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PIEZOCONE IN SILTY TAILING MATERIALS

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Abstract: Countries with large mining industry operations face serious environmental risks resulting from large-scale mining activities. Although there has been a significant improvement in the design and management of tailings storage facilities, there are still major economic and technical constraints that cause important environmental impact in discharge areas. From a technical perspective, investigations of water table configuration, aquifer boundaries, site characterization and determination of short- and long-term properties of tailings materials are important requirements for engineering of tailings. These aspects are evaluated in this paper from the results of piezocone tests, with focus on aspects regarding segregation, shear strength and consolidation properties of gold and alumina mining tailings. Attention is given to identification of essential features that link the rate of cone penetration to drainage effects, which is achieved by expressing the results in a space that correlates a dimensionless velocity V with the degree of drainage U. In this space, partial drainage is identified and the risk of overestimating properties assessed from field tests is avoided.

1. INTRODUCTION

In the past three decades, governments have been concerned about implementing an effective anti-pollution legislation and about ensuring sustainable development without environmental degradation. Focus has been placed on operation, closure and remediation of mine sites and tailings storage facilities (TSFs) in order to prevent environmental contamination by toxic waters, acidic leachate and leaching of metals and heavy metals from the TSF and to ensure that the site is safe when the mine is closed down.

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 a previous stage (i.e., the dam crest moves “upstream” during construction). Although this is a low-cost process, the building of an upstream embankment is a high-risk operation, particularly because (a) upstream dams are particularly susceptible to liquefaction caused by seismic ground motion and (b) dam stability is endangered if the rising rate of the dam is high due to excess pore pressure built up 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 the field and laboratory studies of physico-mechanical characteristics of tailings dam deposits.

Recent research projects in Brazil allowed in situ tests (vane shear and CPTU) and laboratory tests (triaxial and oedometer) to be carried out in active iron ore, gold and alumina residue storages. This includes a four-year consecutive site investigation of an alumina storage in northern Brazil that provided an opportunity to examine the state of tailings from the beginning of operations to closure. Details are reported in MSc and PhD thesis (BEDIN [1] and VILLAR [15]), international publications (e.g., SCHNAID [11]; Schnaid et al. [12]).

This paper explores one aspect of this study: the use of piezocone tests applied to (a) the characterization of tailings materials in storage facilities, (b) evaluation of segregation that results from discharge process, (c) assessment of material properties and (d) identification of drainage conditions.

2. BACKGROUND

Several publications provide comprehensive reviews on the technical details related to site characterization, design, performance, evaluation of geotechnical parameters, environmental impact and risk of mined areas, tailing dams and other waste storage facilities (e.g., MARTIN and MCROBERTS [6], DAVIES and MARTIN [2], FAHEY et al. [3]).

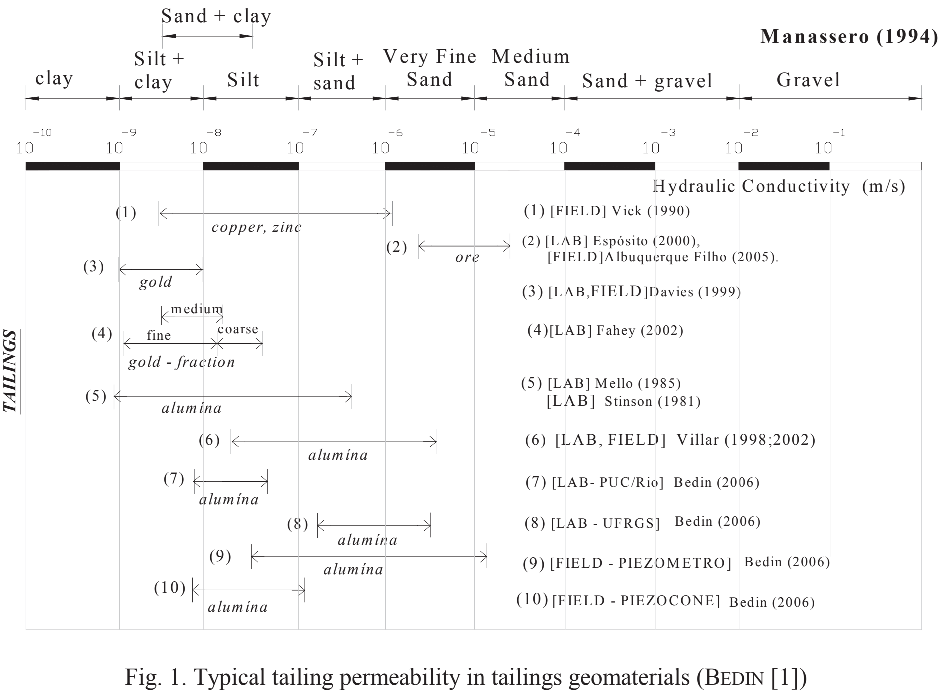

Fig. 1. Typical tailing permeability in tailings geomaterials (BEDIN [1])

