Determination of Geotechnical Parameters of a Heterogeneous Tropical Soil Deposit Through Different Penetration Rate CPTu Data

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ABSTRACT

Assessing soil properties through geotechnical tests is a crucial activity to understand its behaviour. Field tests serve as a good approach to characterize the geotechnical behaviour of materials according to their in-situ condition. However, the interpretation of these tests often relies on empirical correlations, which can become complex when dealing with soils with notable heterogeneity. This paper objective is to determine the strength parameters and discuss the consolidation effects for a heterogeneous tropical soil deposit using data from field tests with different rates of penetration and laboratory tests. A layer identified as low-strength soil classified as silty-sand to silty-clay exhibited partial drainage during a standard-rate cone penetration. The approach proposed by Randolph and DeJong (2012) was used to determine the penetration rate necessary to mobilize an undrained behaviour of the material, since the cone penetration results shown that the material is mostly contractive and clay-like. CPTu tests were also conducted with penetration rates of 60 mm/s and 100 mm/s, to proper estimate the undrained shear strength (Su). These tests reinforced the presence of a preconsolidated upper layer, enabling the estimation for the overconsolidation ratio (OCR). For the normally consolidated portion of the residual soil, rapid tests that achieved a normalized velocity (V) associated with distinctly undrained penetration were used to derive the undrained shear strength (Su), with a cone factor (N_{kt}) estimated from standard-rate tests available. The geotechnical parameters estimated were then compared to the laboratory data results showing a convergence with the parameters estimated by the field tests.

Keywords: Cone penetration test; penetration rate; partial drainage; field and laboratory tests.

1. Introduction

The evaluation of soil properties is essential for understanding the complex behaviours exhibited by soils. Geotechnical tests play an essential role in providing understanding into the characteristics that define soil responses to various conditions. Among these testing methodologies, field tests stand out as a practical approach, offering a means to characterize the geotechnical behaviour of materials in their natural, in-situ state.

While field tests provide a tangible perception of the main properties of soil in its natural state, interpreting these tests often faces challenges, especially when dealing with notable heterogeneity in soil compositions. The reliance on empirical correlations introduces complexities, emphasizing the need for diverse methodologies to navigate the intricacies of diverse soil profiles and highlighting the demand for refined testing and interpretation approaches.

This complexity is further pronounced in tropical soils, as observed in the Brazilian Amazon region. Favourable climatic conditions, including warm weather, high rainfall, and drainage conditions, contribute to the formation and development of different soil horizons, promoting the formation of residual soils known for their significant spatial heterogeneity and anisotropy (Carvalho, 2006).

In this context, achieving a proper characterization of geotechnical properties, particularly resistance parameters, for this type of soil may require not only laboratory tests but also essential field tests. The latter provides a broader and detailed assessment of the local stratigraphic profile. By combining both testing methodologies with sophisticated interpretation techniques, a more accurate evaluation of the materials' geotechnical behaviour and resistance profile can be ensured, understanding its variability.

2. Drainage and Cone Penetration Rate

Understanding the drainage and saturation conditions of the material in field can be challenging. In the Cone Penetration Test (CPT), which measures tip resistance (q_c), sleeve friction (f_s), and dynamic pore pressure (u_1 or u_2), the presence of interstitial water induces different behaviours in the soil during shear: drained, when the generation of pore pressure is low during penetration, or undrained, when there is a significant generation of pore pressure with difficulty in dissipating it, as exemplified by Silva et al. (2006).

However, some soil types may induce an intermediate condition, when the standardized penetration rate of the test, set at 20 mm/s, is not sufficient to mobilize an undrained state, leading to a condition known as partial drainage. Materials with significant heterogeneity, especially those with intermediate grain sizes like silts, may experience partial drainage effects during the execution of cone penetration tests, and according to Robertson (2010), during dissipation testes, values of t_{50} below 30 seconds may indicate partial drainage.

