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Characterization of unsaturated tropical soil site by in situ tests

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ABSTRACT: Geotechnical site characterization consists in determining the stratigraphical profile, the groundwater level and the estimative of geo-mechanical designs parameters required for each project. In situ tests techniques can offer the best available and most economical way to achieve this characterization for different site conditions. This paper presents and discusses CPT, DMT, seismic (down-hole) and laboratory tests carried out in an unsaturated tropical sandy soil site, which the top 13 m is a colluvium overlaying a residual soil from sandstone. The results showed that the CPT and DMT tests were efficient for detailed stratigraphic logging, estimative of geotechnical parameters, however, temporal variability should be considered for proper site characterization of unsaturated tropical soils.

1 INTRODUCTION

The main objective of site characterization is to define the stratigraphical profile, which consists in identifying the soil layers, thickness, soil type, groundwater level and physical and mechanical properties. For this purpose, in situ and laboratory tests can be used. Some in-situ testing methods (e.g., CPT and DMT) can be used as an alternative to the traditional approach of drilling, sampling and laboratory testing, mainly in cohesionless soils, where reliable soil samples cannot be retrieved. Combining stratigraphic logging with a specific measurement at the some in situ test is a modern approach available for site characterization.

The cone penetration test (CPT) and the flat plate dilatometer test (DMT) are simple, remarkably operator-independent, rapid and they have been used more and more in geotechnical engineering practice. Both tests provide information about strength-stiffness soil behavior.

Tropical soils are predominantly formed by chemical-physical weathering of the rock. It is includes two classes: lateritic and saprolitic soils. Unsaturated tropical soil profiles have a cohesive-frictional behavior, where factors such as macro and microstructure, cementing, nonlinearity of stiffness, anisotropy, genesis and disintegration show greater influence on their behavior than the stress history (Vaughan et al. 1988). These factors have to be considered in the site characterization of this unusual geomaterial.

CPT, DMT and seismic test data from an unsaturated tropical soil are presented and discussed in this paper. The estimated soil parameters are compared to the available reference values determined by laboratory and others in situ tests. The seasonal site variability is considered and discussed from CPT tests carried out in two different weather conditions (wet season and dry season).

2 STUDY SITE

The study site is located at the experimental research area of the Research Group on Geotechnical Engineering from São Paulo State University - Bauru Campus. It is located on the central part of São Paulo State on the vicinities of the scarps of "cuestas" at the Paulista Central Plateau. The geographical coordinates are: 22º05' to 22º26' latitude south and 49º to 49º16'3 longitude west. The schematic position of São Paulo State, Bauru city, the Unesp campus and the research site in Brazil is shown on Figure 1.

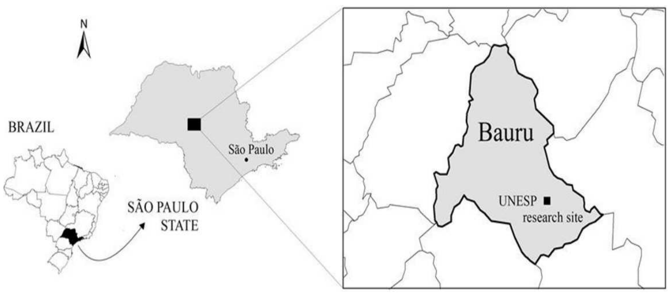

Figure 1: The location of the study site.

The Bauru city is located in the Bauru Group, which is formed by Marília and Adamantina Formation. In general, Marília Formation is composed by coarse and fine-grained sandstones. This rock mass also presents massive banks among tenues cross-stratifications, including layers of siltstones, mudstones and plane parallel-stratified sandstones. Moreover, sandstones present disseminated carbonate cementation configured by nodules and concretions. The Adamantina Formation consists of fluvial deposits with predominance of fine sandstones with lenses of sandy siltstones and mudstones. It presents cementation in the form of carbonate nodules. The studied profiles are generally unsaturated porous sandy soils with a high saturated hydraulic conductivity. An important geotechnical problem in this area is the soil collapsibility caused by wetting.