A characteristic feature of tailings soils is their spatial variability, producing tailings in the so-called intermediate permeability range from 10^{-5} to 10^{-8} m/s. As illustrated in figure 1, this range covers a variety of materials from TSF operations. Unfortunately, there are no standardized recommendations to guide engineers on how to perform in situ tests or interpret test results in these materials. Since numerical assessment is restricted to the consolidation characteristics of clays, recommendations accepted for intermediate soils are empirical and are based on field observations (e.g., MCNEILAN and BUGNO [7], SENNESET et al. [13], HIGHT et al. [4]). This paper explores the ideas from recent studies in clay and silt soils and describes a method designed to recognize consolidation patterns that may take place during penetration.

3. SOIL CHARACTERIZATION

CPT soundings and pore pressure dissipation tests are the preferable tools for assessing tailings properties and hydrogeologic conditions within the impoundment. Parameters measured during cone penetration are as follows: cone resistance q_c, sleeve friction f_s and pore pressure u, from which soil stratigraphy, spatial variability and soil segregation of store facilities can be evaluated.

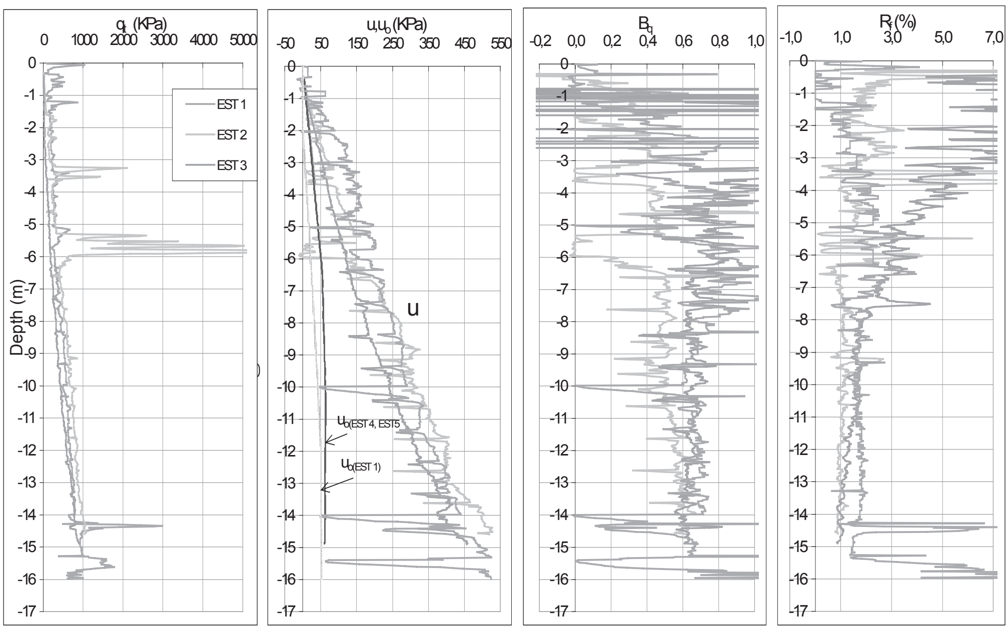

Fig. 2. Typical CPT profiles in alumina tailings deposit

The profiling capability of the piezocone is demonstrated in figures 2 and 3, which show a series of typical CPT profiles representative of alumina and gold deposits, respectively. The differences in the waste characteristics (ore type, mine processing, mineralogy) as well as the placement process during disposal tend to affect the geomechanical behaviour of tailings and produce a highly stratified and layered profile. In the alumina area, the values of the pore pressure parameter B_q range from 0.5 to 0.8, indicating undrained paths during cone penetration. Tests carried out in the gold impoundment produced B_q values ranging from 0.1 to 0.5, a range in which partial drainage is likely to occur.