DeJong & Randolph (2012) states that partial drainage during cone penetration causes pore pressure dissipation during the test. This results in increased mean effective stress, a corresponding reduction in void ratio, and a significant decrease in total stress, influencing the q_{cnet} and u_2 values, and therefore also affects the normalized parameters used to characterize the soils penetrated by the cone.

In this scenario, obtaining strength parameters for undrained loading conditions becomes limited and inaccurate, as the penetration conditions do not represent a distinctly undrained condition.

However, this condition can be overcome by modifying the penetration rate of the cone. Authors such as Randolph (2004), Chung *et al*. (2006), Jaeger *et al*. (2010), DeJong (2012), and others have investigated the impacts of varying penetration rates to define layers exhibiting drained or undrained behaviour when the soil demonstrates partial drainage effects under the standard cone penetration rate.

Partial drainage effects become prominent when employing a standard penetration rate. However, for the same soil, it is possible to induce a drained behaviour with a sufficiently slow penetration rate. Conversely, achieving an undrained condition requires a rapid penetration to minimize or eliminate dissipation during the cone penetration test.

The determination of an appropriate penetration rate can be achieved by considering the normalized penetration velocity (V), relative to the standard penetration rate. The condition of fully undrained penetration typically occurs when V is greater than approximately 30-100, whereas fully drained penetration occurs when V is less than about 0.03-0.01 (DeJong & Randolph, 2012). The normalized test rate is defined in Eq. (1).

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

Where v represents the standard cone penetration rate (conventionally = 20 mm/s), d is the cone diameter; and c_h is the coefficient of consolidation in cases where the primary direction of pore water flow is horizontal.

3. Preconsolidation Effects

Preconsolidation of soil relates to the compression or consolidation that occurs before applying a current load. This condition is often influenced by historical processes, such as prior loads or sedimentation, resulting in previous compression of the soil. In tropical soils with a clayey composition, preconsolidated behaviour is frequently observed. This is attributed to factors like the presence of fine sediments and high plasticity, making the soil more susceptible to prior consolidation.

The consolidation behaviour can be discerned through field tests, specifically by employing dissipation tests and cone penetration tests.

Chai, et al. (2012) conducted an in-depth examination of pre-consolidation behavior in the context of piezocone dissipation tests carried out in overconsolidated clay deposits. Their findings revealed distinctive dissipation curves in overconsolidated clays, characterized by an initial increase in pore water pressure followed by a subsequent decrease. As for the cone penetration test, the distribution of excess pore water pressure around the cone's peripheric area in preconsolidated materials is initially influenced by the dilatancy angle of the soil, often resulting in negative values at the cone shoulder (position u_2). The magnitude of these negative values is contingent upon the soil's dilatancy characteristics.

4. Field Tests on Heterogeneous Tropical Soil

Field tests were performed on a water dam in a tropical Amazonian climate region, revealing a heterogeneous layer with low resistance in the foundation. In conjunction with the CPTu tests, pore pressure dissipation tests were carried out at various depths, and undisturbed samples were collected for basic characterization and direct simple shear tests (DSS).

Initially, cone penetration tests were conducted at a standard penetration rate of 20 mm/s, utilized for the characterization of the foundation's stratigraphy. A soil layer was identified with significantly low cone tip resistance (q_t) and predominantly contractive behaviour. However, the pore pressure profile exhibited an ambiguous response regarding the undrained condition.

The dissipation tests within the heterogeneous layer consistently showed notably low t_{50} values, ranging from 5 to 40 seconds. These values suggest the potential occurrence of partial drainage effects. Given that the testing campaign aimed to understand the behaviour of materials, particularly in the heterogeneous layer, and determine undrained resistance parameters, the occurrence of partial drainage limits the application of traditional methodologies to obtain these parameters in tests with standard penetration rates.

In response to this observation, the normalized velocity and penetration rate required to induce a full undrained penetration in the material were defined using Eq. (1). Therefore, additional CPTu tests were performed at rates of 60 mm/s and 100 mm/s adjacent to the boreholes at standard rate.

