Influence of hydrogeological conditions on estimation of undrained shear strength by CPTu tests: case study in a tropical soil

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ABSTRACT

CPTu tests have gained prominence in the geotechnical characterization of materials, registering a significant increase in their application in the Brazilian context, especially due to requirements to consider undrained resistance in analyses guided by more recent regulations. However, the interpretation of these tests often lacks a detailed and personalized approach, as they disregard specific nuances of each location. In this study, the foundation of a dam made up of tropical soil with a specific hydrogeological condition, characterized by bottom drainage with deep percolation, previously identified in other research campaigns, was evaluated. The interpretation of the CPTu test aimed to estimate the undrained resistance of the material through two different approaches: considering the dissipation tests carried out to model the in-situ pore pressure according to the elevation versus a hypothetical hydrostatic condition, which could be misinterpreted in places where there is a predominance of SPT tests and insufficient geological knowledge. Multiple methodologies were evaluated to interpret undrained shear strength, including approaches that use B_q directly and that exclusively considers the laboratory characterization of a sample and the overconsolidation ratio at that point. In this case analyzed, it was observed that the change in pore pressure conditions resulted in a considerable variation in the undrained shear strength ratio, over 10% when pore pressures are considered in the equations. The results highlight the relevance of considering local hydrogeological conditions when interpreting field tests, especially for foundations of large structures.

Keywords: CPTu; Tropical soil; Undrained shear strength; Dissipation test.

1. Introduction

Dam safety is associated with knowledge of their physical and hydraulic characteristics and how the structure behaves over time. To achieve such knowledge, proper geotechnical characterization of the materials under different loading and flow conditions is necessary, through field and laboratory tests.

According to the most recent Brazilian regulations update, it is important to evaluate the undrained resistance (S_u) of the materials that compose a stability analysis section of a dam. This parameter can be measured by Vane Tests or be estimated through the interpretation of triaxial compression tests, or CPTu.

Changes in the physical-chemical characteristics (cyclic moisture variations) or structural characteristics (weathering profiles) of a soil can be crucial for understanding soil behavior and it is still a challenge to replicate the soil's dynamic balance with the environment in the laboratory (Carvalho and Gitirana Jr., 2021). According to these authors, this is due to a variety of geomorphological, biological, and geological factors, in addition to possible unintentional chemical changes in the soil itself or in the environment in.

Ferreira and Massad (2022) highlight that specific tests at the study site have significant importance in validating the study method and correctly identify the local geological history, so they are not replaceable.

CPTu tests allow the sectorization of the geological-geotechnical profile (stratigraphy and type of soil behavior) and the estimation of engineering parameters for geotechnical projects (Schnaid, 2009). The parameters estimated by the test can indicate the detailed resistance at different depths, being able to differentiate materials based on their stress history, in addition to being an indication of the drainage condition existing at the site.

Furthermore, it is important to have a correct approach when processing such data, so that the correlations used and the modeling in percolation and stability programs are as close as possible to the performance studied.

Thus, this work seeks to shed light on an aspect not addressed in structures lacking vast investigations: the importance of modeling phreatic water in CPTu tests for their correct interpretation.

2. Materials and methods

This section presents the geological context of the studied site, the available tests and the methodology used to evaluate this study.

2.1. Materials e context

The study area is between the states of Amazonas and Pará, Brazil, inserted in the geological context of the Amazonas Sedimentary Basin (Alter do Chão formation). It is a mining region for the extraction of bauxite, which has already been mined and currently has dams to contain tailings from this process.

The interpretation of the dam section used in this study took place through successive stages. Initially, the SPT tests were interpreted and, subsequently, with a CPTu test, the B_q and OCR were interpreted, improving the geological-geotechnical understanding/knowledge, and establishing the division of the foundation material according to its behavior. The geological-geotechnical section is presented in Fig.1.

Only foundation layer B will be analyzed in this study, as presented in the following items. The specific weights of the materials were estimated through on-site geotechnical investigation and laboratory tests in the region and used to estimate the *in-situ* stress at the points studied, together with each of the two phreatic surfaces evaluated.

As it is a tropical soil, common in Brazil, generated in places with high rainfall and solar intensity, such as intertropical zones, some extra care is necessary. Such soils have greater resistance and permeability than soils generated in temperate climates that have similar particle size distributions, requiring a more careful assessment in identifying their geotechnical properties due to the heterogeneous conditions imposed by weathering (Huat et al., 2006).