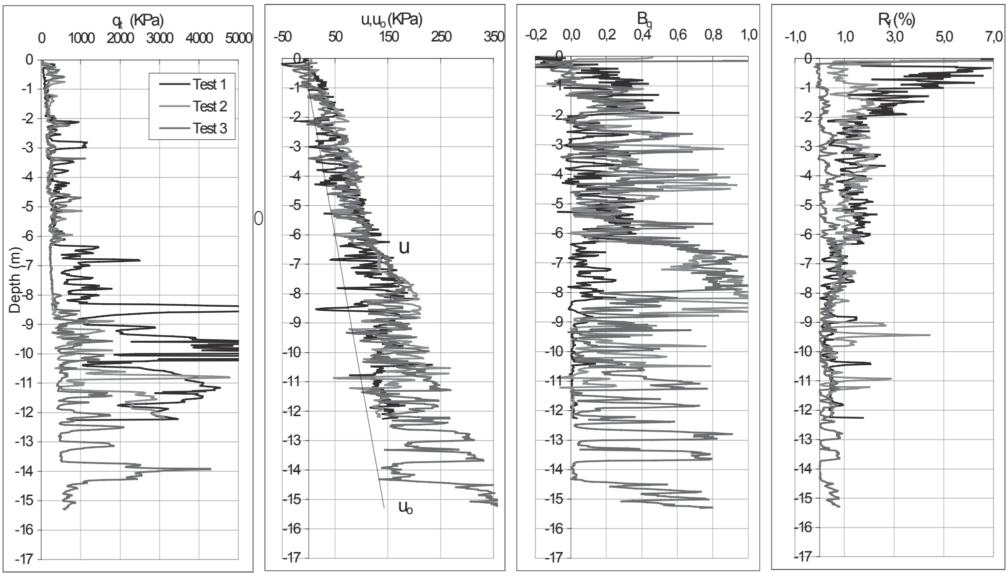

Fig. 3. Typical CPT profiles in gold tailings deposit

In the site investigation, close attention has been given to a precise determination of the actual position of the water table in slurries which due to consolidation had been deposited over perviously free drained foundation. This is achieved by a close inspection of a series of dissipation tests carried out 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}, as illustrated in figure 4.

