Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Considerations on the Site Characterization of Tropical Soils by In Situ Tests

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ABSTRACT

The fundamentals for predicting the mechanical behavior of soils by in situ tests have been developed for conventional soils (either clay or sand) based on the stress history. The behavior of unusual geomaterials, such as the tropical soils, is characterized by bonding and structure, anisotropy as well as by the unsaturated condition. The behavior of tropical soils cannot be correctly predicted by models and correlations developed by the Classical Soil Mechanics. This paper presents the fundamentals of the behavioral classifications used to interpret *CPT* and *SDMT* and discusses their applicability to tropical soils, especially those of pedogenetic evolution of sandstone. Laboratory and in situ tests (*CPTu* and *SDMT*) were carried out at two research sites in São Paulo state, Brazil, at different periods of the year to better understand the soil behavior and the seasonal effects. Classifications and correlations to estimate soil parameters from *CPTu* and *SDMT* are assessed. Interrelationships between elastic parameters of small (G_0) and large to medium strain parameters (q_c, E_D, M_{DMT}) determined by in situ tests are presented to identify the presence of microstructure and unusual soil behavior. Classification criteria based on these relationships to identify collapsible soils also is presented.

Keywords: Site characterization, unusual soils, CPT, SDMT, tropical soils.

1. Introduction

Geotechnical site characterization can be defined as the process of identifying the geometry of relatively homogeneous zones and developing index and strength properties for the soils within these zones.

Tropical soils exhibit a unique mechanical behavior due to their genesis, cohesive-frictional behavior, bonding/structure, and unsaturated condition. Identifying the unusual behavior is the first step of the site characterization program in tropical soils, since it can lead to greater or lesser applicability of classification methods and in the estimative of geotechnical parameters (Vaughan et al. 1988).

Not all soils in tropics are considered tropical soils (Committee on Tropical Soils of ISSMFE, 1985). Those materials formed predominantly by chemical alteration of the rock which have peculiar properties and behavior that cannot be explained by the principles of the classical soil mechanics are considered tropical soils.

The term tropical soil includes both lateritic and saprolitic soils. The first can be either residual or transported and are distinguished by the occurrence of laterization process, which is an enriching of a soil with iron and aluminum and their associated oxides, caused by weathering in regions which are hot, acidic, and at least seasonally humid. Following laterization, high concentration of oxides and hydroxides of iron and aluminium bonds support a highly porous structure. The second soil has structural or chemical bonding retained from the parent rock. The contribution of this cementation to the soil stiffness depends on the strain level the soil will experience.

This paper presents the basics of the behavioral classifications used to interpret Cone Penetration Test (*CPT*) and Seismic Flat Dilatometer Test (*SDMT*) and discusses their applicability to tropical soils, especially those of pedogenetic evolution of sandstone that occur in the experimental research sites of *USP* São Carlos and *Unesp* Bauru. Laboratory and in situ tests (*CPT* and *SDMT*) were carried out at different periods of the year to better understand the soil behavior and the seasonal variability. The potentialities to use relationships between elastic parameters of small (G_0) and large to medium strain parameters (q_c, E_D, M_{DMT}) determined by in situ tests to identify cementation soils (bonding/structured) as well as collapsible soils will also be presented and discussed.

2. In situ testing

In situ testing methods can be used as the alternative to drilling, sampling, and laboratory testing (Giacheti et al. 1999). In-situ tests can be divided in stratigraphic logging (e.g., Standard Penetration Tests; Cone Penetration Tests) and specific tests (e.g., Vane Test; Pressuremeter Test). Laboratory tests are expensive, time consuming, and provide only discrete values at select locations, while in situ tests provide the stratigraphy and quick assessment of soil properties during the site investigation.

Today, hybrid in-situ geotechnical tests (e.g. *SCPTu* and *SDMT*) provide an optimization of data collection by combining two or more techniques into a single sounding (Mayne 2000). *SCPTu* and *SDMT* have been used as a logging tool for site characterization as well as to determine the shear wave velocity (Vs) and the maximum shear modulus (G_0) based on elastic theory. Tests that gather both small and large strain data at the same sounding, such as the seismic piezocone or the seismic flat dilatometer, would allow a more comprehensive and reliable site characterization of unusual soils, as discussed by Mayne (2000), Schnaid and Yu (2007), and Rocha et al. (2021).