The climate of the region is subtropical with the concentration of rainfall in summer (between December to March). Total annual average rainfall in the Bauru city, varies in range from 870 mm to 1,720 mm. Figure 2 presents the average month water precipitation between 1981 to 2015. It is also possible to observe that the months of June, July and August present low average month precipitation value when compared to other months.

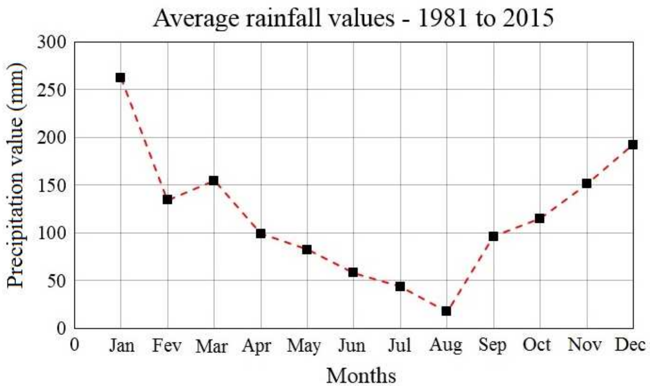

Figure 2: Average monthly precipitation values along 1981 and 2015 (IPMet, 2016)

3 SITE CHARACTERIZATION

SPT, SPT-T and different types of laboratory test were carried out to determine reference values for defining geotechnical soil parameters for the study site. Relevant geotechnical characteristics are summarized in Figure 3.

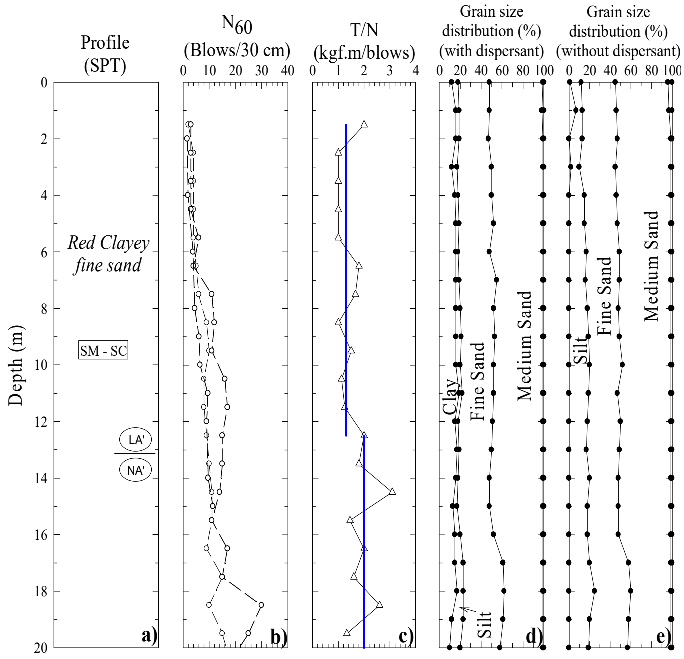

Figure 3: In situ and laboratory tests data (Rocha et al., 2015).

The soil profile is a red clayey fine sand identified based on SPT data. MCT Classification System (Nogami & Villibor 1981) classified the top 13 m as lateritic soil behavior (LA') followed by a non-lateritic soil behavior (NA'). N SPT values from SPT increase almost linearly with depth, up to 13 m depth (Fig. 3b). One SPT-T (Ranzine 1988) was carried out at the site and the T/N ratio profile is presented on Figure 3c. Figure 3c shows two different trends for the T/N ratio with average values of 1.3 for the top 12.5 m and 2.0 bellow this depth.

Grain size distribution for the soil samples retrieved every meter from one of the SPT were determined using dispersant (Fig. 3d) and without dispersant (Fig. 3e) as suggested for site characterization of tropical soils. It can be observed that clay and silt particles are naturally aggregated by oxides and hydroxides of iron and aluminium, which is typical in tropical soils.