Fig. 1 provides a comparison of the key results from tests conducted at different penetration rates. It was noted that the test conducted with the penetration rate of R = 60 mm/s still showed a result influenced by partial drainage. Following the evaluation of data from tests conducted at a higher penetration rate and through the comparison of normalized velocities, the parameters were based solely on tests at a rate of 100 mm/s, which indicated a condition of a fully undrained condition. Additionally, it was found

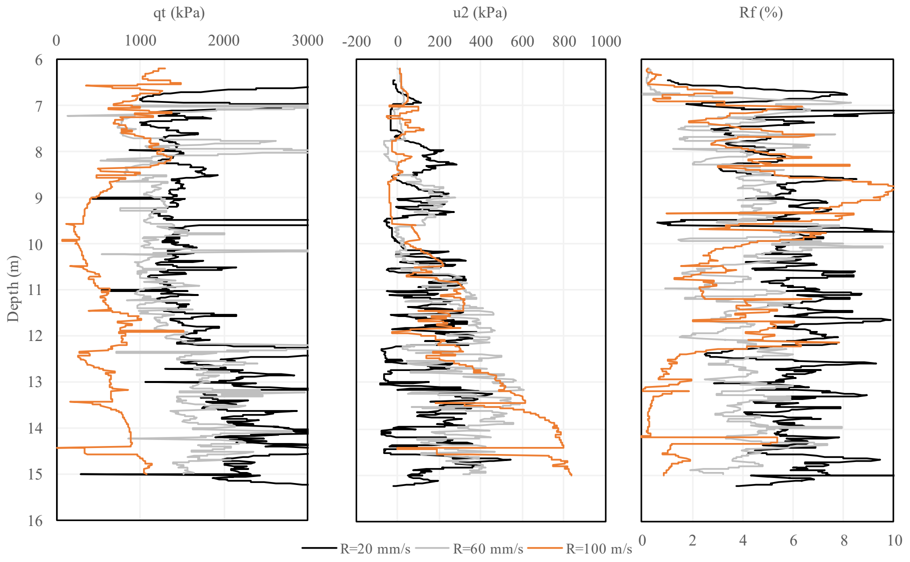

Figure 1. Tip resistance, pore pressure, and friction ratio for tests with different rates.

that the t_{50} values in the dissipation tests were on the same order of magnitude as those conducted at standard speed.

When comparing the results of cone tests with different penetration rates, specifically between the standard velocity (20 mm/s) and a velocity of R = 100 mm/s, some pertinent observations stand out regarding the overall behavior of the heterogeneous layer.

In the test conducted with R = 100 mm/s, a significant reduction in tip resistance (q_t) was noted, especially in the lower portion of the layer. This result supports the hypothesis that partial drainage occurred in tests with lower penetration rates, allowing some dissipation during cone penetration. In tests with lower rates, this is reflected in lower readings of u_2 and, consequently, higher measurements of q_t, indicating an inability to mobilize a fully undrained behavior.

A similar pattern was observed in the friction ratio (R_f), where the series corresponding to the R = 100 mm/s test showed a deviation from the other tests from a depth of 123 m onwards. Mayne *et al.* (2023) suggest that an Rf < 1% is indicative of behavior associated with clean sand or, in more critical cases, sensitivity to quick clays. When analyzing other parameters in this segment, a significant increase in u_2 with low tip resistances is highlighted, suggesting the predominance of a sensitive clay behavior. However, it is notable throughout the material profile that the R_f varies greatly, emphasizing the heterogeneity of the layer.

The most notable distinction, however, was in the profile of pore pressures between tests conducted with different penetration rates. This may have been the most enlightening indicator regarding the layer's behavior, where an increase in penetration rate not only resulted in an increase in u_2 but also emphasized the consolidation behaviors of the layer.