3. Description of sites and in situ tests

3.1. *USP* site

The soil profile at the USP research site can be divided into a brown clayey fine sand, Cenozoic Sediment with lateritic behavior (*LA'*), up to about 6 m depth and exhibits collapsible behavior upon wetting (Machado and Vilar 1998). There are pebbles of about 0.5 m thick under this layer. The last layer is a residual soil from Sandstone, red clayey fine sand with non-lateritic behavior (*NA'*). The *MCT* Soil Classification System (Mini, Compacted, Tropical) proposed by Nogami and Villibor (1981) for tropical soils was used to define and classify the soil with regards to its lateritic behavior. The groundwater table varies seasonally between 9 and 12 m below the ground surface (Morais et al. 2020; Rocha et al. 2021).

Four in situ tests campaigns were performed in this site. Three *CPTs*, three *DMTs* (including two *SDMTs*) and, one soil sampling was performed in each campaign. These campaigns were performed in March and October/2016 and, April and October/2017 (dry season – October/2016 and October/2017; wet season – March/2016 and April/2017).

3.2. *Unesp* site

The soil profile at the Unesp research site consist of a red clayey fine sand identified based on SPT data. According to De Mio (2005), this site includes a colluvial Neo-Cenozoic deposit up to 13 m in depth, followed by a residual soil formed during the Quaternary. *MCT* Classification System (Nogami & Villibor 1981) classified the top 13 m as lateritic soil behavior (*LA'*) followed by a non-lateritic soil behavior (*NA'*).

This soil profile has undergone pedogenic and morphogenetic processes, which typically take place in tropical zones, resulting in partly saturated high-permeability soils (10^5 to 10^6 m/s) with cohesive-frictional and collapsible behavior. The groundwater table is not found up to 30 m depth at the site.

Four in situ tests campaigns were performed in this site. Three *CPTs*, three *DMTs* (including two *SDMTs*) and, one soil sampling was performed in each campaign.

4. Test data interpretation

Tropical soils are unusual geomaterial since they present bonding structure, which generates a cohesive-frictional nature, anisotropy due to relic structure, unsaturated condition, and low influence of stress history (Vaughan et al. 1988). In this sense, the following sections present some aspects for a better site characterization of tropical soils by in situ test, such as the identification of unusual behavior from *CPT* and *DMT*, soil suction influence in *DMT*, soil classification from *CPT*, parameters estimation from *DMT*, G_0/q_c and G_0/M_{DMT} ratio for tropical soil identification, as well as an approach to identify collapsible soils from *SCPT* and *SDMT*.

4.1. Unusual behavior identification

Schnaid et al. (2004) state that q_c can be compared to G_0 and the ratio G_0/q_c provides a measure of the ratio of the elastic stiffness to ultimate strength and may therefore be expected to increase with sand age and cementation, primarily because the effect of these on G_0 are stronger than on q_c. These authors proposed a chart and boundaries by correlating G_0/q_c *vs* q_{c1}, a dimensionless normalized parameter defined by Eq. (1):

$$q_{c1} = \left(\frac{q_c}{p_a}\right) \cdot \left(\frac{p_a}{\sigma'_v}\right)^{0.5} \tag{1}$$

where p_a is the atmospheric pressure and σ'_v is the vertical effective stress.

According to Schnaid et al. (2004), this chart should be used in addition to traditional *CPT* classification charts to identify compressible soils, as well as the effect of aging and cementation.

In the same way, Cruz et al. (2012) developed charts for detecting the presence of cemented structured based on Seismic *DMT* (*SDMT*) data. The author plotted the *SDMT* data on charts G_0/E_D *vs* I_D and G_0/M_{DMT} *vs* K_D for this purpose.

Fig. 1 shows the G_0/E_D *vs* I_D (Fig. 1a) and G_0/M_{DMT} *vs* K_D (Fig. 1b) charts, respectively, obtained from average values of G_0, I_D, K_D, E_D and M_{DMT} for the *Unesp* site. The *DMT* parameters (I_D, K_D, E_D and M_{DMT}) were calculated by Marchetti's (1980) equations. Fig. 2 presents G_0/q_c ratio *vs* q_{c1} obtained from four in situ tests campaigns at the *USP* site.

Fig. 1 and Fig. 2 indicate the presence of cemented structures for all the soils from *Unesp* and *USP* sites. The bonded structure of unsaturated tropical sandy soils produces G_0/E_D, G_0/M_{DMT} and G_0/q_c which are systematically higher than those measured in sedimentary soils. Moreover, it is possible to observe that the lateritic soils present a higher bonded structure than the saprolitic soils.

