On the Characterization and Classification of Bauxite Tailings

F. Schnaid, H.P. Nierwinski, J. Bedin, E. Odebrecht

Abstract. Large-scale mining operations generate vast quantities of tailings that are deposited in hydraulic-fill tailing dams in the form of slurries. Stability of these impoundments require investigation of water table configuration, aquifer boundaries, site characterization and determination of short and long term properties of tailings. These aspects are evaluated in this paper from a comprehensive site investigation that comprises both laboratory and field tests from a bauxite tailing deposit in northern Brazil. The purpose is to enhance the understanding on the mechanical properties of bauxite tailings in order to select or develop appropriate constitutive models for predicting the behavior of tailings impoundments. Attention is given to the characterization and classification of silt tailings from the combination of measurements from independent tests expressed on the basis of the ratio of the elastic stiffness to penetration tip resistance.

Keywords: bauxite tailings, critical state, piezocone, liquefaction.

1. Introduction

Many countries with large mining industry operations are active in implementing effective environmental legislation to ensure sustainable development with minimum ecosystem degradation. Tailing storage facilities is one subject of major concern, given the potential environmental impact in discharge areas. The most popular type of embankment for tailings dams is the upstream construction where new parts of the embankment are built on top of the slurries impounded during the previous stage (i.e. the dam crest moves “upstream” during construction). Although this is a low cost process, the upstream embankment type is a high risk operation, particularly because (a) upstream dams are particularly susceptible to liquefaction under seismic ground motion and (b) dam stability is endangered if the raising rate of the dam is high due to excess pore pressure built within the deposit during construction. Since tailings have different properties compared to natural materials and the way of testing tailings material need to be calibrated for these differences, there is a need for field and laboratory studies of physico-mechanical characteristics of tailing dam deposits.

Recent research projects in Brazil comprise comprehensive in situ (CPTU, DMT, Vane) and laboratory characterization (triaxial and oedometer) in active iron ore, gold, bauxite and zinc residue storages. This includes a decade of consecutive site investigation research all over Brazil, providing an opportunity to examine the state of tailings from the beginning of operations to closure (e.g. Schnaid, 2005; Bedin et al., 2008; 2012; Schnaid et al., 2013). This paper explores some features of this study with focus on fundamental aspects of behavior, as well as the characterization and classification of bauxite tailings in storage facilities.

2. Laboratory Testing Program

An extensive laboratory testing program has been carried out to study the geotechnical properties and behavior of gold, bauxite and zinc (e.g. Bedin et al., 2012; Schnaid et al., 2013). Some characteristic features are common to all silty tailings and are highlighted here from tests carried out on bauxite. Characterization comprises identification of minerals, grain size distribution and microscopy (Table 1). The material disposed in ponds is predominantly low to non-plastic, silty clay (typically 80% silt, 15% clay and 5% sand) with an average unit weight of 16 kN/m$^3$ and high specific gravity (2.70 $< G < 3.00$) reflecting the high iron content of the tailings. Microscopy reveals well-rounded as well as angular grains, forming loosely arranged structure that due to angularity may result in relatively high drained shear strength.

Undisturbed samples in silts are typically too difficult or costly to obtain and, for this reason, reconstituted samples need to be prepared for laboratory testing. Disturbed samples were retrieved using a bucket type of sampler which allows samples to be extracted without losing water. The moist tamping method has been used to reconstitute specimens at their average in situ density. Samples were prepared by mixing the soil with small amount of water and compacting the mixture in a mold, in layers prepared of equal volume lifts to produce homogeneous mixtures (e.g. Lade, 1978). The mixture is partially saturated when placed and the inter-particle suction is utilized to allow high voids ratio to be achieved.

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One dimensional compression and hydraulic conductivity tests have been carried out in specimens reconstituted at different void ratios, ranging from 2.6 to 1.4, which covers the maximum and minimum determined in situ values. The vertical effective stress-void ratio relationship presented in Fig. 1 gives a description of the soil compressibility. The vertical stresses were not sufficiently high to identify the normal compression line (NCL), and an attempt to fit a straight line to points measured at high stresses give a slope $c_{10}$ equal to $0.093$ to an initial void ratio of $1.7$.

The hydraulic conductivity has been determined by constant head tests carried out in the oedometer cells at different vertical stresses. An average value of $2 \times 10^{-8}$ m/s was taken as representative.

Undrained triaxial tests were performed to evaluate the stress-strain-pore pressure response of bauxite tailings. Saturation of soil specimens was accomplished by application of a back pressure of around $500$ kPa to produce $B$ values higher than $95\%$. All reported test specimens were isotropically consolidated from a single initial void ratio to their desired consolidation pressure before shearing at $0.1$ mm/min under undrained conditions. Results on saturated samples are presented in Fig. 2, in which deviatoric stress ($\sigma_1 - \sigma_3$) and pore pressures are plotted against axial strains. Tests generate considerable excess pore pressure and gentle strain softening. Fifteen percent maximum axial strain was sufficient to establish critical state conditions in these undrained tests, as shown in Fig. 2 using the Cambridge $(p' - q)$ and $(e - \ln p')$ planes. The isotropic and oedometric compression lines are presented in the same diagram for reference. Results show the idealized behavior of a unique critical state line (CSL) described by parallel ICL and CSL (despite the fact that NCL and ICL do not produce a match) The shear strength properties were zero cohesion and effective angle of internal friction angle typically of $36^\circ$, and the state parameter of the order of $0.08$.

### 3. Field characterization

Field tests are the preferable alternative to assess tailing properties and hydrogeologic conditions within the impoundment. In situ water content, unit weight and specific gravity in this bauxite tailings are shown in Fig. 3. Typical profiles from a series of SCPTU are shown in Fig. 4. Measured cone resistance $q_c$, sleeve friction $f_s$ and pore pressure $u$ are plotted against depth revealing a relatively homogeneous profile down to about $16$ m. Although the piezocone tests were conducted about $10$ m away from each other, two profiles revealed lenses of granular materials that are not taken into consideration in the forgoing analysis.