Carvalho and Ribeiro (2021) highlight that it is necessary to develop specific classification methods for tropical soils, as most of the correlations were established for soils in temperate areas and present lower predictive results when applied to tropical areas.

2.2. Soil Investigation

Close to the analyzed section, a sample was collected for laboratory testing, characterizing the material in accordance with current Brazilian regulations. The results of this characterization are summarized in Table 1.

Table 1. Material characterization.

Tests		**Results**
Granulometry	% Clay	29.8
	% Silt	48.4
	% Sand	15.3
	% Gravel	6.5
Atterberg Limits	w_L	52.7
	w_P	26.6
	IP	26.1
Gs* (g/cm³)		2.67
water content (%)		30.32

* Specific gravity of the soil particles.

2.3. In-situ pore water pressure modeled

The in-situ foundation layer presents a hydrogeological condition of bottom drainage, identified by dissipation tests in the area and consolidation of investigations along with the geological context of the region. Therefore, the hydrostatic phreatic condition does not apply to the site, and dissipation and modeling tests are important to better characterize the field behavior.

During the CPTu test, pore pressure dissipation tests were conducted at depth beyond 95% dissipation of excess pore pressure (Δu_2), to estimate the value of local in situ pore pressure (u_0). One of the dissipation tests is shown in Fig.2 for illustration.

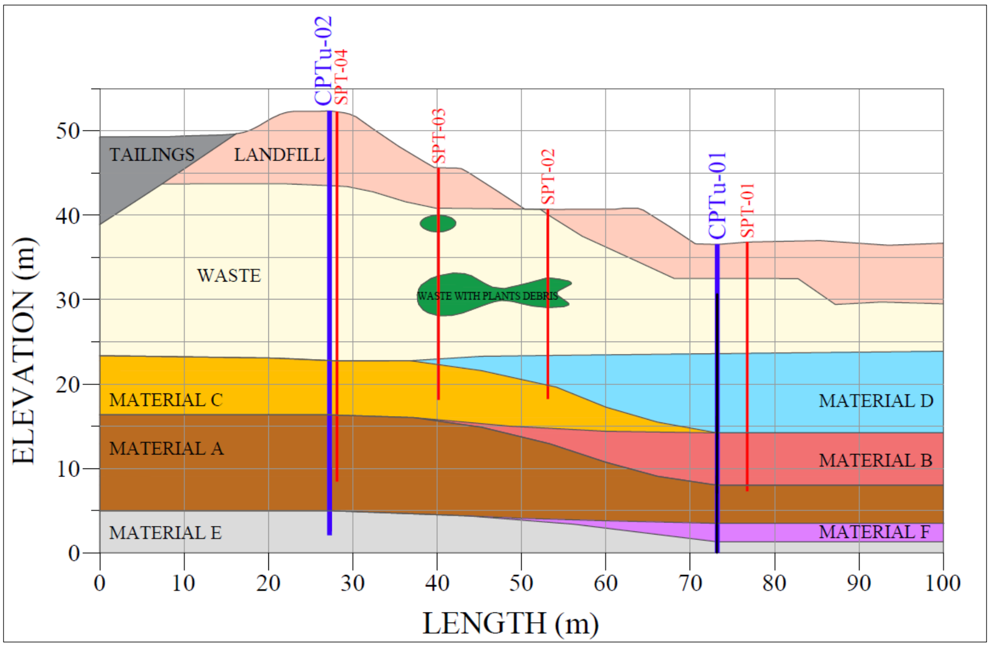

Figure 1. Geological-Geotechnical Section.

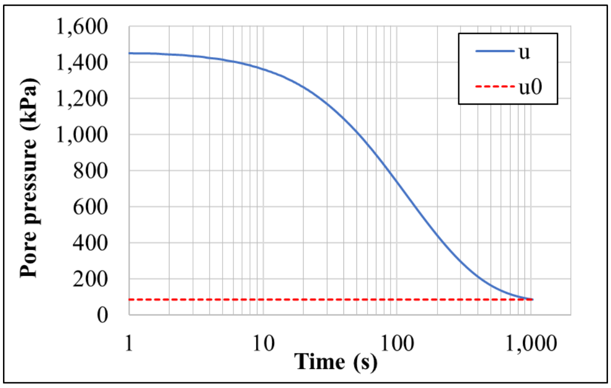

Figure 2. Pore pressure dissipation test.

