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Using Piezocone Tests for Analysis of Phreatic Water Conditions and Prediction of Soil Behavior in Tailing Dams

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Abstract

In this work the possibility of identifying two important aspects in the process of adopting soil parameters for calculating stability analysis models in tailing dams is discussed. The use of commercial computer programs for stability calculations allows obtaining numerically exact results. Its representativeness, however, will be linked to the correct definition of the phreatic regime and to the prediction of volumetric soil behavior during shearing (contractile vs. dilating materials). The theoretical principles for the selection of soils parameters for different failure models are briefly presented. Also, how the incorrect assumptions regarding material behavior can significantly affect the estimation of tailing dams' stability. The results of CPTu tests for the diagnosis of the phreatic and mechanical condition of the materials are discussed and two examples are presented to remark on the care that should be taken to avoid incorrect soils parameters adoption.

Keywords

CPTu Piezocone, Dissipation Test, Soil Behaviour, Shear Strength, Tailing Dams

1. Introduction

The use of field tests as an alternative to the extraction of samples for laboratory tests on materials whose structure is sensitive to sampling effects, in particular tailing dams, requires a correct characterization of the geotechnical scenario based on the effective stress criterion. Among the different failure mechanisms of mining waste structures, piping, overtopping and slope failures stand out. Recent rupture episodes (Samarco and Brumadinho in Brazil) suggest that the failure was related to undrained events. These historical cases reinforced the idea of the care that must be taken in those materials where shear strength depends not only on the pore pressures that exist before the event, but also on those generated during the rupture. In these materials there is also the difficulty of extracting undisturbed samples (preserving the field void ratio) that allow representative reproduction of undrained stress paths to calibrate advanced constitutive models. In this way, the practical alternative consists of using semi-empirical models from in situ tests such as SPT or CPTu (Been & Jefferies, 2016; Robertson, 1990). The unequivocal definition of the phreatic condition constitutes the second component to establish, both for drained and undrained analyzes. Again, for this purpose, the CPTu tests are an accurate tool to characterize the water flow and bottom drainage performance of these structures (Schnaid, 2009).

2. Estimate of Strength Parameters

In the context of stability analysis, three possible resistance envelopes can be defined for use in the calculation models available in commercial stability programs (Brown & Gillani, 2016), and whose relationship with the results of the CPTu tests requires some discussion.

Unconsolidated Undrained failure: is normally applicable for short term conditions where the added total stress due the construction leading to no change in the effective stress and no increase in shear strength.

Consolidated Undrained failure: is the available strength of a consolidated and sheared material under undrained conditions. From CPTu test results the calculated undrained resistance is normalized to the estimated effective stress level. In this way, in unconsolidated or normally consolidated materials, the pore level reference pressures must be precisely defined. Undrained models incorporated in commercial programs based on limit equilibrium have Su/σ’v relations as alternative input data whose use requires special care in the definition of initial effective stresses.

Drained failure: used to define long-term stability parameters. Care must be taken in those materials that present dilating behavior. This characteristic is also identifiable from CPTu test results. The presence of shallow overconsolidated low permeability soil layers constitutes a situation that requires special care since the undrained shear strength resistance is due to negative pore pressures. In long term condition, the available shear strength could be less than the undrained shear strength once the negative pore pressure was dissipated. The pore pressure measurements recorded during the CPTu tests (lower than the hydrostatic equilibrium values) help in the identification of these conditions.

3. Reference Pore Pressures

The correct estimation of pore pressures is essential in stability analysis. An incorrect estimate of pore pressures can lead to errors in the definition of the effective stresses state and consequently in the available shear strength. In a general case, several pore pressure components are distinguished:

- Pore pressures in situ in permanent conditions (or in dissipation in the case of recent deposits). The configuration can be established by flow analysis, and the values are measurable by instruments such as electrical piezometers, or during dissipation tests to total stabilization in CPTu tests.
- Pore pressures generated by overload variations in low permeability saturated materials. Also measurable through instruments such as electrical piezometers or dissipation tests in CPTu tests.
- Pore pressures generated by shear stresses in saturated materials. They are due to the tendencies to volumetric variations induced by shear stresses. They can be positive, in contractile materials (typical of mining waste) or negative, in the case of dilating materials. They cannot be measured directly in the field, only laboratory like during CIU triaxial tests. Special care must be taken in calculation scenarios involving undrained resistance in expanding materials. Classification methods (Robertson, 2012) allow the identification of soil layers that exhibit contractile or dilating tendencies. In the research programs that incorporate CPTu tests, dissipation tests are commonly specified to estimate consolidation properties of clay or silt layers. In mining waste, total pore-pressure equalization is achieved in times typically less than 60 minutes, allowing the piezometric situation to be defined without adding special conditions for the total duration of tests in conventional campaigns. The existence of some sandy layers in the profile is also highly advantageous in defining the hydrostatic regime as well as verifying the bottom drainage operation, typically used in tailing dams (Robertson & Campanella, 1983).