![Figure 1 - Results from oedometer tests.](image-url)
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**Figure 2** - Bauxite critical state conditions.

**Figure 3** - *In situ* water content, unit weight and specific gravity in the bauxite tailing dam.
wave velocity measurements show monotonic increase with depth and yield shear modulus in the range of 20 to 50 MPa.

Values of the pore pressure parameter $B_q$ range from 0.5 to 0.8 indicating undrained paths during cone penetration. High $B_q$ is consistent with the measured hydraulic conductivity values and the contractive response in shear.

In these site investigations, close attention has been given to a precise determination of the position of the water table at the time of the investigation programme, which changes with time in these recently deposited, under consolidation slurries placed over a pervious free drained deposit foundation. This is achieved by a close inspection of a series of dissipation tests obtained by recording the values of the pore water pressure with time during a pause in pushing and whilst the cone penetrometer is held stationary. Although dissipation tests are often held for the time that takes for 50% consolidation, $t_{50}$, in tailings a special recommendation is made to hold the penetrometer stationary for longer periods corresponding to a time interval between $t_{90}$ to $t_{100}$.

Values of $c_s$ and $c_v$ can be also estimated from these dissipation tests following the analysis proposed by Houlsby & Teh (1988). A summary of values obtained in the alumina STF is summarized in Fig. 5. Although values of $c_v$ range between $2 \times 10^4$ and $8 \times 10^4$ cm/s, there is no distinct variation trend with depth. An average $c_s$ value of about $8 \times 10^5$ is representative of this alumina tailing deposit.

4. Classification

Several attempts have been made to combine the piezocone measurements in order to produce classification charts designed to describe soil type for engineering applications (Douglas & Olsen, 1981; Senneset & Janbu, 1985; Robertson et al., 1986; Robertson, 1990; Jefferies & Davies, 1991). Published CPTU soil classification charts are typically constructed from dimensionless ratios such as $Q_t (=(q_t - \sigma_v)/\sigma_v)$, $B_q (=\left(u - u_o\right)/(q_t - \sigma_v))$ and $F_r (=f/q_t - \sigma_v) \times 100\%$). The original chart by Robertson (1990) produces very scattered data with soil ranging from sandy-silt to clay (Fig. 6).

The normalized soil behavior index $I_c$ proposed by Robertson (1990) is shown in the Fig. 7 and characterizes silty-sand and sandy-silt soils ($1.90 < I_c < 2.82$).

An alternative relationship uses the ratio of the elastic stiffness to penetration tip resistance ($G/q_c$), following the concept that a material that is stiffer in deformation may be stronger in strength. An approach developed by Robertson (2010) correlating $G/q_c$ and $Q_t$ is shown in Fig. 8. In addition CPT data can be expressed in the unified plot proposed by Shuttle & Cunning (2007) using the $Q_t(1 - B_q) + 1$ vs. $F$ space (Fig. 9), where strain softening is a predominantly response.

A similar plot has been suggested by Schnaid et al. (2004) and Schnaid (2005) in which the the $G/q_c$ ratio is related to the normalized dimensionless parameter $q_{cr}$, defined as:

$$q_{cr} = \left(\frac{q_c}{\sigma_v} \right) \left(\frac{p_a}{\sigma_v}\right)$$  \hspace{1cm} (1)$$

where $p_a$ is the atmospheric pressure. Results shown in Fig. 10 define a specific region in the $G/q_c$ vs. $q_{cr}$ space that falls outside, above and to the left of the region established for sand. Independent sets of data from gold and zinc high
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**Figure 5** - Values of coefficient of consolidation.

**Figure 6** - Classification of bauxite tailings on the chart proposed by Robertson (1990).
plasticity slurries have been added to the same plot, falling on the very same region established for bauxite tailings. The classification method was then considered to provide an adequate representation of the fines influence by grouping all materials in a single area that appears to be representative of compressible materials that may exhibit strong strain softening (e.g. Schnaid et al., 2013). This evidence is in accordance to laboratory observations.

5. Conclusion

The purpose of this paper is to study the mechanical properties of bauxite tailings and to evaluate how the current site investigation practice is able to identify factors related to tailing response and to stability problems of impoundments. The hydraulic conductivity of tailings varies from point to point in a deposit and, for the present study, a location representative of fine, non-plastic, silt tailings has been selected. Laboratory tests were carried out on reconstituted samples leading to measured coefficient of hydraulic conductivity of the order of $2 \times 10^{-8}$ m/s, zero cohesion, friction angle of 36° and state parameter of 0.08. Drained shear strength is often higher than that for similar natural soils due to high particle angularity.

The piezocone test is the most popular technique used to characterize tailing impoundments and it successfully delineated the stratigraphy of bauxite. Predominantly undrained penetration enabled strength and stiffness to be assessed with reasonable accuracy. The coefficient of consolidation of bauxite slurries is in the range shown by

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Figure 7 - Normalized soil behavior index $I_0$ of bauxite tailings proposed by Robertson (1990).

Figure 8 - Classification of bauxite tailings on the chart proposed by Robertson and Fear (1995).

Figure 9 - Unified classification chart (Shuttle & Cunning (2007 & 2008)).
natural clays. Undrained strength of these slurries is important in evaluation of liquefaction behaviour.

Finally the usefulness of the $G_o/q_c$ ratio in tailings classification is highlighted, because combination of elastic stiffness to ultimate strength provides direct means to identify deposits that are highly compressible and may be susceptible to liquefaction.

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References