Therefore, the unusual behavior of unsaturated tropical soils cannot be correctly predicted by classical models for interpreting in situ tests and do not always apply to these soils. Thus, modifications/updates may be necessary for each site or for the geology (Robertson 2016).

4.2. Soil suction influence on in situ test data

The soil suction affects the geotechnical behavior of tropical soils (soil classification and parameter estimation). Relatively simple alternatives, such as the determination of soil water content profiles during the investigation stage and knowing the soil water retention curves (*SWRCs*) should be incorporated for a better interpretation of in situ tests on tropical soils.

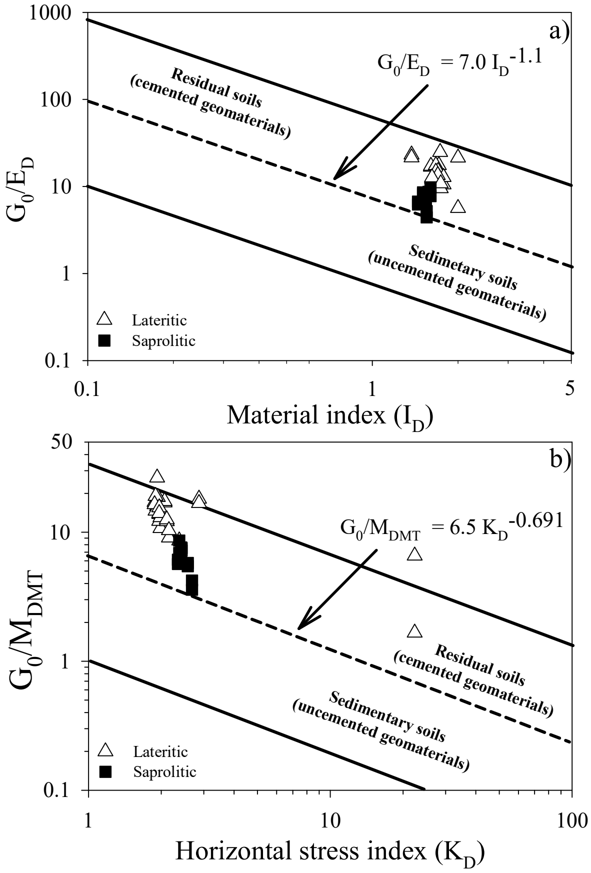

Figure 1. Seismic *DMT* data plotted on *G_0/E_D vs I_D* (Fig. 1a) and *G_0/M_{DMT} vs K_D* (Fig. 1b) charts for the *Unesp* site (adapted from Cruz et al. 2012).

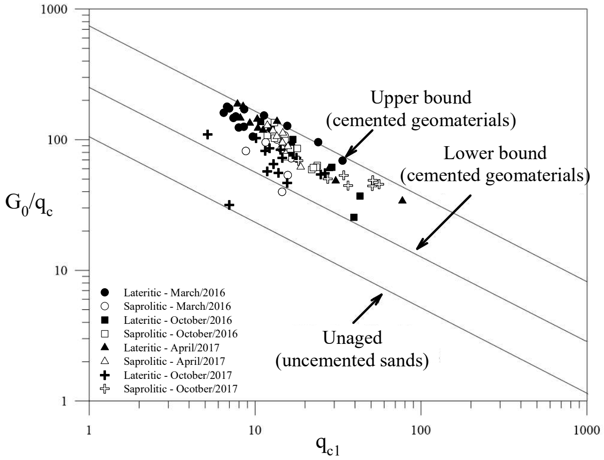

Figure 2. Seismic and *CPT* data plotted on Schnaid et al. (2004) chart for the *USP* site.

Fig. 3a shows the seasonal variability in terms of water content determined in March/2016, October/2016, April/2017 and October/2017 for the *USP* site. However, the interpretation of tests on unsaturated soils should be based on the suction state variable, rather than the moisture content. Fig. 3b shows the moisture values determined in the four campaigns plotted on the retention curves determined by Machado (1998) for 2, 5 and 8 m depths. In this figure (Fig. 3b) the water content values determined in October/2017 campaign are lower than 15.6% and are in the Region 2 of the *SWRCs*. On the other hand, the water content values from all the other campaigns (March/2016, October/2016 and April/2017) are higher than 15.6% and are in Region 1 of the *SWRCs*.