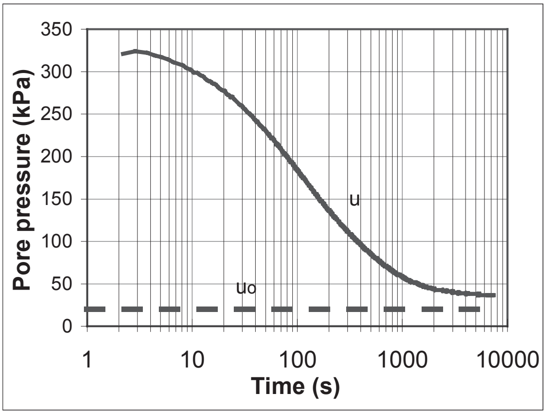

Fig. 4. Typical dissipation test in tailings geomaterial

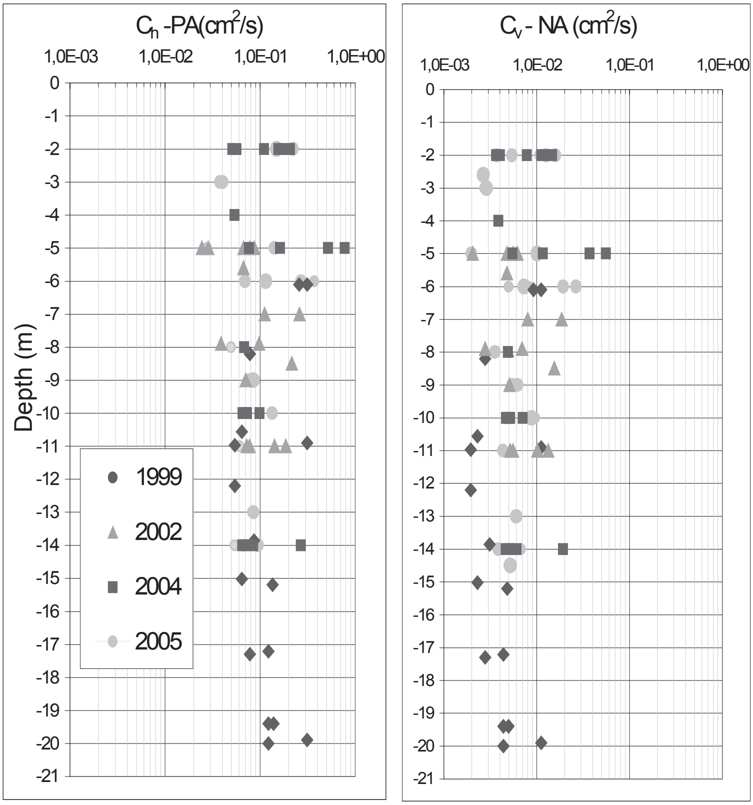

Fig. 5. Coefficient of consolidation in alumina tailings deposit

In addition, the values of C_h and C_v can also be estimated from these dissipation tests following the analysis proposed by HOULSBY and TEH [5]. A summary of the values obtained in the alumina STF is given in figure 5. Although the values of C_h range between 2×10^{-2} and 8×10^{-1} cm^2/s, there is no distinct variation trend with depth. An average C_h value of about 8×10^{-2} is representative of this alumina tailings deposit.

4. SEGREGATION

Segregation is an important factor to be considered in the characterization of tailings. Construction of upstream or downstream embankment starts with a starter dyke. Tailings are usually discharged from the top of the starter dam crest either by cycloning or by creating a beach that becomes the foundation for future embankment rise (VICK [14]). Natural segregation occurs with the coarse fraction of the material settling closest to the spigot and the fines furthest away. Multiple spigot discharge produces a series of coarser areas in the vicinity of the point of discharge that exhibit higher shear resistance and higher permeability than finer materials that sediment in

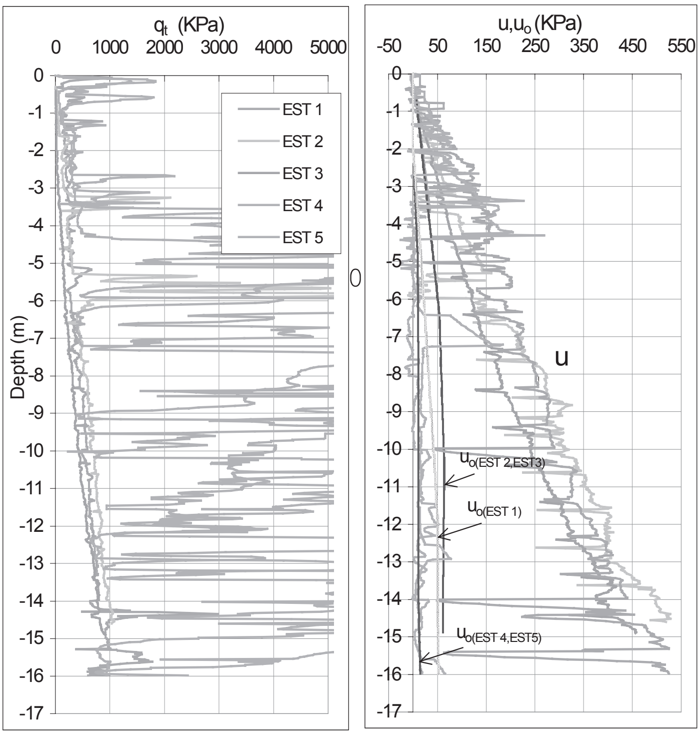

Fig. 6. Characteristic segregation in alumina tailings storage facility

the surrounding areas. The same occurs if central discharge towers are used. This effect is illustrated in figure 6, in which it is possible to observe the nature of coarser material in the zone around the discharge point, characterized by drainage penetration (B_q~0), in contrast to the finer materials in other areas that induced larger B_q values during penetration. Stability analysis strongly depends on proper assessment of particle segregation in tailings storage facilities given the impact of the segregation process on both shear strength and permeability.