It was found that the pore pressure dissipation tests interfered with the continuity of the pore pressure measurements (u_2), resulting in outliers. This interference was identified up to three sequential measurements after the dissipation test. Therefore, these outliers were excluded during the data processing.

The positioning of the water table was established by interpreting the results of CPTu and pore pressure dissipation tests. Fig. 3 shows the pore pressure measurements by the CPTu test and the dissipation test, showing the points of maximum pore pressure and final pore pressure.

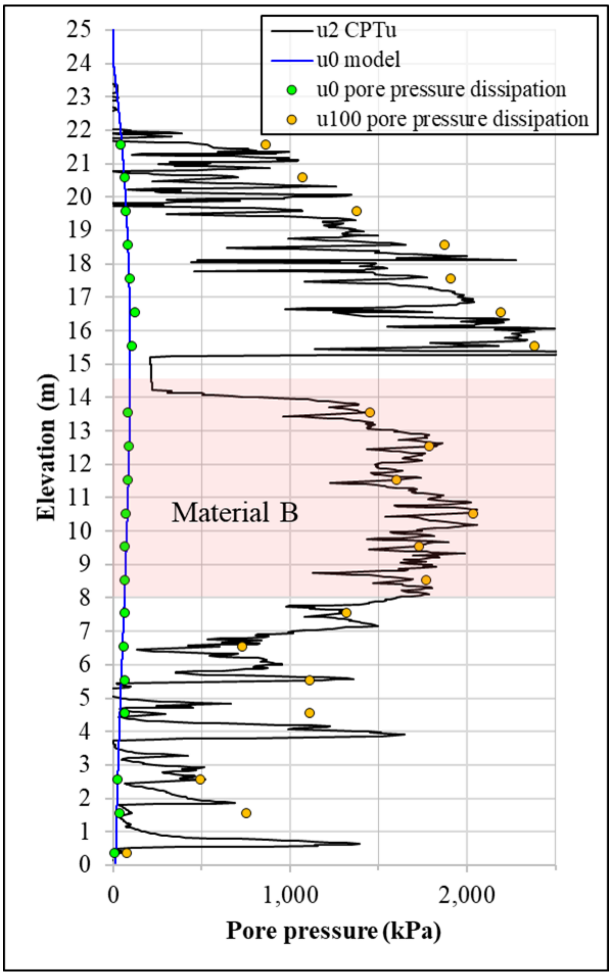

Figure 3. Pore pressures measured in CPTu and dissipation tests.

Interpolation of the points measured by the dissipation test was used with a polynomial regression equation to estimate the depth values and interpret the CPTu. In this way, a phreatic that indicates a bottom drainage flow was obtained, as shown in blue in Fig.4. In this work, a hydrostatic condition was assumed for purposes of comparing the impact of an erroneous interpretation, shown in red in Fig. 4.

These two different models were used to obtain the value of u_0 in the interpretation of the CPTu test, interfering in the values of σ'_{v0} and, therefore, in the values of Q_t and B_q. Therefore, this work will evaluate the S_u/σ'_{v0} calculation for a hypothetical case of hydrostatic phreatic and for a case of modeled phreatic, indicating a bottom drainage flow in the considered foundation.