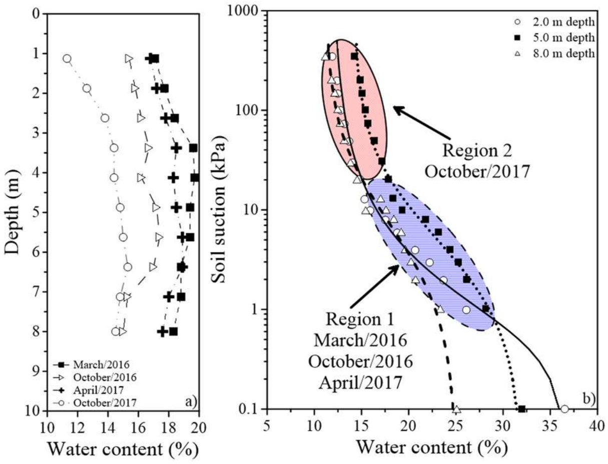

Figure 3. Seasonal variability in water content profiles (a) and Soil water retention curves (*SWRCs*) with water content values (b) for the *USP* site (adapted from Machado 1998 and Rocha et al. 2021).

In Region 1, the water content varies greatly with slight suction variation while the opposite occurs in the Region 2, where the values of suction vary significantly with little water content variation. This behavior can significantly affect the in-situ tests results, and consequently the soil classification and soil parameter estimation by in situ tests.

Fig. 4 shows the average *DMT* parameters determined from each campaign performed at the *USP* site. So, in this figure it is possible a better visualization of soil suction influence in *DMT* data. The top layer (up to 1.0 m) was not considered because it is a heterogeneous desiccated fill.

Soil classification from *DMT* data is done by the material index (I_D). It is possible to observe in Fig. 4a a little influence on soil classification due to soil suction. The *USP* site profile was classified manly as silt by *DMT*. However, this site profile was classified as clayey fine sand by samples collected by *SPTs*. According to Marchetti et al. (2001), sometimes I_D misdescribes silt as clay and vice-versa, and of course a mixture clay-sand would generally be described by I_D as silt.

Figs. 4b and 4c presents, respectively, the average K_D and E_D profiles determined in each test campaign. It is interesting to note that the K_D and E_D values determined in October/2017 showed higher values than those determined in March and October of 2016 and April of 2017 down to approximately 6 m depth. Such behavior can be explained by the soil water retention curve (*SWRC*) and the water content profiles. The October/2017 campaign presents water content profile in the Region 2 (Fig. 3b) where the soil suction varies significantly with little water content variation. A similar behavior (decrease on K_D and E_D with increase on water content and little change on I_D) was observed by Lutenegger (1988). Thus, in situ tests performed on unsaturated tropical soils should be interpreted considering variations in water content profile and the *SWRC*.

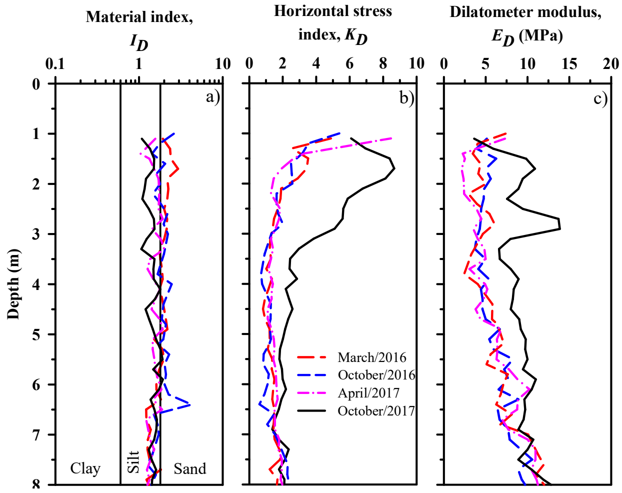

Figure 4. Average *DMT* parameters from each campaign performed at *USP* site (adapted from Rocha 2018 and Rocha et al. 2021a).

4.3. Soil classification by in situ tests

The *CPTu* data (q_c: cone resistance, f_s: sleeve friction, u: pore pressure) are useful for determining soil stratigraphy, identifying soil type, and defining the mechanical parameters from well-established correlations for conventional soils (Robertson 2016). However, more research of the *CPTu* interpretation in unusual geomaterials such as tropical soils are necessary.

As previously presented, a total of twelve *CPTus* (three test for each campaign) were carried out at the *USP* site. The average *CPT* data were plotted in Robertson´s (2009) chart (Fig. 5) and the Eslami & Fellenius's (1997) chart (Fig. 6) for the soil classification. Figure 5 shows that the *USP* site profile was classified as silt mixtures (clayey silt to silty clay) up to 2.0 m depth, and as clay (silty clay to clay) below 2.0 m depth. Moreover, it is interesting to note that almost all the soils present a dilative behavior at large strains and undrained behavior. The *USP* site profile was classified mainly as silty clay at the Eslami & Fellenius's (1997) chart (Fig. 6).