5. DRAINAGE CONDITIONS

Tailings deposits typically have intermediate permeability and moderate rate of consolidation that affect short- and long-term stability analysis. For intermediately permeable

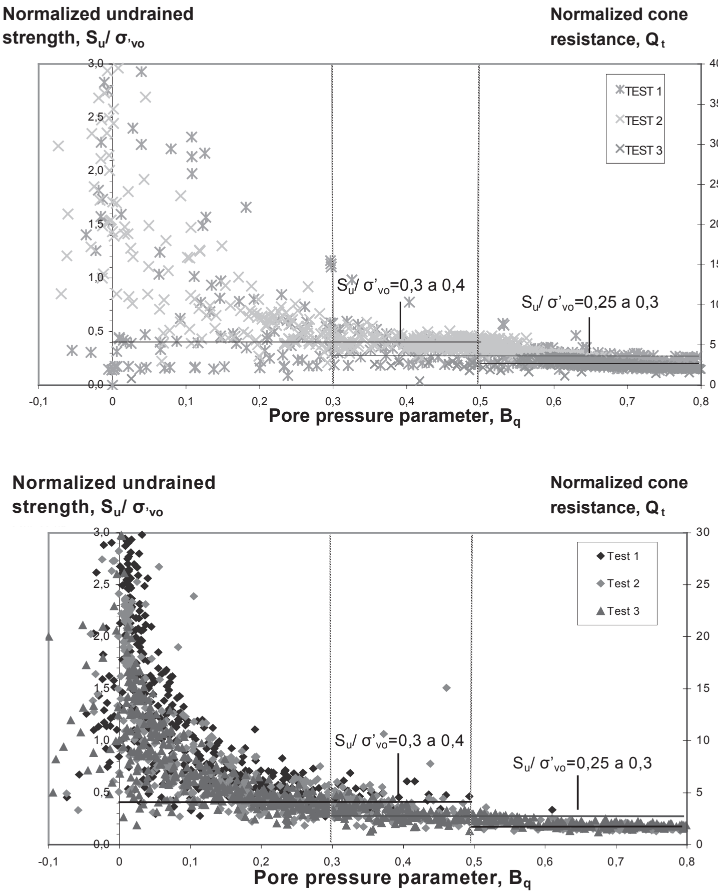

Fig. 7. Drainage conditions on a silt gold tailings

tailings geomaterials, the simplest idealized approach of a broad distinction between drained (gravels and sand) and undrained (clay) conditions for the interpretation of in situ tests cannot be applicable since test response can be affected by partial consolidation and consequently the existing analytical, numerical or empirical correlations can lead to unrealistic assessment of geotechnical properties (MCNEILAN and BUGNO [7], SENNESET et al. [13], HIGHT et al. [4], RANDOLPH [9], SCHNAID et al. [12], SCHNAID [11].

It is largely accepted that at a standard rate of penetration (20 mm/s), undrained response will occur if the permeability of the soil is less than about 10^{-7} m/s. A simple guideline for evaluating drained conditions during penetration in intermediate soil of permeability between 10^{-9} and 10^{-6} m/s has been suggested by HIGHT et al. [4] and later extended by SCHNAID et al. [12]. These authors propose to explore the relationships between B_q, $(q_t - \sigma_{v0})/\sigma'_{v0}$ and s_u/σ'_{v0}, where σ'_{v0} is the effective overburden pressure. Their analyses suggest that penetration is fully undrained for the values of B_q greater than 0.5. A normally consolidated soil of Cam Clay type should yield a ratio of S_u/σ'_{v0} ranging between 0.25 and 0.30, depending on shearing mode. Deviation from this pattern is related to (a) overconsolidation, (b) partial drainage or (c) a characteristic behaviour of silty soils that does not fully comply with Cam Clay models.