The region where the dam's body is located is known to exhibit a notable influence of preconsolidation in the more clayey layers of the foundation. Despite the material's heterogeneity, as verified in subsequent characterization tests, the tests demonstrated a predominance of clay-like behavior in the layer, as demonstrated in Fig. 2.

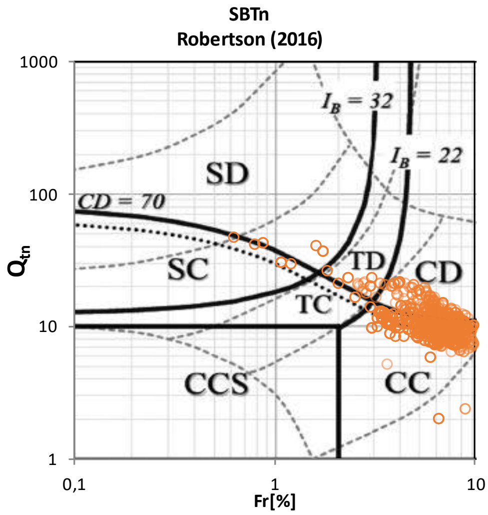

Figure 2. SBTn chart (Robertson, 2016) demonstrating the clay-like behavior of the material.

Thus, when analyzing the layer, it was possible to distinguish two segments with predominant behaviors. The initial segment (upper layer), between depths of 6.5 m and 9.5 m, and a final segment (lower stratum), between depths of 9.5 m and 15.5 m.

The lower stratum exhibited a behavior expected for tests with higher penetration rate, where the average u_2 values for the R = 100 mm/s test surpassed the measurements for the same segment of the standard penetration rate test. This occurs because the increased penetration rate of the cone minimizes or even eliminates partial dissipation during the cone penetration, thus limiting the effects of partial drainage during the test. However, the upper layer drew attention because, in this portion, the opposite effect was observed; u_2 measurements in the higher rate test were considerably lower than those in the standard rate test.

To verify if this observed result referred to the influence of preconsolidation in the layer, the

Overconsolidation Ratio (OCR) was evaluated using the methodology proposed by Chen and Mayne (1996), considering the standard penetration rate test. Although OCR values along the layer did not show a significant distinction, slightly higher values were noted, with OCR in the range of 4 to 8 in the upper segment of the layer compared to the lower segment, which had an average OCR of 3. Although the application of the correlation for tests with a different rate than the standard is not recommended, only for comparative purposes, the same correlation was applied to the R = 100 mm/s test. In this case, the distinction between the OCRs of the layers became more pronounced, separating a noticeably preconsolidated segment in the upper part (OCR > 4) and a normally consolidated segment in the final segment of the layer (OCR = 1).

Therefore, when observing the u_2 profile of the tests, it is noted that the increase in penetration rate not only induced higher readings of pore pressure in the normally consolidated segment but also emphasized the preconsolidated behavior of the upper portion of the layer, reflecting in lower and even negative u_2 readings, a behavior typically attributed to preconsolidated materials, as described by Chung *et al*. (2006).

Another result that corroborated with the aforementioned hypothesis was the behavior of the dissipation tests conducted throughout the layer. When the tests were performed in the upper portion of the stratum, the curves indicate an initial increase in pore pressure relative to u_2, followed by a decrease and stabilization in the value of $u_{100\%}$, typical behavior of pre-consolidated materials. On the other hand, tests conducted in the normally densified portion showed that the pore pressure generated during driving (u2) is the highest in these tests, followed by a decrease and stabilization in the value of $u_{100\%}$, typical behavior of normally densified materials. Fig. 3 presents the results.