The *CPT* soil classification for both approaches does not represent the soil behavior of this site profile. The soils from the *USP* site profile are characterized as clayey fine sand with contractive behavior in the drained triaxial (*CD*) tests and no dilation during failure (Machado 1998).

Two possible reasons to explain the difference between laboratory test condition and *CPTu* data interpretation are the unusual behavior of the *USP* site profile, as discussed in section 4.1 of this paper, and the intermediate permeability (10^{-5} to 10^{-8} m/s), typical for the soils of this site (Machado & Vilar 2003).

The *CPTu* data interpretation assumes two conditions: undrained (clays) or fully drained (sands and gravels). In soils with intermediate permeability the cone penetration can be partially drained. It changes the stress state around the cone probe and since this stress cannot be determined, the results of the tests should not be used for soil classification and to estimate soil parameters (Schnaid 2005).

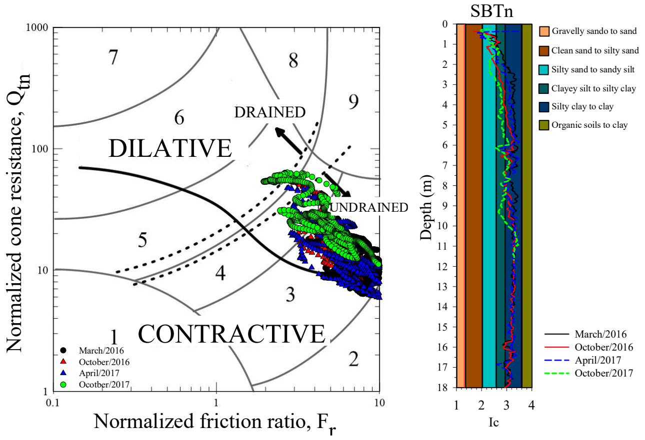

Figure 5. Average *CPT* data from *USP* site in the normalized *CPT* soil behavior from Robertson (2009).

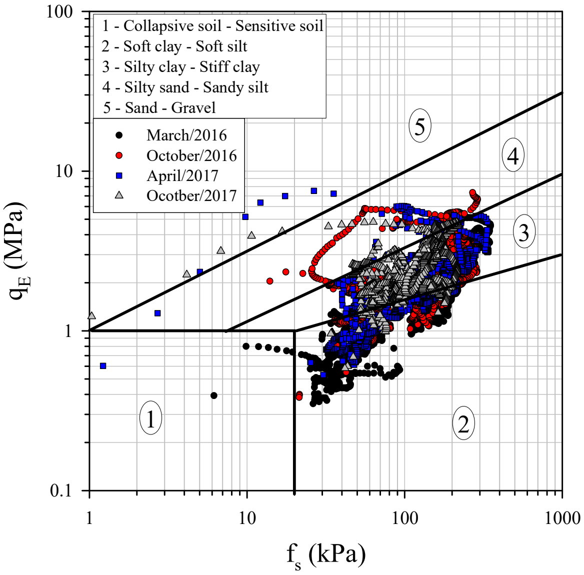

Figure 6. Average *CPT* data from *USP* site in the normalized *CPT* soil behavior from Eslami & Fellenius (1997).

Moreover, according to Robertson (2016), the proposed Normalized Soil Behavior Type (*SBTn*) charts and classical correlations developed for conventional soils (young and uncemented clays and sands) should be carefully used and local adjusts are necessary when applied for unusual soils, such as the investigated unsaturated tropical soils. So, classical correlations for estimating mechanical parameters from *CPTu* data should not be used at this site.

4.4. Estimating Parameters by in Situ Tests on Tropical Soils

One of the main applications of in situ tests is to estimate design parameters. Tropical soils show peculiar behavior due to the processes of pedogenesis/morphogenesis, which are typical in these soils. Therefore, the classic models for estimating design parameters should be applied with caution, and some modifications should be made. In this section, the estimative of design parameters by *SDMT* will be presented for the tropical soil of the *Unesp* site, which has unusual geomaterial (Fig. 1). The total unit weight (γ) of the soil estimated based on the Schmertmann´s (1986) equation is in close agreement with those obtained from undisturbed samples, as presented in Fig. 7a. So, the *DMT* was able to estimate soil density at this site.