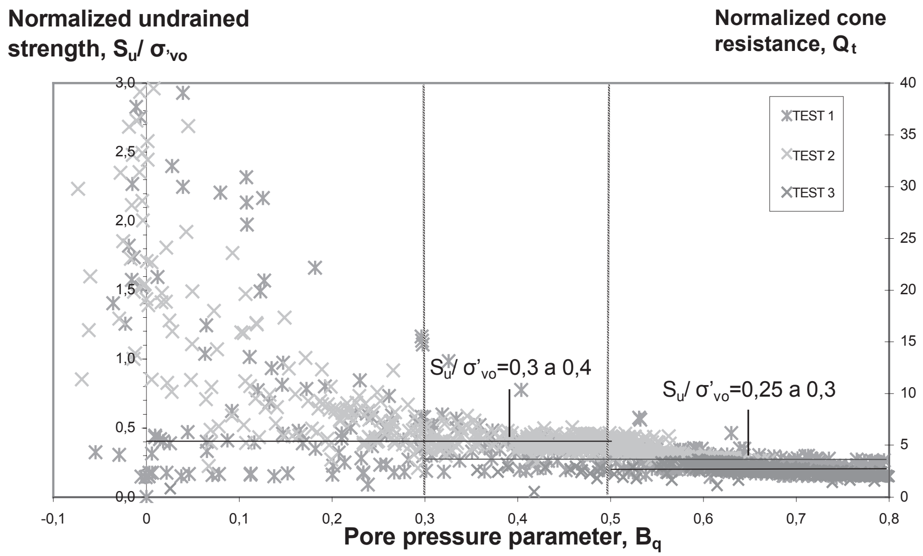

Fig. 8. Drainage conditions on a silt alumina tailings

CPTU data for tailings deposits from gold mines and alumina industry are presented in figures 7 and 8 in terms of the variation of the undrained strength ratio and the normalised cone resistance with the pore pressure parameter B_q. Both deposits are essentially normally consolidated with the value of C_v ranging from 0.01

to 0.2 cm^2/s. A cone factor N_{kt} of 15 was assumed to convert CPT endpoint resistance to undrained strength based on the existing evidence from bauxite residue deposit investigations in Brazil (BEDIN [1]) and as suggested by LUNNE et al. [8]. It is evident that, for both deposits considered, the s_u/σ'_{v0} ratio reduces significantly with increasing the value of B_q, and at the value of B_q equal approximately to 0.5 the *undrained strength ratio* reaches a plateau at a constant value of about 0.25. Since the variations in B_q do not follow any pattern with respect to depth, the changes observed are not related to overconsolidation. For the values of B_q ranging between 0.3 to 0.5, s_u/σ'_{v0} ratio varies within the range of 0.3–0.4 with a tendency to increase slightly with reducing B_q. The calculated values of s_u/σ'_{v0} are consistent with the measured range of ϕ' values, suggesting that the materials under investigation behave essentially as silty soils and that partial drainage is not dominant. B_q equal to 0.3 seems to give a lower boundary below which the undrained strength ratio exhibits considerable scatter and a marked increase to unrealistic values in a normally consolidated deposit. It is then reasonable to consider that partial drainage prevails and that the derived values of undrained shear strength are overestimated, as was already discussed by SCHNAID et al. [12].

An alternative method for the identification of drainage conditions during penetration has been proposed by RANDOLPH [9] and later extended by SCHNAID et al. [12] and BEDIN [1]. In this alternative method, normalisation of penetration results is represented in a space of a non-dimensional parameter V (RANDOLPH and HOPE [10]) versus the degree of drainage U:

$$V = \frac{vd}{C_v} \tag{1}$$

and

$$U = \frac{(q_c - q_{\text{cund}})}{(q_{\text{cdr}} - q_{\text{cund}})}, \tag{2}$$

where:

d – the probe diameter,
v – the penetration rate,
C_v – the coefficient of consolidation,
q_{cund} – the cone resistance under undrained conditions,
q_{cdr} – the cone resistance under drained conditions.

The results in this space are represented by a "drainage characteristic curve" adopted to identify the transition from drained to partially drained or undrained penetration.