The soil retention curve is an important information since the soil suction affects strength and stiffness parameters. Figure 4 shows the retention curves (drying method) for the soil samples collected at 1.5, 3.0 and 5.0 m depth from the study site.

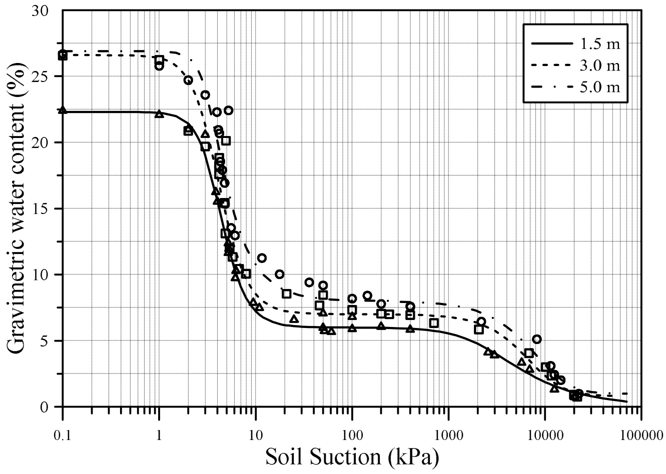

Figure 4: Soil-water retention curves (drying method) for 1.5, 3.0 and 5.0 m depth (after Fernandes et al. 2016).

4 TEST RESULTS AND ANALYSIS

4.1 *DMT*

Two DMTs were carried out at the study site and Fig 5 presents the tests data in terms of p_o, p_1, I_D, K_D and E_D where I_D, K_D and E_D calculated by Marchetti's (1980) equations. The soil behavior type was identified based on the I_D parameter (Fig. 5b) and the total unit weight was estimated by using the Marchetti & Crapps (1981) chart, which relates I_D and E_D values (Fig. 6).

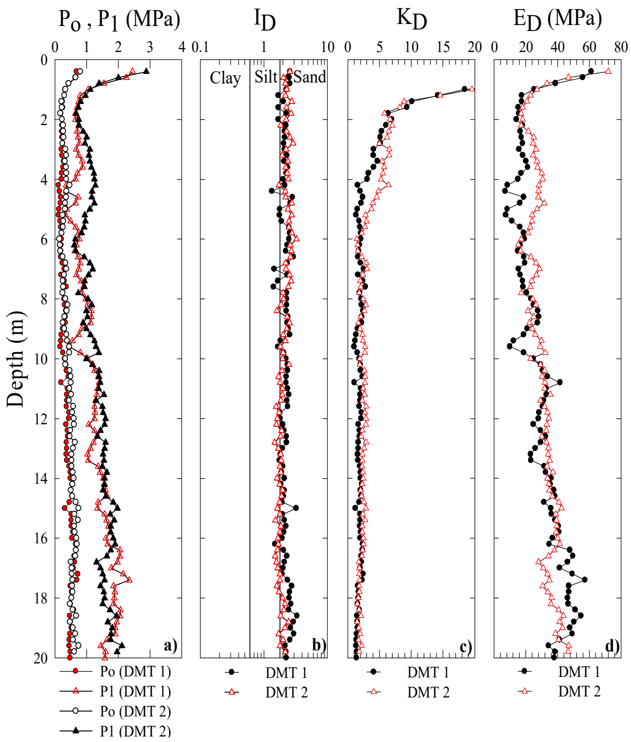

Figure 5: DMT tests data for the study site (adapted from Rocha et al., 2015)

4.1.1 *Soil Classification*

It can be observed in Figure 5b that the soil from the study site behaves like a silty sand. The grain size distribution determined in laboratory using dispersant according to the Brazilian standard (ABNT NBR-7181, 1988) classifies this soil as a clayey fine sand (Fig. 3.d). According to Marchetti et al. (2001), Material index (I_D) is not a result of a sieve analysis; instead it reflects the mechanical response of the soil to the DMT membrane expansion. Usually this index indicates that a mixture of clay and sand would generally be described as silt, which was obtained from grain size distribution without dispersant (Fig. 3e).