It's important to remark that a great advantage of using CPTu tests in mining waste deposits is the possibility of planning geotechnical investigation programs with dissipation tests that equalize 100% of the excess pore pressures generated during driving. The permeability of these materials in general allows these tests to be carried out without additional costs. This situation is different in clayey soils, where engineering practice is to carry out dissipation tests that reach only 50%, because the low permeability of these materials leads to longer test times that are impractical and very expensive.

4. Soil Behavior Prediction from CPTu Test Results

Robertson (1990) established normalized variables of the data measured during the CPTu test (q_t, f_s) from the effective stresses state in situ pre insertion (σ_{vo}, σ'_{vo}).

$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \tag{1}$$

$$F_r = \frac{f_s}{q_t - \sigma_{vo}} 100\% \tag{2}$$

Robertson & Wride (1998) proposed preliminary definitions of the behavioral index, I_c

$$I_c = \sqrt{\left(3.47 - \log Q_t\right)^2 + \left(1.22 + \log F_r\right)^2} \tag{3}$$

Finally, Zhang et al. (2002) modified the definition of Q_t by including an exponent n, dependent on I_c,

$$Q_{tn} = \frac{q_t - \sigma_{vo}}{100}\left(\frac{100}{\sigma'_{vo}}\right)^n \tag{4}$$

where,

$$n = 0.381\left(I_c\right) + 0.05\left(\frac{\sigma'_{vo}}{100}\right) < 1.0 \tag{5}$$

The data thus modified are graphed to identify the Soil Behavior Type (SBTn) using the Ic index according to **Table 1**.

5. Groundwater Table to Estimate Normalized Undrained Shear Strength

Figures 1-3 show results of CPTu tests carried out in aluminum extraction residues deposits (Sao Paulo State, Brazil) to discuss the hydraulic and mechanical concepts relevant to the stability analysis.

In this profile, dissipation tests until pore-pressure stabilization allow to identify a downward vertical water flow regime. Note in **Figure 3** the envelope of stabilized pore-pressures of the dissipation tests and the hypothetical piezometric line associated with a stationary regime. Also, the times to reach 50% dissipation of excess pore-pressures that are observed in **Figure 2** (mean value 200 sec) allow for defining the undrained condition for the driving of the piezocone (Randolph & Hope, 2004; Schneider et al., 2007). In this way, the undrained resistance calculation models are used based on the piezocone factor Nkt, NΔU (Bosch et al., 2019). **Figure 3** shows the consistency of the Su results for the two types of piezocone factor.

However, additional care should be taken when normalizing the results for

Table 1. SBTn classes by Robertson (1990) and respective I_c values (Robertson & Wride, 1998).

Soil classification (SBTn)	Zone number (Robertson SBT 1990)	SBT Index values
Organic soils: peats	2	$I_c > 3.60$
Clays: silty clay to clay	3	$2.95 < I_c < 3.60$
Silt Mixtures: clayey silt to silt clay	4	$2.60 < I_c < 2.95$
Sand Mixtures: silty sand to sandy silt	5	$2.05 < I_c < 2.60$
Sands: clean sand to silty sand	6	$1.31 < I_c < 2.05$
Gravelly sand to dense sand	7	$I_c < 1.31$