Friction angle values (ϕ') determined by direct shear tests (Giacheti et al. 2006) and by triaxial tests on saturated soil samples (Fagundes & Rodrigues, 2015) were used as a reference when comparing the average ϕ' values determined by the three *SDMTs* (Fig. 7.b). The direct shear tests were carried out on undisturbed samples, in natural condition, up to a depth of 19 m. An average value of ϕ' equal to 32.8º was assumed, which varied from 30.1º at 1 m depth to 34.4º at 19 m depth. The correlation proposed by Marchetti (1997) was used to estimate ϕ' using the *SDMT*.

The ϕ' values determined using the average I_D, K_D and E_D profiles were in good agreement with the reference values (direct shear and triaxial tests) below 2 m depth and it did not occur above a depth of 2 m. It may be related to the effect of soil suction, which increased the values of p_0 and p_1, which affects the determination of mechanical parameters by the *SDMT*. This behavior has been studied by Rocha (2018), Rocha and Giacheti (2018) and Rocha et al. (2021) using *SDMT* and *CPTu*. Menárd pressuremeter test (*PMT*) was also previously carried out at the Unesp Site. Fig. 7.c presents Dilatometer Modulus (E_D) together with Ménard *PMT* modulus (E_{pmt}). This figure shows that despite the existence of just a pair of tests, E_D was similar to E_{pmt} values up to about 11 m depth. E_{pmt} was almost half E_D bellow that depth. Ortigão et al. (1996) investigated the Brasilia porous clay and found that E_{pmt} was less than half E_D. They explain the low *PMT* modulus with soil disturbance and after careful correction of the *PMT* field curves, E_{pmt} was similar to E_D.

The *SDMT* can also be used to estimate the coefficient of earth pressure at rest (K_0). These values were compared with those obtained with the Menárd pressuremeter test (*PMT*). Fig. 7.d shows the K_0 values using the correlations of Marchetti (1980) and Baldi et al (1986), as well as the K_0 values interpreted from the *PMT* data. The K_0 value determined by the *PMT* was 3.5 at 0.5 m depth and 1.3 at 1.5 m depth. This parameter assumed a practically constant value of 0.8 up to a depth of 8 m and below this depth K_0 was equal to 0.5. So, it can be considered that there was a good agreement between the values obtained by *SDMT* and *PMT*.

Overconsolidation ratio (*OCR*) and Constrained Modulus (M_{oed}) values obtained from oedometer tests carried out on undisturbed soil samples (Saab 2016) were used as a reference for comparison with the values estimated by *SDMT*. Monaco et al (2014) present two correlations to calculate *OCR* in sands. These equations are based, respectively, on the M_{DMT}/q_c ratio and on K_D. For this reason, a typical cone tip resistance profile (q_c) was defined based on three *CPTs* previously carried out at this site.

The *OCR* value determined by the oedometer test was 2.0 for 1.0 m depth and presented an approximately constant value equal to 1.0 up to 5 m depth (Fig. 7e). Fig. 7e also shows a good agreement between the *OCR* values estimated by the *SDMT* and those determined by the oedometer tests. Fig. 7f shows the M_{DMT} values estimated by *SDMT* and those obtained from the oedometer tests (M_{oed}). The M_{oed} value was 6.5 MPa at a depth of 1.0 m, and this parameter showed a value of 8.0 MPa at a depth of 5.0 m. Similarly to the *OCR*, the M_{DMT} values were in good agreement with those obtained from the oedometer tests (Fig. 7f).

The *SDMT* was an interesting tool for estimating design parameters for the *Unesp* site, which has unusual behavior. Therefore, methodologies for interpreting in situ tests on tropical soils have to be assessed for their application to such soils.

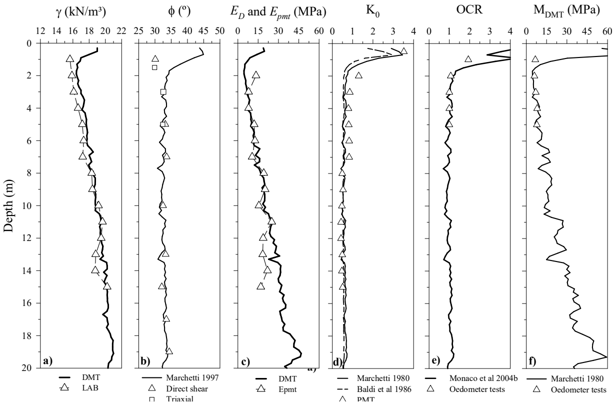

Figure 7. Estimated parameters from *SDMT* test for the Bauru Site and results from other tests.