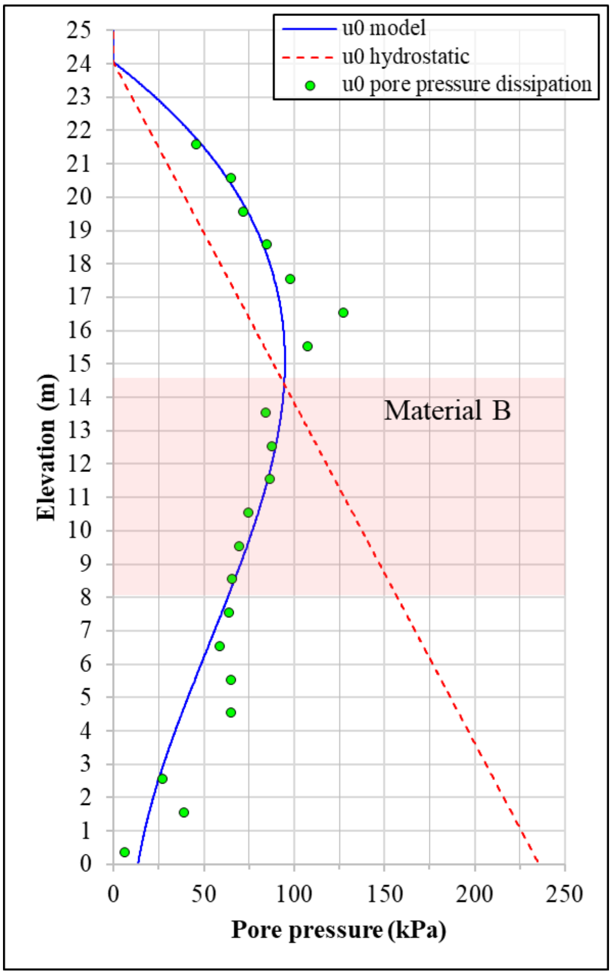

Figure 4. Model phreatic and hydrostatic phreatic.

2.4. Method for estimating undrained shear strength.

Considering the water tables that will be evaluated in this study, some methodologies were used to estimate the value of undrained shear resistance. The recommendations of Wroth (1988 *apud* Schnaid (2009) highlight the importance of using normalized parameters to correct any effects related to tension levels, which is why this study uses values of S_u/σ'_{v0}.

In the estimates made, only material B was considered for conditions, where $B_q \geq 0.4$, since the soil is clayey silt and Schnaid (2009) recommends this minimum value to guarantee an undrained anchoring of the CPTu.

To obtain the undrained resistance (S_u) from CPTu tests, Eq. (1) and Eq. (2) are used, already consolidated among researchers, and presented by Robertson and Cabal (2014), which use the factors: load capacity factor N_{kt} (based on corrected tip resistance, q_t) and the factor $N_{\Delta u}$ (based on pore pressure), which will be estimated by some selected methodologies.

$$S_u = \frac{q_t - \sigma_{v0}}{N_{kt}} = \frac{q_{net}}{N_{kt}} \tag{1}$$

$$S_u = \frac{u_2 - u_0}{N_{\Delta u}} = \frac{\Delta u}{N_{\Delta u}} \tag{2}$$

As some methodologies use OCR values, this will be estimated in depth using Robertson's Eq. (3). It should be noted that this work is not evaluating methodologies for estimating OCR, which should be verified by complementary laboratory tests.

$$OCR = 0.25(Q_t)^{1.25} = 0.25\left(\frac{q_t - \sigma_{v0}}{\sigma'_{v0}}\right)^{1.25} \tag{3}$$

The methodologies used in this evaluation were: Robertson and Cabal (2014), and Mantaras et al. (2014).

Robertson and Cabal (2014) recommend conducting a Vane Test on soils to determine the N_{kt} value in situ, which varies between 10 and 18 and tends to increase as soil plasticity increases. In this case, the fixed coefficient N_{kt}=14 was used. Furthermore, the authors correlate the values of N_{kt} and $N_{\Delta u}$ through B_q, according to Eq. (4).

$$N_{\Delta u} = B_q N_{\text{kt}} \tag{4}$$

Mantaras et al. (2014) proposed some correlations for estimating N from I_R values. For Brazilian soils, the authors suggest representative typical values: M=1.2 (ϕ'=30º), I_R=100 and λ=0.75, simplifying $N_{\Delta u}$=8.4. The use of such an equation is encouraged by these authors for cases where $B_q \geq 0.4$ and IP≥20% in quaternary clays. This simplified value will be used in this study to help evaluate the behavior of the methodologies given the difference in hydrogeological flow considerations.

3. Results and Analysis

After applying the equations already mentioned, the results of S_u/σ'_{v0} were estimated for each method used and for the two water tables considered (modeled phreatic and hydrostatic level). These results are presented in Fig. 5.