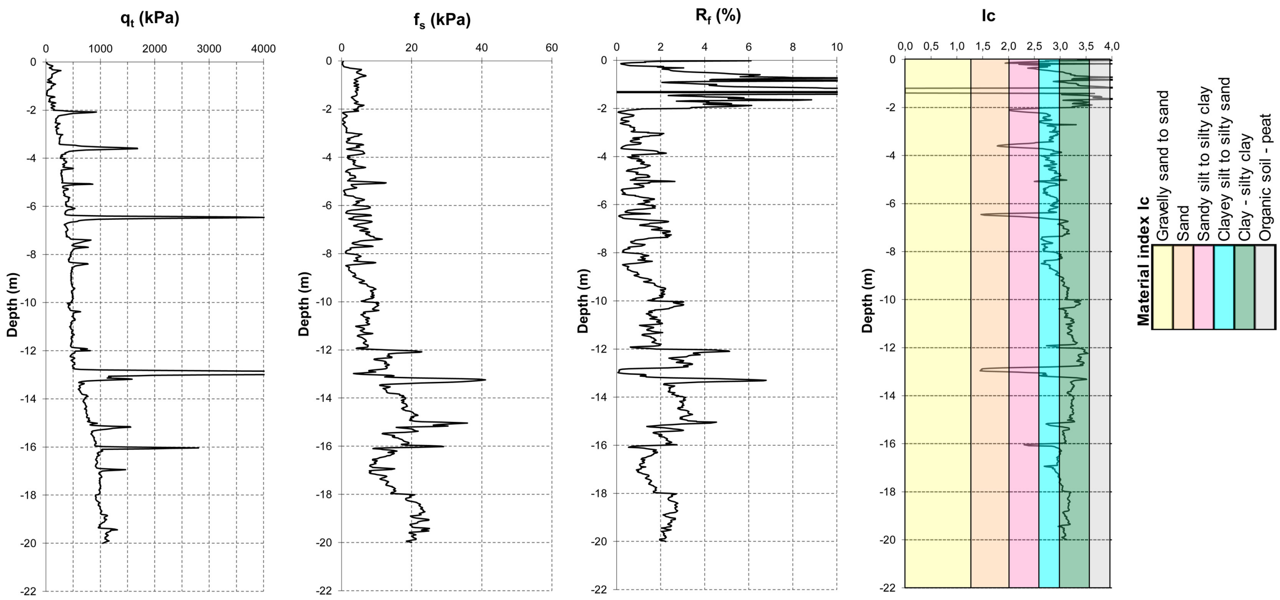

Figure 1. Soil behavior from CPTu test results.

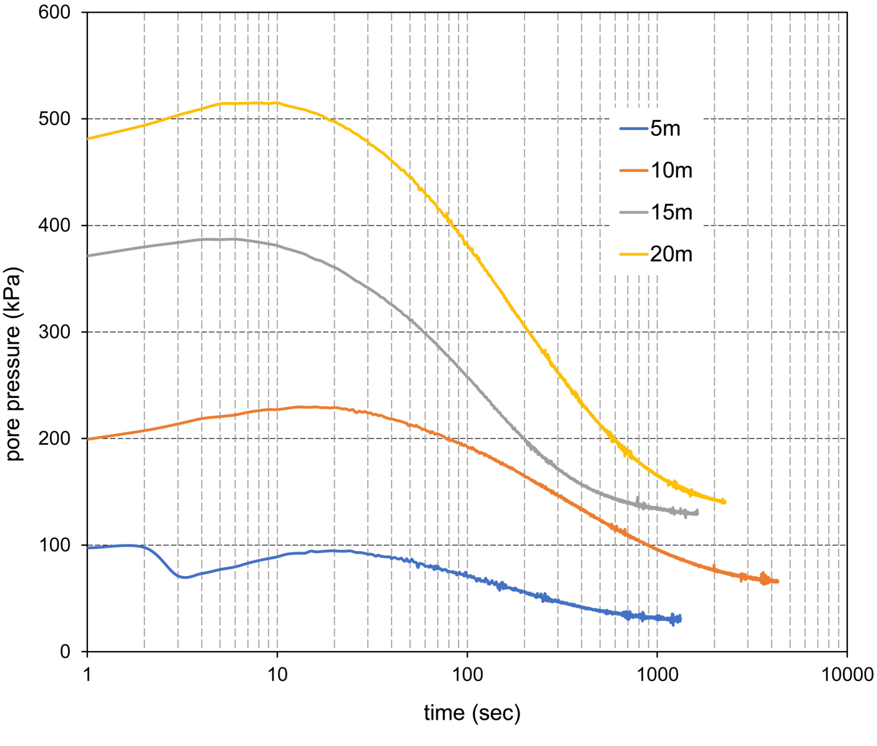

Figure 2. Dissipation tests carried out.

effective stress levels, which is one of the data entry formats of commercial programs (e.g. ROCKSCIENCE®) as illustrated in **Figure 4**. If the real water table is not considered (polygonal line defined in the dissipation tests) and a linear hypothesis is adopted based only on a linear estimation of the water table, significant errors may be incurred against safety, as mentioned by Brown & Gillani (2016).