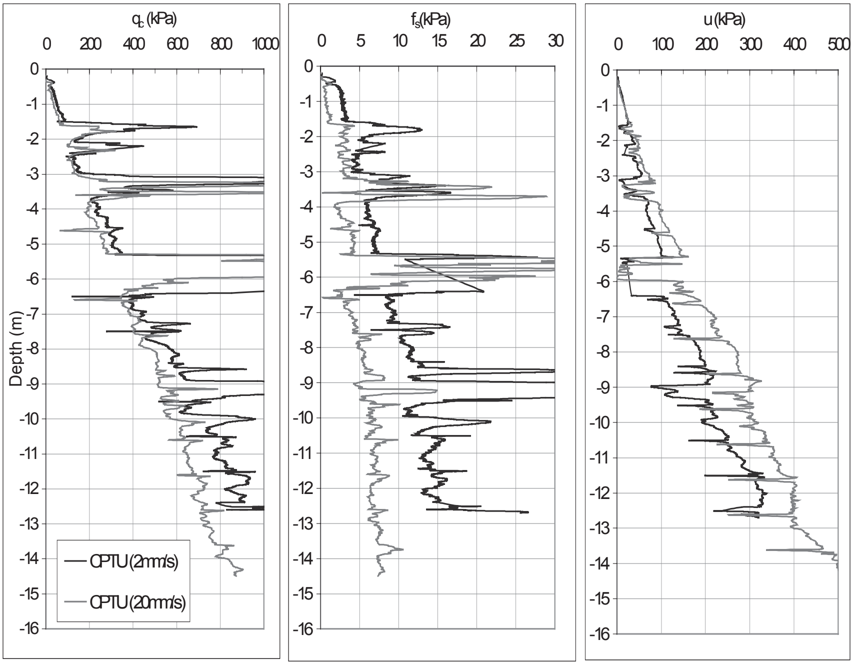

Fig. 9. Influence of penetration ratio on penetration measurementes

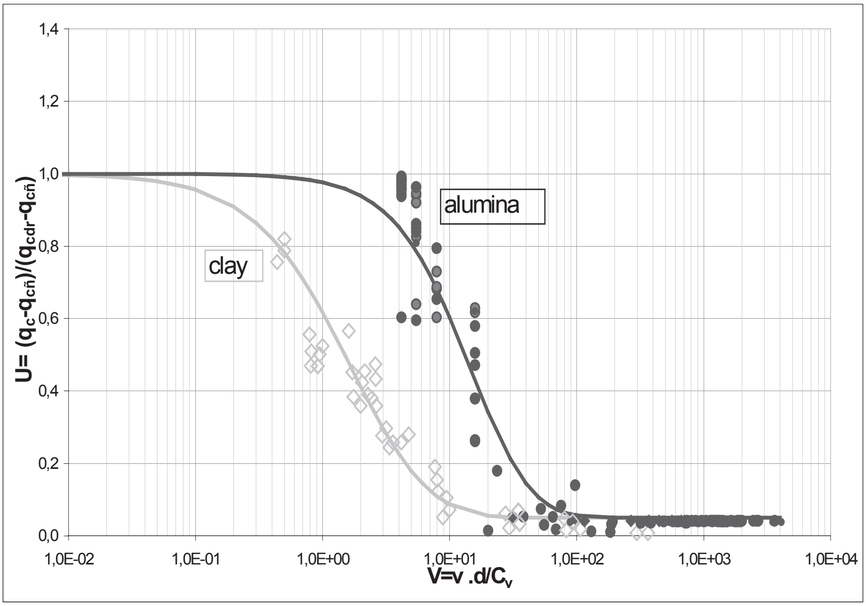

Fig. 10. Non-dimensional velocity V versus degree of drainage U

Studies carried out to evaluate drainage effects in aluminia industry TSF consist in testing two different penetration rates, corresponding to 20 mm/s and 2 mm/s, in different areas within the deposit (i.e., different C_v values). Typical penetration profiles illustrated in figure 9 show a distinct influence of penetration ratio on all penetration measurementes (q_c, f_s and u). Normalised results are presented in figure 10 for two different geomaterials, one representative of a soft kaolin soil (RANDOLPH [9]) and another of alumina industry tailings (BEDIN [1]). There is a clear indication that the so-called "drainage characteristic curve" is not unique, since it changes as a function of material properties. Despite the variations in these drainage characteristic curves, the onset of a fully undrained condition occurs for a normalised velocity V of ca. 100. The transition point from partially drained to drained response starts at a normalised velocity of $V \approx 1$ for the alumina industry tailings and much later for the kaolin ($V \approx 10^{-2}$). A much stiffer transition between drained and undrained penetration is observed in the tailings and it appears that the drainage characterization curve is fairly sensitive to material properties, as previously indicated by SCHNAID [11].

6. CONCLUSIONS

Characterization of tailings is an essential step in the evaluation of geoenvironmental issues during operation, closure and remediation of mine sites. Acknowledging the profiling capability of the piezocone is a general recognition of the usefulness of this test for geotechnical and geoenvironmental applications in tailings storage facilities. In these materials, a reliable evaluation of the mass permeability is a preliminary requirement for interpretation of piezocone tests, assumed to be undertaken under fully drained or fully undrained conditions. Very frequently, tailings geomaterials exhibit coefficients of hydraulic conductivity in the range of transitional soils, a range over which partial drainage is often observed for currently adopted rates of penetration. Implications are that the undrained shear strength derived from penetration tests can be grossly overestimated. Specific recommendations have been made along this paper to evaluate partial drainage from CPTU data in a space of non-dimensional velocity versus degree of drainage.

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