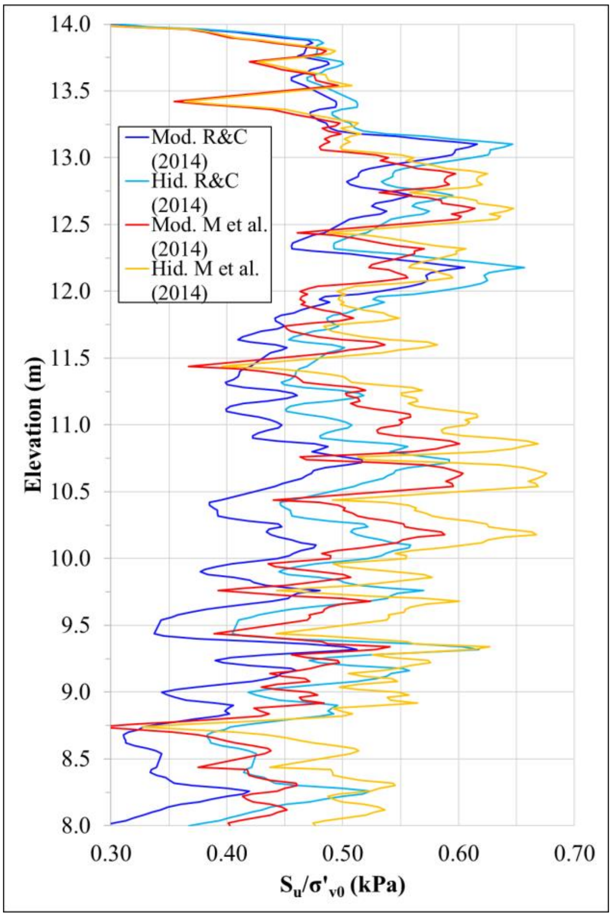

Figure 5. Comparative S_u/σ'_{v0} (kPa) for both phreatic conditions.

It is observed for both methodologies in depth, that the difference in the value of S_u/σ'_{v0} increases as the hydrostatic and modeled water table move apart. Fig. 4 indicates that they are closest at the highest elevations and are farthest apart from material B at elevation 8 m.

The modeled phreatic generated lower S_u/σ'_{v0} estimates than the hydrostatic level, since the pore pressure value is lower.

To facilitate the evaluation of these results, some presentations were made in the MiniTab® version 19 software. Fig. 6 shows the probability distribution for the data being presented in a normal distribution, indicating that it is representative.

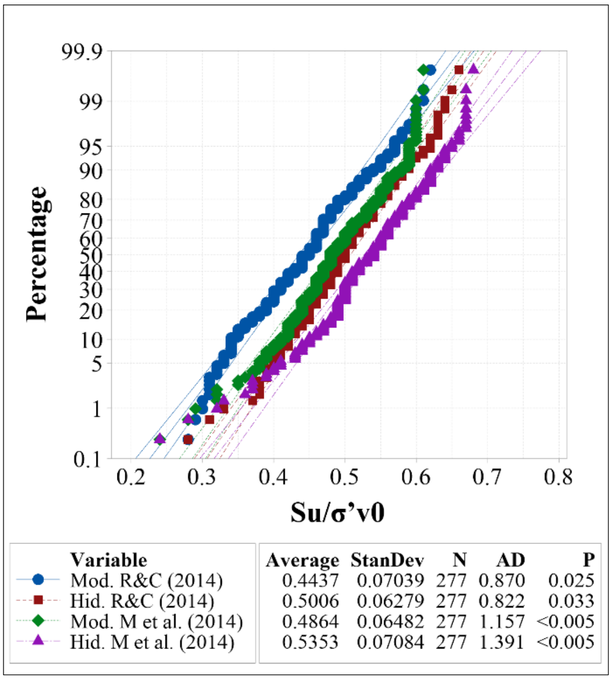

Figure 6. Verification of the fit into normal distribution.

Thus, we proceeded to Fig. 7 and Table 2, which shows the normal distribution histogram of the results.

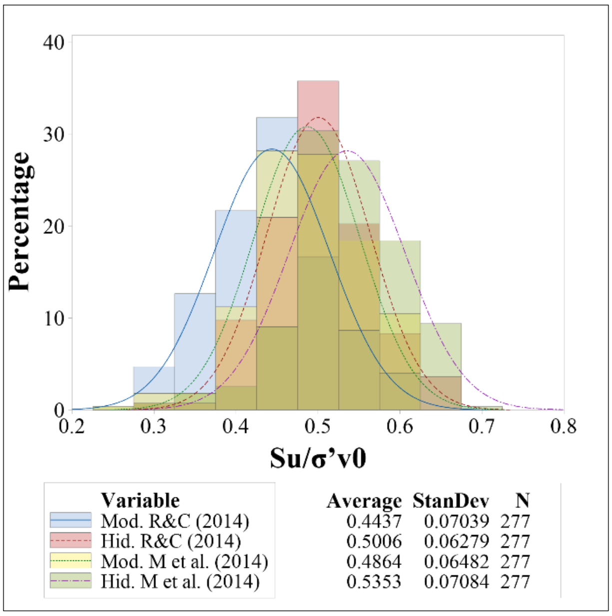

Figure 7. Normal distribution histogram.