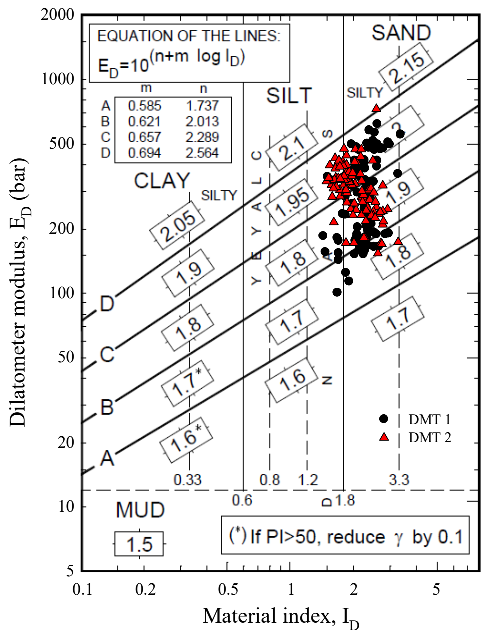

Figure 6: Study site testing data on the schematic DMT soil classification chart proposed by Marchetti & Crapps (1981).

4.1.2 *Geotechnical parameters*

One of the most important information for geotechnical projects are the strength parameters. Classical Soil Mechanics considers that sands are frictional geomaterials (ϕ') while unsaturated tropical soils have a cohesive-friccional behavior, so soil suction should be considered to proper represent their behavior. Fagundes & Rodrigues (2015) studied the influence of soil suction (s) on the shear strength of an undisturbed sample extracted from 1.5 m depth from the study site. They concluded that the friction angle (ϕ') values varied from 26.8º for the saturated condition and 32.7º for the higher suction value with an average value equal to 29.3º (Fig. 7a). The intercept of cohesion increased with suction from zero on the saturated condition to 3 kPa (s = 50 kPa), to 11 (s = 200 kPa) 16 kPa (s = 400 kPa) and to 34 (s = 33 MPa). The same study was carried by Fernandes et al. (2016) on undisturbed samples collected at 3 and 5 m depth. The authors also observed the increase on shear strength with soil suction. For 3 m depth the friction angle (ϕ') values varied from 32.6º for saturated condition and 33.8º for 400 kPa suction value, with an average value equal to 33.4º as shown on

Figure 7a. The intercept of cohesion increased with suction from 1.2 kPa on the saturated condition to 6.5 kPa (s = 50 kPa), to 13.4 kPa (s = 200 kPa) and 21.5 kPa (s = 400 kPa). The friction angle (ϕ') values varied from 32.4º for the saturated condition and 34.9º for the 400 kPa suction value with an average value equal to 33.8º for the sample collected at 5 m depth (Fig. 7a). The intercept of cohesion increased with suction from 5.3 kPa on the saturated condition to 10.3 kPa (s = 50 kPa), to 24.2 kPa (s = 200 kPa) and 28.7 kPa (s = 400 kPa).

Giacheti et al. (2006) presented reference friction angle determined using direct shear tests under consolidated drained condition (CD) on undisturbed soil samples up to 19 m depth at its natural soil condition for this site, as show in Figure 7a. The ϕ' angle varied from 30.1º to the soil from 1 m depth to 34.4º to the one from 19 m depth, with average value equal to 32.8º. The reference values were compared with friction angle based on Marchetti (1997) equation, which is depended of K_D values (Fig. 8a).