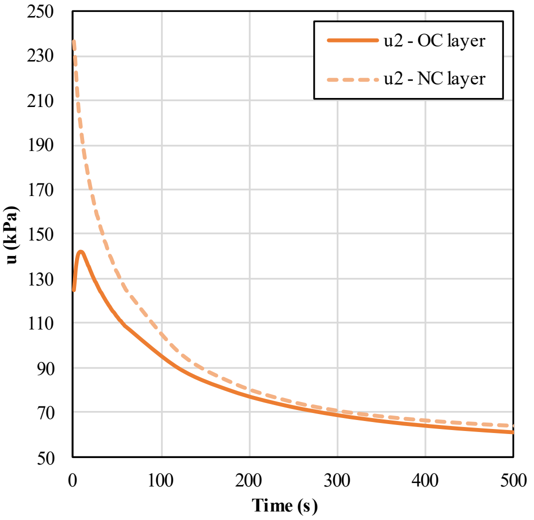

Figure 3. Results from the dissipation tests conducted in the overconsolidated layer and in the normally consolidated layer in the standard rate CPTu.

4.1. Undrained Shear Strength

The focus of the testing campaign was to determine the undrained shear strength for the heterogeneous layer of low resistance. It is important to emphasize that, given uncertainties regarding the applicability of some commonly used correlations for cone penetration tests, the classical equation for estimating the undrained strength was adopted, as shown in Eq. (2).

$$S_u = \frac{q_t - \sigma_v}{N_{kt}} \qquad (2)$$

Where q_t represents the tip resistance, σ_v is the vertical stress, and N_{kt} is the cone factor.

Special attention was given to the cone factor due to its significance in determining the parameter. Its determination was based on the application of the correlation proposed by Mayne and Peuchen (2022), as stated in Eq. (3).

$$S_u = 10.5 - 4.6\, ln\, (Bq + 0.1) \qquad (3)$$

However, its application was restricted to tests conducted at the standard penetration rate. Fig. 4 illustrates the histogram of N_{kt} for the foundation's target layer.

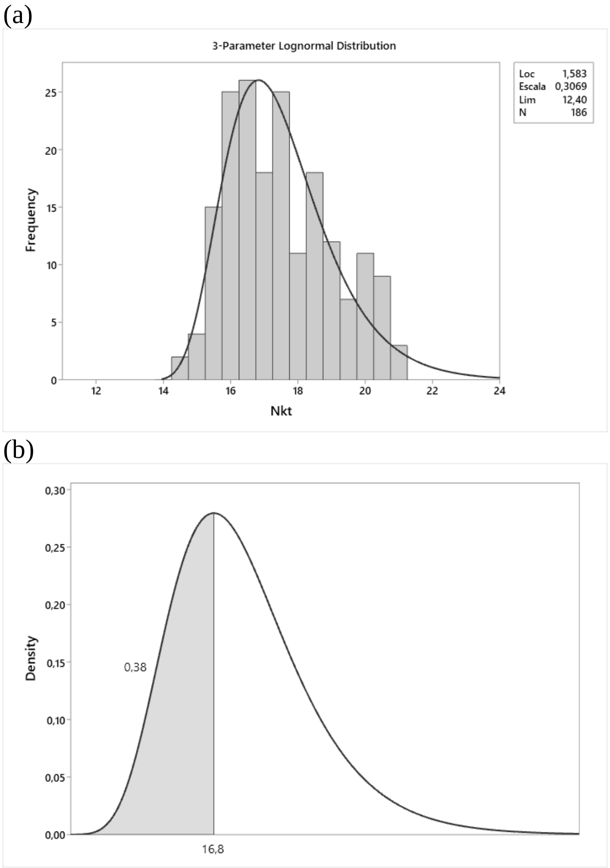

Figure 4. Histogram of the Nkt values considering the standard rate test (a) The data with the best fitting curve (b) the results estimated.

Following the assessment of the field test conducted at the standard penetration rate, a statistical analysis using histograms was performed. The representative Nkt value for the layer was determined as the mode from the best-fit distribution (3-parameter lognormal distribution). The analysis converged to an Nkt value of 17 as representative for the material examined.