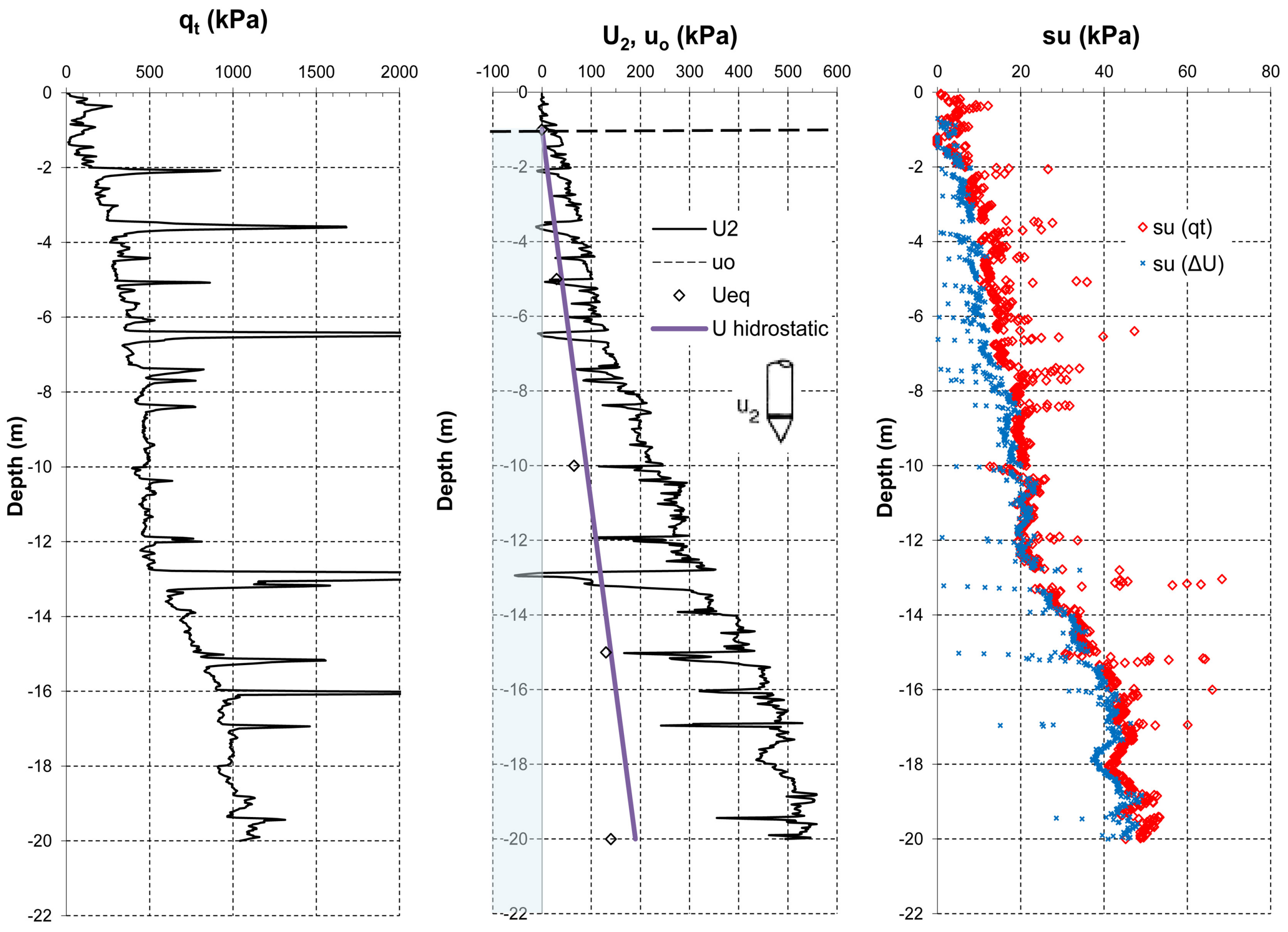

Figure 3. Undrained shear strength (*Su*) estimated from CPTu tests.