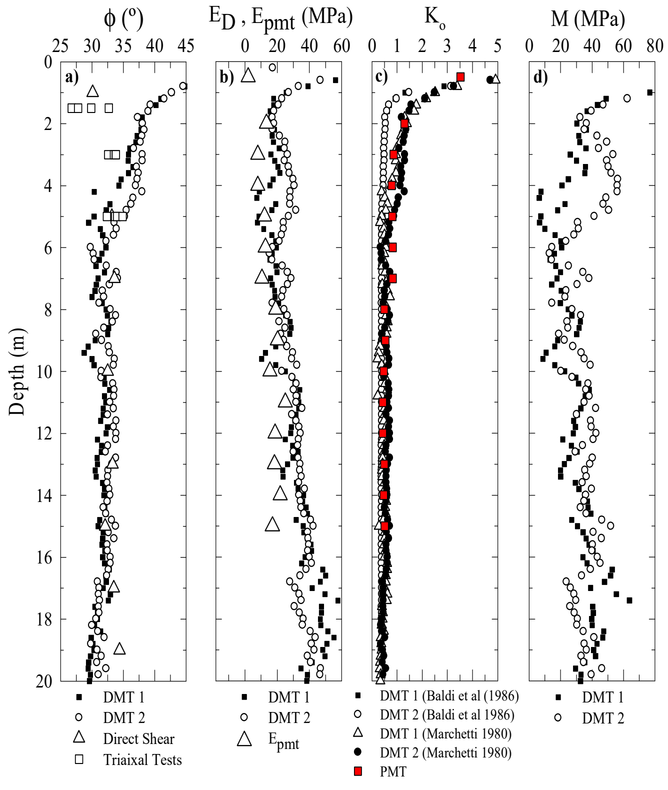

Figure 7: Estimated parameters from DMT tests data

It can be observed in Figure 7a that the estimated DMT friction angle values were reasonable below 5 m depth, with an average value of about 33º. However, the estimated DMT ϕ' values are much higher than the reference ones for the 5 m topsoil. This difference are caused by the influence of soil suction, which provides mainly an increase on the intercept of cohesion. Moreover, the estimated DMT ϕ' values incorporates the component of cohesion as a friction angle, since it assumes the soil behaves like sands.

Pressuremeter modulus (E_{pmt}) and coefficient of earth pressure at rest (K_o) obtained from Ménard pressuremeter tests (PMT) carried out by Cavalcante et al (2005) in this site will be used to evaluate the K_o and E_D determined using DMT correlations. Figure 7b shows E_D plotted together with Ménard PMT modulus (E_{pmt}). It can be observed that DMT data are produced reasonable estimates for deformability parameters, however, the E_D is always higher than E_{pmt} values. It can be explained by soil disturbance due to penetrations of DMT and PMT (Ortigão et al. 1996 and Giacheti et al. 2006).

Figure 7c presents K_o values estimated based on DMT data using Marchetti (1980) and Baldi et al. (1986) correlations plotted together with the K_o values interpreted based on PMT data. K_o from PMT is equal to 3.5 at 0.5 m depth, 1.3 at 1.5 m depth and it assumes an almost constant value equal to 0.8 up to about 8 m depth. For this part of the soil profile K_o predicted using Marchetti (1980) correlation better matched PMT K_o values. Below 8 m depth, the estimated K_o values from Baldi et al. (1986) correlation are closer to the PMT K_o values, which assumed almost a constant value equal to about 0.5 from 8 to 20 m depth.

One of the major application of the DMT is prediction settlements by use of Constrained Modulus (M_{DMT}). Figure 7d presents the constrained modulus estimated based on DMT data. The average M_{DMT} is equal 36.2 MPa between 1 to 6 m depth, 23 MPa between 6 to 10 m depth and 35.8 MPa below 10 m depth. Unfortunately, there are no oedometer tests for this site to provide reference constrained modulus values.

4.2 *CPT*

Figure 8 shows the average profiles from two CPTs campaigns carried out at the study site in a dry and in a wet season. The water content profiles for each of these seasons are also presented on this figure. They were measured based on soil samples collect using mechanical helical auger. These profiles are very different above 4 m depth (Figure 8). Considering the information from the water retention curves presented on Figure 4 it can be assumed that the soil suction values along all the soil profile is low during the wet season. In the other hand, during the dry season, soil suction values are much higher from 0 to 4 m depth.