Table 2. Statistics

	Modeled Phreatic		**Hydrostatic Phreatic**	
	Average	**σ_z***	**Average**	**σ_z***
Robertson and Cabal (2014)	0.44	0.50	0.50	0.07
Mantaras et al. (2014)	0.49	0.54	0.54	0.06

* Standard Deviation of the vertical measurements

For this case under study, it is observed that there was no tendency for the standard deviation to increase for any of the water tables, as this depends on the methodology applied and how it relates to the data that depend on the value of u_0.

This condition showed that hydrostatic phreatic, which estimates higher values of pore pressure at depth (as shown in Fig. 4), presented higher calculated values of S_u/σ'_{v0}. When compared in relation to the average modeled water table value, an increase of 12.8% and 10.1%, respectively, can be seen when applying the methodology of Robertson and Cabal (2014) and Mantaras et al. (2014). This exercise can be done with other methodologies to estimate this value.

Finally, the boxplot with the values of S_u/σ'_{v0} (for all cases) is shown in Fig. 8. The median value (line that appears in the middle in boxplot) was used as a reference and the outliers (crosses) are shown when existing.

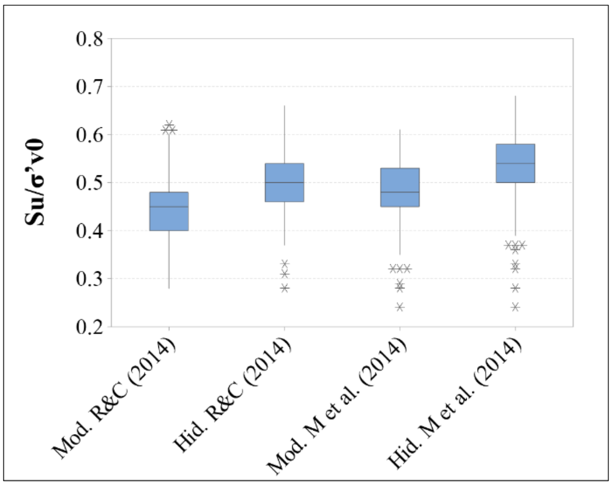

Figure 8. Boxplot S_u/σ'_{v0} (kPa) for both phreatic conditions.

The results show the importance of this in-depth flow modeling, therefore, whenever possible, the use of numerical modeling programs can help to better understand the local context, compiling several tests, estimating pore pressure values at depth, and checking the modeled value with the value measured in piezometers installed at different depths.

4. Conclusions

The CPTu test interpretation aimed to estimate the undrained resistance of the material through two different approaches: considering the dissipation tests carried out to model the in-situ pore pressure according to elevation versus a hypothetical hydrostatic condition, which could be misinterpreted in places where there is a predominance of SPT tests and little geological knowledge.

The purpose of this work is not to criticize or evaluate the CPTu interpretation methodologies applied here, but to demonstrate the importance of evaluating local hydrogeological conditions even before requesting tests and, mainly, during their interpretation. The methodologies for estimating OCR were also not evaluated, and it is important to complement them with laboratory tests when applying them to projects.

In the case studied, if pore pressure dissipation tests had not been conducted to understand the pore pressures along the depths, the local bottom drainage condition might not have been identified, hence the importance of the local hydrogeological context. This information can be confirmed later with the installation of piezometers at different depths and numerical modeling of such information, comparing with tests obtained at depth.

It was assessed that the difference in water tables had an impact of more than 10% on the S_u/σ'_{v0} results, which could make a significant difference in the assessment of the structure's stability.

The importance of carrying out joint and often redundant tests to confirm information that directly impacts geotechnical design is understood, to ensure better sizing of structures through understanding the expected behavior over time. This will also allow future monitoring to be correctly applied to modeling and verifying the stability of the structure.

Acknowledgements

The authors are grateful for the support provided by Federal University of Ouro Preto (UFOP) and CAPES (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*).

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