6. Undrained Shear Strength in Dilating Clay Materials

For these materials, a profile of colluvial material of natural clay silt layers in the Minas Gerais State Brazil is analyzed as an example, in which dissipation results are available for the calculation of consolidation coefficients Ch. According to the behavior classification criterion, Ic, illustrated in Figure 5, the profile is composed of materials with intermediate behavior.

Figure 6 presents the dissipation test results, obtaining an average value of t50% = 40 seconds. The pore pressure data generated during the driving, as well as the dissipation tests, indicate that the material below 18 m of depth exhibits dilating behavior. Note that the behavior of the pore-pressure equalization curves below 19 meters is different from those above.

According to the criteria for defining drainage conditions (drained—partially drained—undrained) the material found below the phreatic level exhibits undrained behavior for the execution speed of the CPTu test. According to the behavior type identification criteria, I_c, up to the water table depth it corresponds to use criteria for determining effective resistance parameters as estimated in Figure 7. However, the difficulties in analyzing the soil response measured during the test in a single variable (friction angle φ) are recognized.

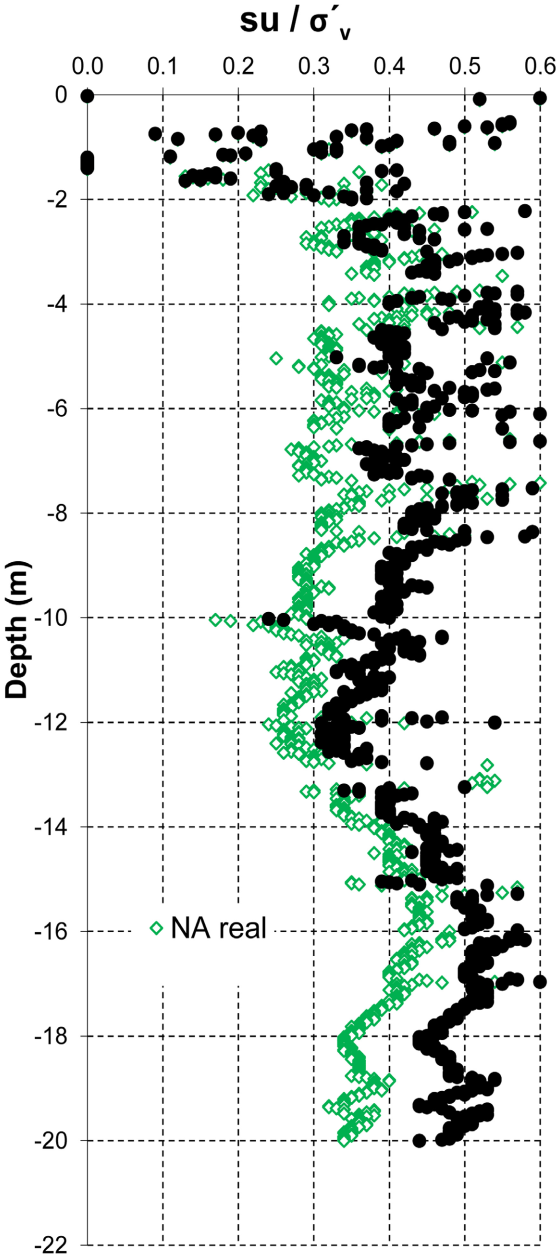

Figure 4. Estimated normalized undrained shear strength (Su/σ'_v).

Below the groundwater table and according to the identification criterion, Ic, the undrained shear strength of the saturated layers can then be calculated from classical formulations $su = \frac{q_t - \sigma_{vo}}{N_{kt}}$ illustrated in **Figure 8**. However, it must be verified that the estimated undrained shear resistance is lower than the resistance in effective stresses available in the long term conditions.