It can also be observed in Figure 8 that the CPT data were affected by soil suction up to 4 m depth, since the other relevant characteristics of the soil profile did no significantly varied (relative density, grain size and stress history). As a result, q_c and f_s increased due to a higher suction during the dry season. The q_c and f_s profiles presented similar behavior below this depth (4 m) during the wet and the dry season, since soil suction varied very little. It is important to point out that the range of variation on the water content in the field at the study site corresponds to the end of desaturation of the soil-water retention curves (Fig. 4). Changes on water content values reflected high changes in soil suction up to for 4 depth. It can explain significant differences on suction values up to this depth, which caused differences on q_c and f_s profiles determined in the different seasons up to the same 4 m depth.

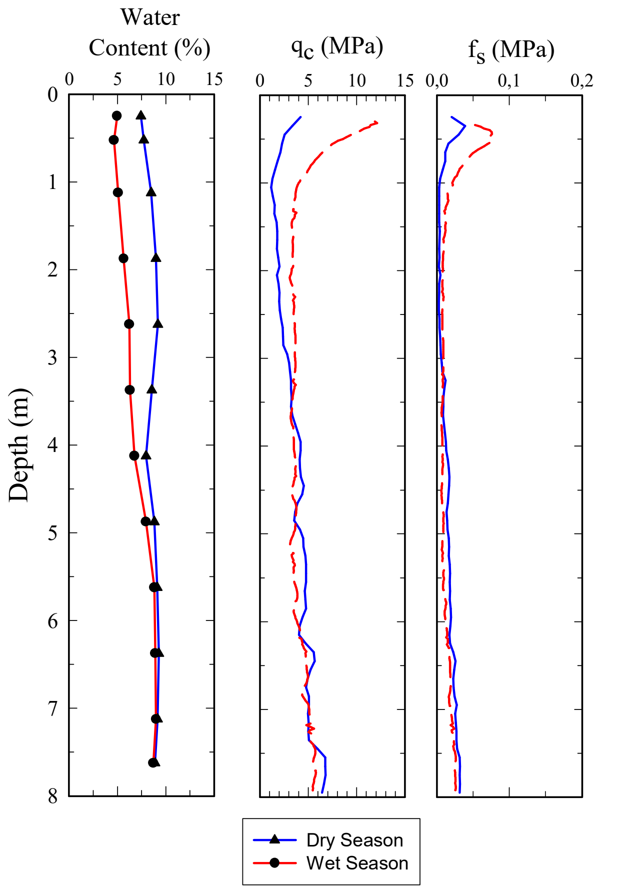

Figure 8. Water content, suction and two CPTs carried out in a dry and in a wet season at the study site (After Bezerra 2016).

4.2.1 *Soil Classification*

Robertson (2012) chart was used to show the influence of soil suction on the interpretation of CPT data. Figure 9 shows the two CPT data up to just 4 depth during the wet and the dry seasons. It can be observed in this figure a predominant contractive soil behavior for the CPT carried out in the wet season and a dilative behavior for the CPT from the dry season.

Fagundes & Rodrigues (2015) carried out suction-controlled triaxial drained shear tests (CD) to evaluate the influence of suction of the mechanical behavior of the 1.5 m depth soils of the study site. Figure 10 shows stress-strain and volume change curves obtained by CD tests at five different suctions (0, 50, 200, 400 kPa and 33 MPa) for 50 kPa confining pressure, which corresponds to mean effective stress for first meters of the study site.