4.5. Combined Seismic and Penetration Tests on Tropical Soils

Robertson et al. (1995), Schnaid et al. (2004), Schnaid and Yu (2007), Cruz (2012) and Robertson (2016) show that using the maximum shear modulus of the soil (G_0) in conjunction with data from penetration tests (*CPT* and *DMT*) is an interesting approach to characterize unusual geomaterials, such as tropical soils. The G_0/q_c, G_0/M_{DMT} and G_0/E_D ratios allow the unusual behavior of these soils to be identified, including sensitivity, aging, and cementation. Soils such as these cannot always have their design parameters defined by classical correlations. Fig. 8 shows G_0/q_c, G_0/M_{DMT} and G_0/E_D ratio for the *Unesp* site. Fig. 8 shows that the G_0/q_c, G_0/M_{DMT} and G_0/E_D ratios are higher in the more developed part of the site profile (the lateritic soil layer) and tend to decrease with increasing depth. The G_0/q_c ratio shows an average value of 63 up to a depth of 8.0 m, 53 between 8.0 and 10.0 m depth, 41 between 10.0 and 14.0 m depth and 30 below that depth. The G_0/E_D ratio shows an average value of 18 up to 6.0 m depth, 15 between 6.0 and 8.0 m depth, 12 between 8.0 and 11.0 m, 10 between 11.0 and 13.0 m and 7 below that depth. On the other hand, the G_0/M_{DMT} ratio shows an average value of 20 up to 6.0 m depth, 16 between 6.0 and 8.0 m depth, 13 between 8.0 and 11.0 m depth, 10 between 11.0 and 13.0 m depth and 6 below that depth. These results are in line with the findings of Schnaid et al. (1998) and Giacheti et al. (1999), where the ratio of elastic stiffness to strength/deformability at intermediate to large deformations increases with age and cementation, since the effect of cementation is greater in G_0 than in q_c, E_D and M_{DMT} and is higher for shallower lateritic soils.

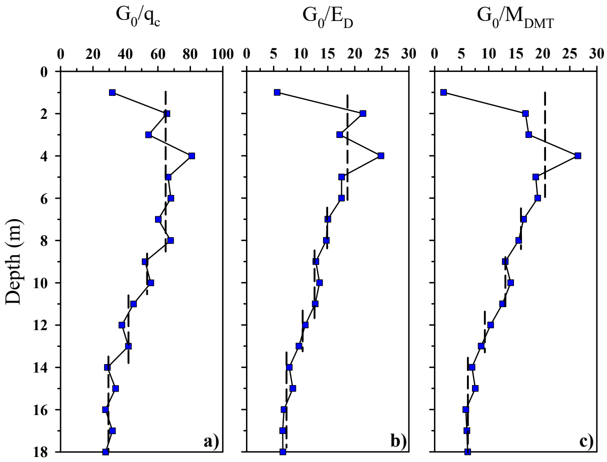

Figure 8. G_0/q_c, G_0/E_D and G_0/M_{DMT} ratios from *SCPT* and *SDMT* for the *Unesp* site.

4.6. Collapsible soil identification by *SCPT* and *SDMT*

Collapsible soils are unsaturated low-density soils that undergo abrupt settlement when flooded without any increase in the in-situ stress level (Vilar & Rodrigues 2011). These soils should be identified in the first stage of the site characterization, thus avoiding foundation settlement as well as wall tilting, and the impairment of water supply and sewage facilities (Rocha et al. 2021b).

Most of the methods available for identifying collapsible soils are based on laboratory test data. Such methods use Atterberg Limits and physical indices or a combination of them, or single or double oedometer tests (Jennings & Knight 1975; Gibbs & Bara 1967). High-quality samples are required for laboratory tests, but the sampling process and sample preparation can lead to disturbances and experimental errors when determining the geotechnical parameters used to identify collapsible soils. In addition, it is not feasible to obtain samples at great depths. An interesting alternative would be to use in situ tests such as the Seismic Cone (*SCPT*) and the Seismic Dilatometer (*SDMT*) to identify sites where collapsible soils are or to guide the definition of sampling spots for laboratory tests. Rocha et al. (2021) and Rocha et al. (2023) present and discuss two charts to identify collapsible soils from *SDMT* and *SCPT*, respectively. These authors used a comprehensive database with laboratory (single and double oedometric tests) and in situ (downhole, *CPT*, and *SDMT*) tests. They used the ratio G_0/M_{DMT} *vs* K_D for *SDMT* and the ratio G_0/q_c *vs* q_{c1} for *SCPT*.

