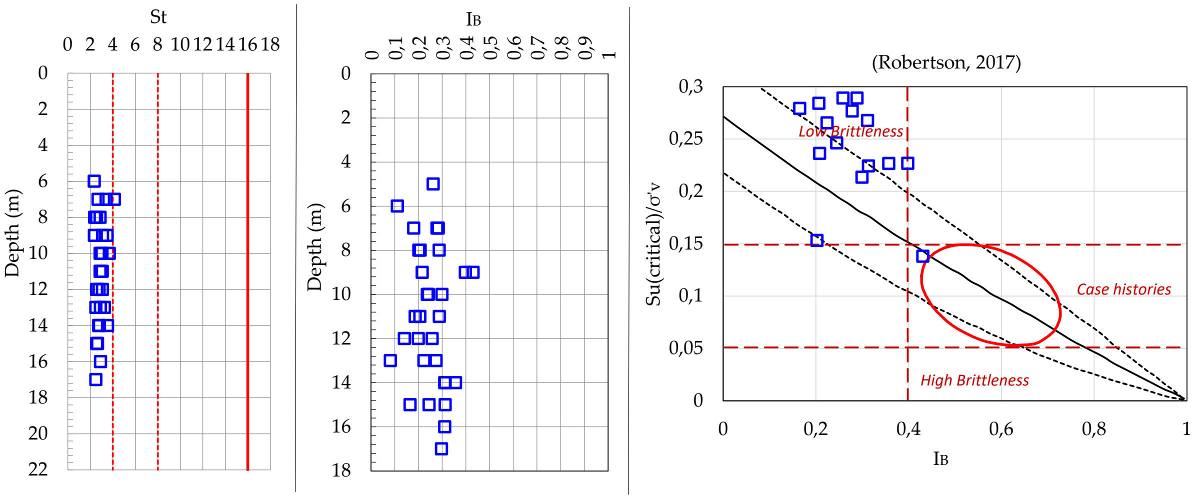


**Figure 4** Evaluation of the contractive behavior of the tailings using the CPTu tests

### *Vane Shear Test*

The sensitivity and brittleness indexes resulting from the Vane Shear Test were plotted against depth in Figure 5, which also presents the chart proposed by Robertson (2017). Most of the results indicated a clay of medium sensibility, 2< St < 4 (Skempton & Northey, 1952), and low brittleness (Robertson, 2017), IB < 0.4.



(a) (b) (c)

**Figure 5** Vane Shear Test results: (a) Sensitivity; (b) Brittleness Index; (c) Ranges of brittleness proposed by Robertson (2017)

### *Triaxial Compression Test*

The undrained triaxial compression test results showed that the material did not indicate an abrupt strength loss during shear (strain softening). Most curves were plotted on the generally non-brittle area (IB < 0.2) proposed by ICOLD Bulletin 194 (ICOLD, 2022). Just two samples indicated a moderately brittle behavior at an axial strain higher than 12%, which can be associated with the low quality of the test results at high strain rates due to the restriction of the used equipment. Therefore, the material did not show a high brittleness index (IB > 0.4) to indicate a susceptibility to flow liquefaction, considering the tests performed with confining pressures between 50 kPa to 200 kPa.

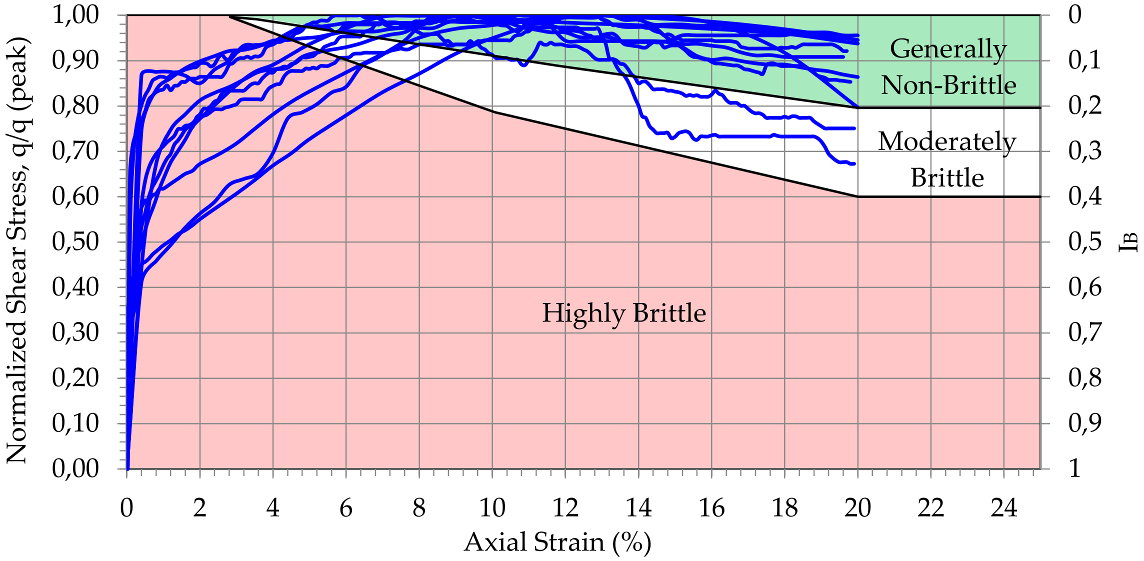


Figure 6 Undrained triaxial compression tests plotted on the boundaries proposed by the ICOLD Bulletin 194 (ICOLD, 2022)

## CONCLUSION

This paper presented a case study focusing on the evaluation of the susceptibility of a bauxite tailings to flow liquefaction. The geotechnical characterization of the tailings was conducted by determining i) its grain-size distribution curves, ii) water contents, iii) Atterberg Limits, and iv) the specific gravity of soil solids (Gs). The classification of the tailings using the Unified Soil Classification System (ASTM D2487) indicated that the tailings are predominantly classified as clay and silt.

The susceptibility of the tailings to flow liquefaction was conducted by the evaluation of i) grain-size distributions curves, ii) Atterberg Limits, iii) CPTu tests, iv) Vane Shear Tests, and v) Triaxial Compression tests. The results showed that none of the grain-size distribution curves of the tailings analyzed fitted the susceptibility limits proposed by Ishihara et al. (1980) and Carneiro (2021). Just one sample was classified as susceptible to cyclic liquefaction using the Atterberg Limits, according to Bray & Sancio (2006). The CPTu tests indicated contractive behavior using the chart proposed by Robertson (2016) and Shuttle & Cunning (2008). The Vane Shear Tests indicated a loss of strength, but not to the range of high brittleness. Finally, the triaxial compression tests showed moderate strain softening without brittle behavior.

The evaluation of the susceptibility to flow liquefaction requires a range of tests to identify all the aspects necessary for the phenomenon to occur: i) contractive state, ii) strain-softening in undrained shear, and iv) high brittleness. As described by Robertson (2017), "not all contractive soils are strain-softening, and not all soils that are strain-softening have high brittleness".

## ACKNOWLEDGEMENTS

The authors thank Pimenta de Ávila Consultoria for providing the data and encouraging the academic production of practical applications.

## NOMENCLATURE

| | |
|---|---|
| Fr | normalized friction ratio |
| fs | sleeve friction resistance |
| $G_S$ | specific gravity of soil solids |
| $I_B$ | Brittleness Index |
| OCR | overconsolidation ratio |
| Qtn | normalized cone resistance |
| Qtn,cs | normalized clean sand equivalent |
| q | deviator stress |
| Su | undrained shear strength |
| St | sensitivity |
| w | moisture content |
| Ψ | state parameter |

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