For comparison purposes, **Figure 8** also presents the shear strength values in effective stresses τ estimated from the adoption of an effective friction angle value φ' = 30, which appears to be the lower boundary of the granular matrix above

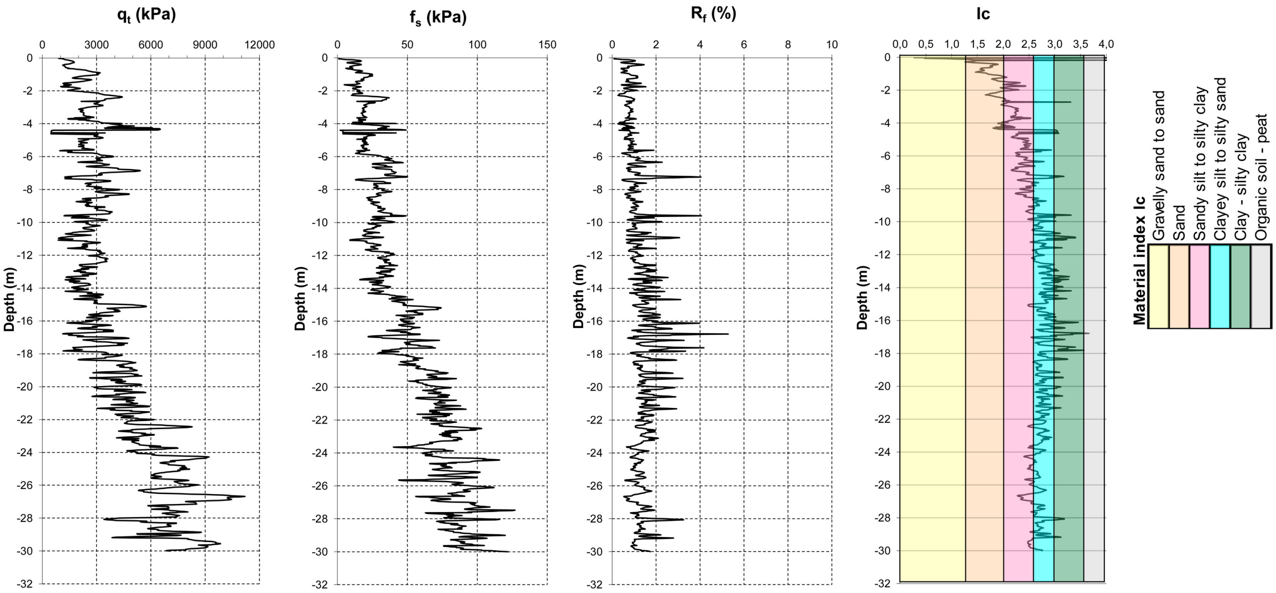

Figure 5. Soil behavior from CPTu test results.

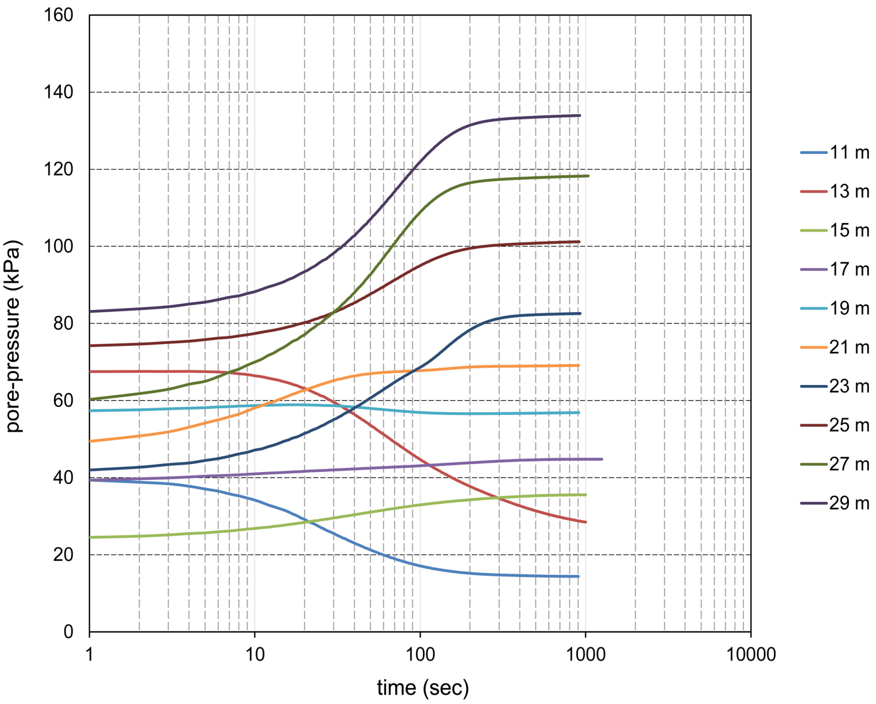

Figure 6. Dissipation tests carried out.

of the phreatic level (**Figure 7**). For the calculation of the shear strength $\tau = \sigma' \times \mathrm{tg}(\varphi')$, in this figure two criteria were adopted to choose effective stresses, the effective vertical stress σ'_v and a mean stress $p' = \sigma'_v(1+2Ko)/3$, with *Ko* estimated as $(1-\sin\varphi' = 0.50)$.