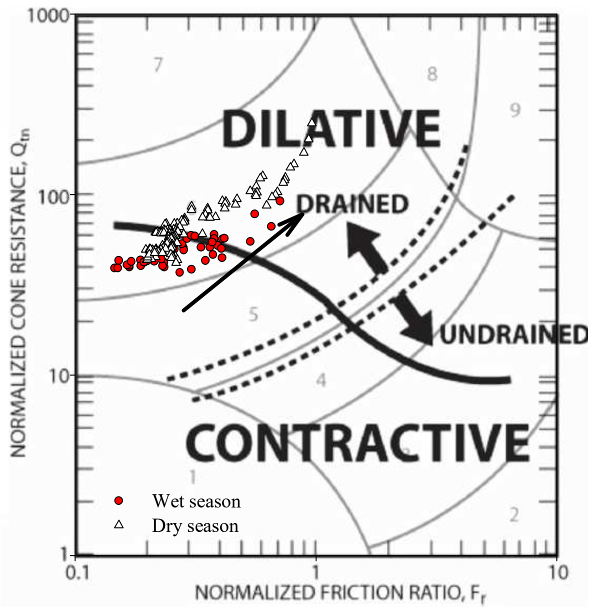

Figure 9: Q_{tn} vs F_t average values for wet and dry seasons I the Robertson (2012) chart.

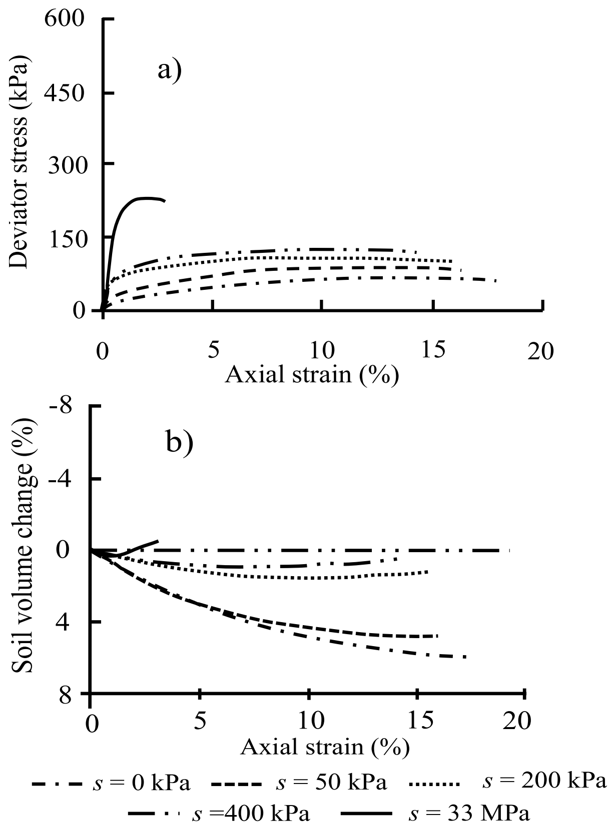

Figure 10: Stress-strain and volume change for unsaturated soil from 1 m depth (adapted from Fagundes & Rodrigues, 2015).

It can be observed in this figure a tendency for dilation during shear with increasing suction. Similar behavior was observed on the CPTs carried out in the dry season, due to higher values soil suction up to 4 m depth, which brought the points on Robertson (2012) chart from a contractive to a dilative behavior during the plastic deformation of the soil.

Considering the fact that the tests were carried out at the same position (to neglect the spatial variability), it is possible to consider the importance of the temporal variability (caused by water content and consequently the soil suction) which affects the soil behavior of unsaturated tropical soils.

4.2.2 *Geotechnical Parameters*

There are several correlations to estimate strength-strain properties of soils based on CPT. The estimative of geotechnical parameters from unsaturated soils is affected by soil suction, as previously discussed. Figure 11 shows the profiles of frictional angle (ϕ'), Young's modulus (E) and constrained modulus (M) estimated respectively by Robertson & Campanella (1983), Robertson (2009), Lunne & Christoffersen (1983) correlations, based on CPT carried out at the wet and dry seasons at the study site.