Subsequently, the Nkt value was applied to Eq. (2) to ascertain the undrained shear strength ratio, considering tests conducted at both the standard penetration rate (R=20 mm/s) and the maximum rate of R=100 mm/s. Fig. 5 summarizes the results of the shear strength ratio across the heterogeneous layer profile.

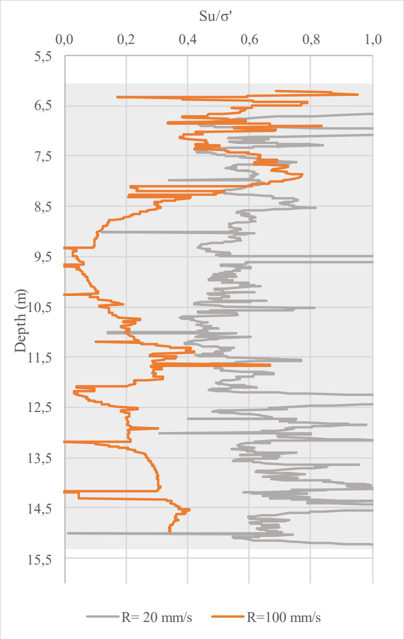

Figure 5. Profiles of undrained shear strength ratio for the heterogeneous layer considering tests conducted at the same location but with different penetration rates.

Noteworthy observations emerged from the analysis of the undrained shear strength ratio (Su/σ') of the material. In summary, a distinct pattern was also observed along the resistance profile, particularly in the lower stratum. In this section, the Su/σ' values at the standard penetration rate consistently exceeded those obtained from tests conducted at a higher rate, suggesting that partial drainage significantly influences test interpretation, leading to an overestimation of strength parameters at the normally consolidated section.

However, the test outcomes for the upper layer showed values of similar magnitude. As per the previously stated hypotheses, this layer displayed behavior suggestive of preconsolidation. Notably, the section between depths of 6 m and 8 m showed minimal impact from partial drainage, likely attributed to the preconsolidated nature of the layer.

From a thorough statistical analysis of data gathered from tests conducted at a penetration rate of R=100 mm/s, an undrained shear strength ratio of Su/σ' = 0.22 was determined for the normally consolidated layer. This value represents the mode, derived from fitting a lognormal distribution to the test data, as shown in Fig. 6.

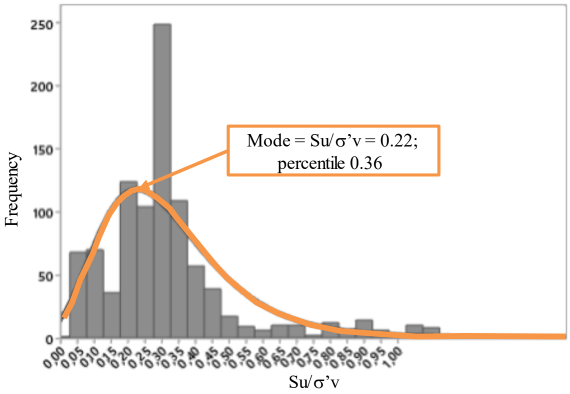

Figure 6. Histogram of the Su/σ' values obtained.

4.2. Laboratory Tests and Comparison with Field Tests

In addition to the field tests, the laboratory tests were conducted on undisturbed samples with the objective of comparing the strength parameters estimated from the cone penetration results at higher penetration rates.

For material characterization, particle size distribution (granulometry) and Atterberg limits tests were conducted. The results demonstrate its heterogeneous nature, as it comprises 51% sand, 16% silts, and 28% clays, as evidenced in the particle-size distribution curve in Fig. 7. This implies a low plasticity and low compressibility to the material, with a liquid limit of 42%, plastic limit of 30%, and a plasticity index of 12%, as shown in the plasticity chart in Fig. 8.