The data was plotted on two dimensionless log-log charts to define regions and boundaries that separate collapsible soils from non-collapsible soils. Fig. 9 shows the data and the boundaries plotted on G_0/M_{DMT} *vs* K_D space, and Fig. 10 shows the data and the boundaries plotted on plotted in G_0/q_c *vs* q_{c1} space.

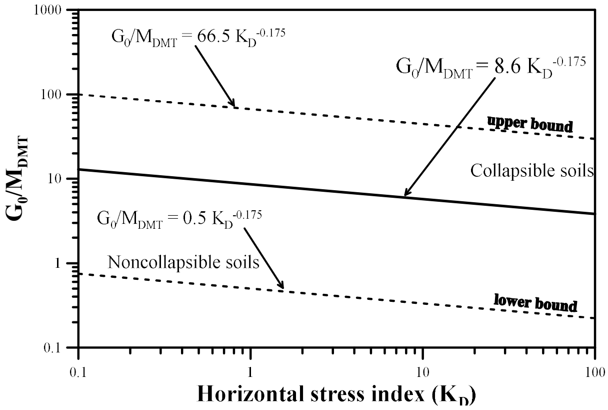

Figure 9. Collapsible soils identification by *SDMT* (adapted from Rocha et al. 2021b).

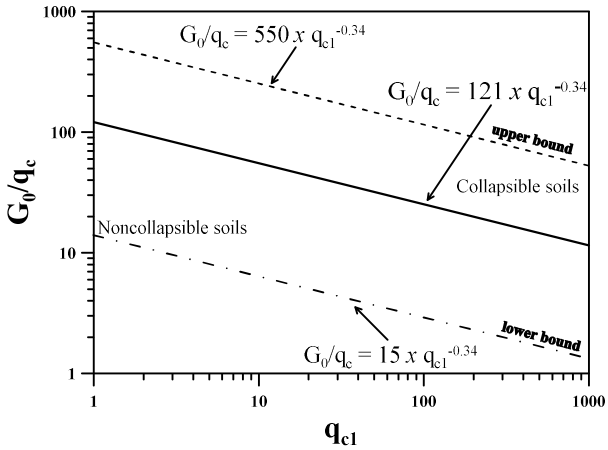

Figure 10. Collapsible soils identification by *SCPT* (adapted from Rocha et al. 2023).

5. Conclusions

Tropical soils exhibit peculiar behavior due to the geological and/or pedological processes inherent in their formation and their unsaturated condition. For this reason, classical soil mechanics has limitations in predicting the behavior of these geomaterials, especially when seasonal variability is considered. In this context, this paper presents and discusses *CPT* and *SDMT* performed on two tropical soil sites, emphasizing some considerations to be incorporated into the interpretation of in situ tests on unusual soils, such as the studied tropical soils. The main conclusions are:

- Tropical soils exhibit unusual behavior, so methodologies for interpreting in situ tests may not always be applicable and site-specific modifications may be required;
- Tropical soils are usually in an unsaturated condition, so the interpretation of in situ tests must take into account the seasonal variability in terms of suction, since it affects the mechanical soil behavior;

- The *CPT* did not allow an adequate definition of the stratigraphic profile at the *USP* site. This may be related to the unusual behavior of this soil, as well as its intermediate permeability;
- *SDMT* was an interesting tool for estimating design parameters for the soil at the *Unesp* site, even though this geomaterial is classified as unusual;
- The use of seismic and penetration resistance/large strain modulus (G_0/q_c, G_0/M_{DMT} and G_0/E_D ratios) using *SCPT* or *SDMT* is an interesting approach for identifying tropical soils, both lateritic and saprolitic. This approach considers both, strength, and stiffness, and reduces the effects of site variability, simplifying the interpretation. It would be more appropriate for a better understanding of soil behavior and would be useful for developing a more rational approach to foundation engineering in tropical soils.
- Collapsible soils should be identified in the early stages of site investigation campaign, in order to avoid geotechnical problems. Two approaches for identifying collapsible soils from *SCPT* and *SDMT* are therefore presented.

Acknowledgements

The authors thank *FAPESP*, the São Paulo Research Foundation (Grant # 2015/17260-0), *CNPq*, the National Council for Scientific and Technological Development (Grant # 2015/308895), and *CAPES*, the Coordination for the Improvement of Higher Education Personnel for supporting this research.

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