The difficulties in estimating the *Ko* state from the available data are recognized. However, it is clear that even in the case of a situation *Ko* = 1, the undrained shear strength (*Su*) calculated with the direct application of the classical

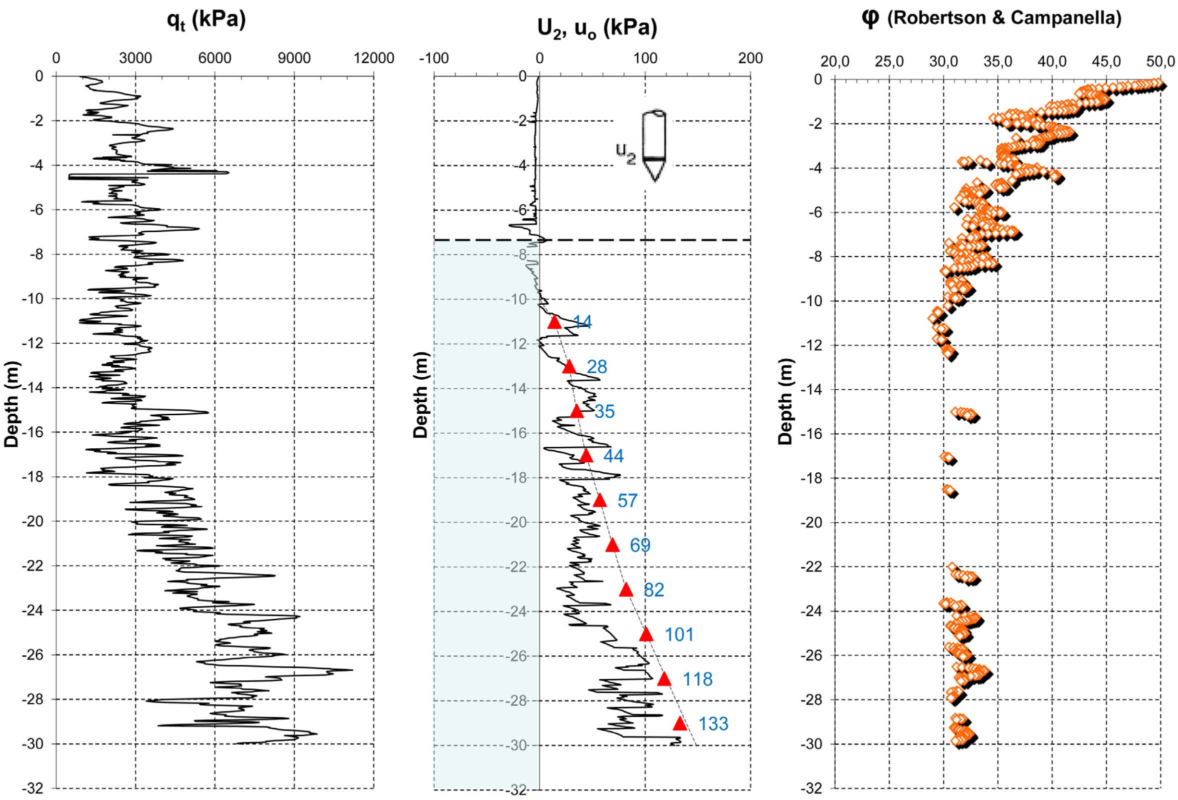

Figure 7. Estimation of effective soil parameters (friction angle φ) from the CPTu test.