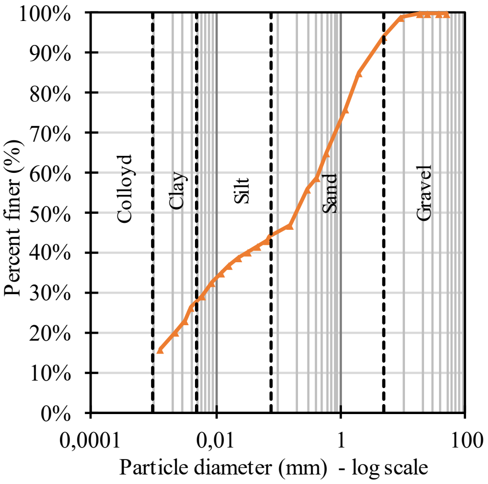

Figure 7. Grain size distribution curve obtained for the material – ASTM D422

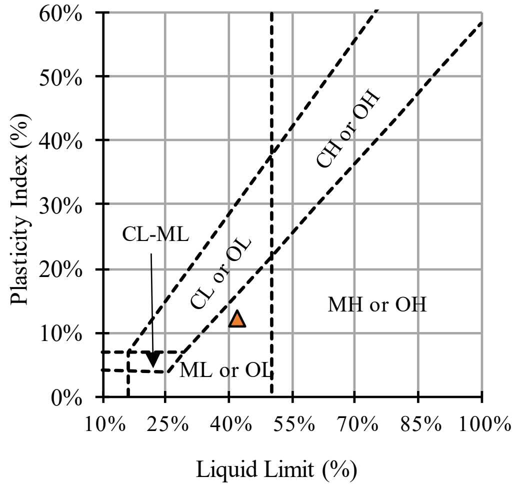

Figure 8. Plasticity chart with the results obtained for the material.

For stress history determination, consolidation tests were performed, revealing a pre-consolidation stress of 250 kPa, as depicted in Fig. 9. The CPTu tests conducted at a rate of R=100 mm/s indicated a low generation of pore pressure at the upper layer, associated with the behavior of preconsolidation, as discussed in the previous sections. The results of the consolidation test conducted suggest that this layer with minimal pore pressure generation has a preconsolidation ratio (OCR) greater than 2, consistent with the findings from the field tests.

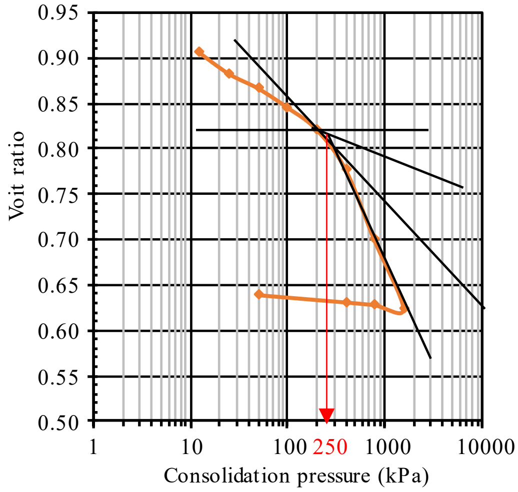

Figure 9. Consolidation curve obtained from de consolidation test conducted on the material.

To assess the undrained strength of the material, direct shear tests (DSS) were conducted at confinement stresses of 50 kPa, 200 kPa, 400 kPa, and 800 kPa. The stress paths from tests at different stresses indicate that the material exhibits dilative behavior at low stresses, attributed to its pre-consolidated nature, and predominantly contractive behavior at high stresses, as shown in Fig. 10.

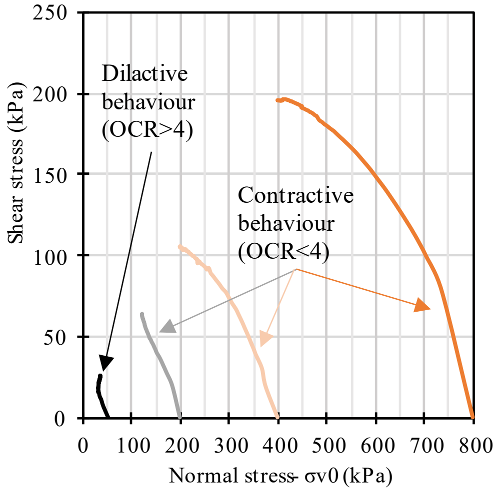

Figure 10. Stress paths obtained from DSS tests conducted on the material.