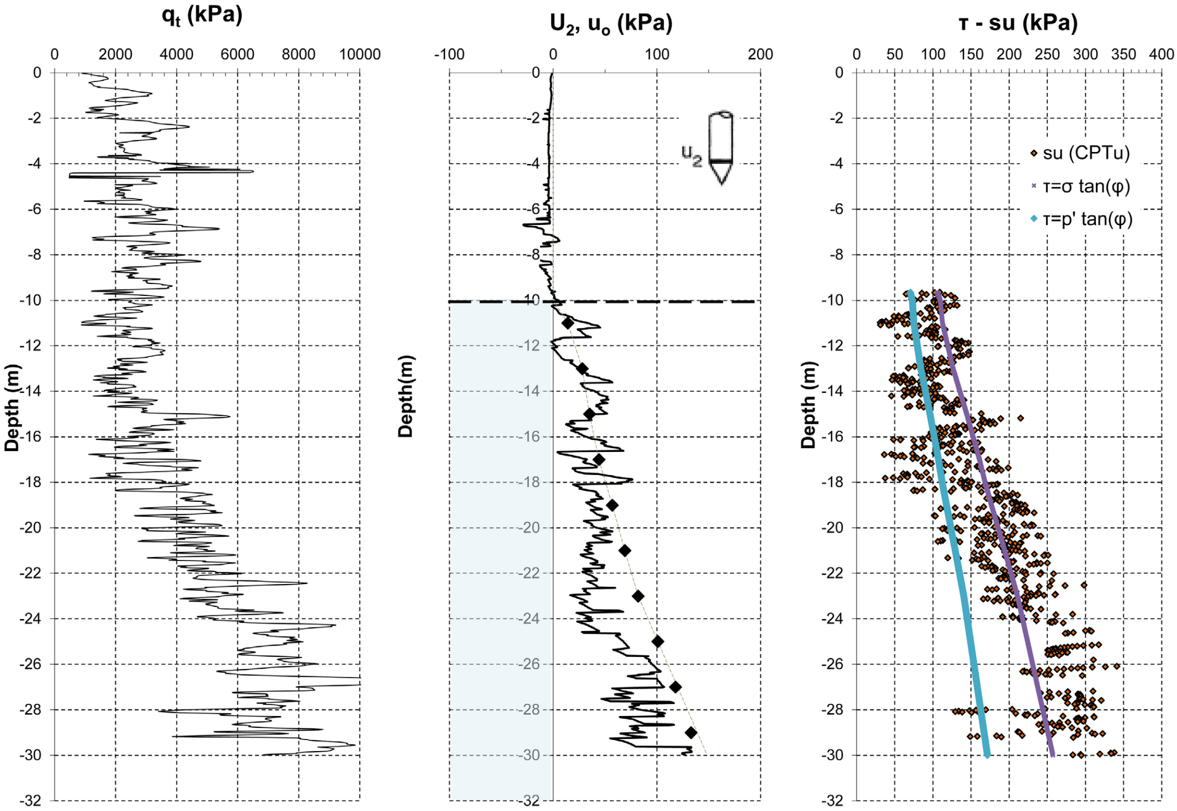

Figure 8. Comparison of undrained shear strength (*Su*) vs shear strength in effective stresses.

expressions for undrained conditions can overestimate the available resistance in a long term effective stresses, that is, when negative pore pressures generated during insertion are dissipated. For these reasons, the use of these results for a project requires a careful analysis of the critical condition (drained or undrained) in cases of overconsolidated clay materials. This situation is also remarked by Brown & Gillani (2016).

7. Closing Remarks

In this work, two cases were commented on where CPTu tests were analyzed to characterize resistance properties in total stresses for later use in tailings dams' stability calculation algorithms. The correct definition of the effective stresses state constitutes a fundamental step for the estimation of the shear resistance to be used in stability or load capacity calculations. The execution of dissipation tests until total stabilization is not practical in clay materials, but in layers of intermediate material or in granular materials it offers accurate information on the groundwater table, allowing also to verify the existence of vertical water flow. By establishing the pore-pressure regime *in situ*, it is possible to determine the normalized undrained shear strength. Also, the detection of negative excess pore pressures during driving in undrained performance materials makes it necessary to consider the envelope of strength in effective stress to obtain safe design soils parameters.

There have been a number of major tailings dams' failures in recent times where the incorrect modelling of materials has led to catastrophic failure. Although this work does not cover all those aspects, which need to be further investigated, it is shown here how the results of the CPTu tests could be used for the diagnosis of the phreatic and mechanical condition of the materials to avoid incorrect soils parameters adoption.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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