For a more comprehensive characterization of the material's strength curve, a Stress History and Normalized Soil Engineering Property (SHANSEP) adjustment was proposed, following Ladd and Foot (1974), incorporating a pre-consolidation stress of 250 kPa (from the consolidation test), a resistance ratio of 0.25, and an exponent m of 0.42. Fig. 11 presents the obtained results.

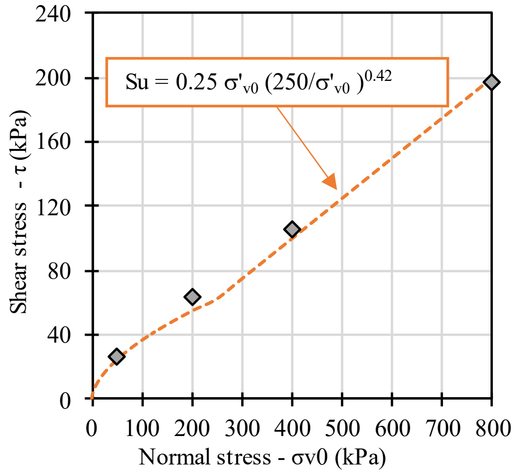

Figure 11. Undrained resistance adjustment obtained from DSS tests conducted on the material.

The statistical SHANSEP adjustment obtained from the conducted DSS test indicates a resistance ratio of 0.25, which closely matches the parameter derived from the field tests in terms of magnitude, slightly higher than the value of 0.22 determined from CPTu test results with a penetration rate of 100 mm/s. The slight difference in parameters can be explained by the conservatism assumed in the parameter estimation from field tests due to the high volume of associated uncertainties.

5. Conclusions

The field and laboratory tests conducted on the foundation material of a water dam in the tropical Amazonian climate region provided an overall understanding of the impact of partial drainage in estimating the strength parameters of a heterogeneous layer beneath the structure.

The field tests allowed the identification of a layer exhibiting low resistance and primarily contractive behavior, coupled with ambiguous responses regarding undrained conditions. The presence of partial drainage effects was evident during the standard test, significantly influencing the interpretation of its results.

The introduction of normalized velocity and penetration rate adjustments addressed these limitations, enabling more accurate assessments of undrained shear strength parameters. Additionally, tests conducted at higher penetration rates helped understand the behaviors associated with both normal consolidation and preconsolidation within distinct segments of the layer. Overall, the increase in penetration rate accentuated the preconsolidated behavior of the upper layer, as evidenced by the pore pressure readings. Additionally, in the normally consolidated section, results indicated significant partial drainage effects, leading to strength parameter overestimation for the standard rate test. A shear strength ratio of Su/σ’ = 0.22 was found for the layer from tests at R=100 mm/s.

Particle size distribution and Atterberg limits tests revealed the material's heterogeneous nature, indicating low plasticity and compressibility. Consolidation tests showed a pre-consolidation stress of 250 kPa, consistent with pre-consolidated behavior observed in CPTu tests at the upper layer. Direct simple shear tests highlighted dilative behavior at low stresses and contractive behavior at high stresses, reinforcing the material's pre-consolidated nature.

To enhance the material's strength curve characterization, a SHANSEP adjustment was proposed, incorporating a pre-consolidation stress of 250 kPa, a resistance ratio of 0.25, and an exponent m of 0.42. The statistical adjustment for the DSS test indicated a resistance ratio of 0.25, slightly higher than the CPTu result (0.22) at a penetration rate of 100 mm/s, showing a convergence with the parameters estimated by the field tests.

6. Acknowledgements

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