It can be seen in Figure 11 that the values of ϕ', E and M for dry season are higher than those estimated for wet season mainly in the upper part of the soil profile (4 m depth) where major influence of soil suction occurs. The tip resistance (q_c) and lateral friction (f_s) from CPT should be normalize to a reference suction value (zero suction) in order to proper take into account the influence of soil suction on the soil behavior, both in terms of soil classification, and geotechnical parameters estimative.

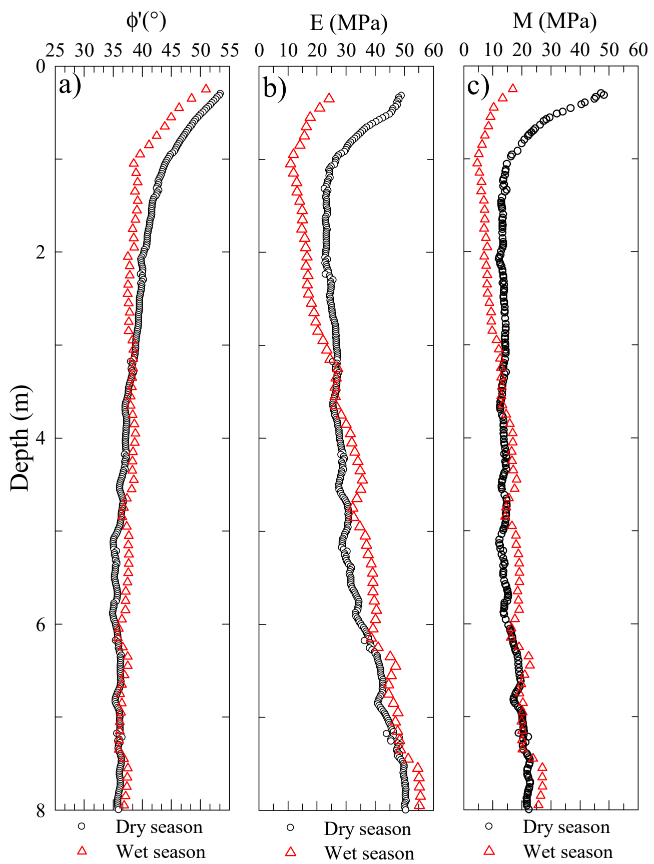

Figure 11: (a) Friction angle (ϕ'), (b) Young's modulus (E), and (c) constrained modulus (M) based on CPT data from the wet and the dry season for the study site.

5 SEISMIC TEST

Robertson et al. (1995), Schnaid et al. (2004), Schnaid & Yu (2007) and Cruz (2010 and 2012) demonstrate that the maximum shear modulus (G_o) together with SPT, CPT or DMT data is a useful tool to identify unusual geomaterials, such as the tropical soils. The G_o/q_c, G_o/M_{DMT} and G_o/E_D ratios allow evaluating the peculiar behavior of these soils (e.g. sensibility, age, cementation, etc.).

Schnaid et al. (2004) suggest that the G_o/q_c ratio provides a measure of the elastic stiffness to ultimate strength and may hence be expected to increase with sand age and cementation, primarily because the effect of these on G_o are stronger than on q_c. Schnaid et al. (2004) use the G_o/q_c *versus* q_{c1} chart, where q_{c1} is dimensionless normalized parameter defined as:

$$qc_1 = \left(\frac{q_c}{p_a}\right) \cdot \sqrt{\frac{P_a}{\sigma'_v}} \quad (1)$$

where p_a = atmospheric pressure and σ'_v = vertical effective stress. According to Eslaamizaad & Robertson (1996) this relationship can be used to evaluate possible effects of stress history, degree of cementation and ageing for a given soil profile.

Cruz (2010) interpreted DMT data and suggested two charts and their boundaries to identify cemented structures in residual soils. The author used the G_o/E_D *vs* I_D and G_o/M_{DMT} *vs* K_D charts.

Six down-hole tests were carried out at the study site. Figure 12 presents the shear wave velocity (V_S) and maximum shear modulus (G_o) profiles.

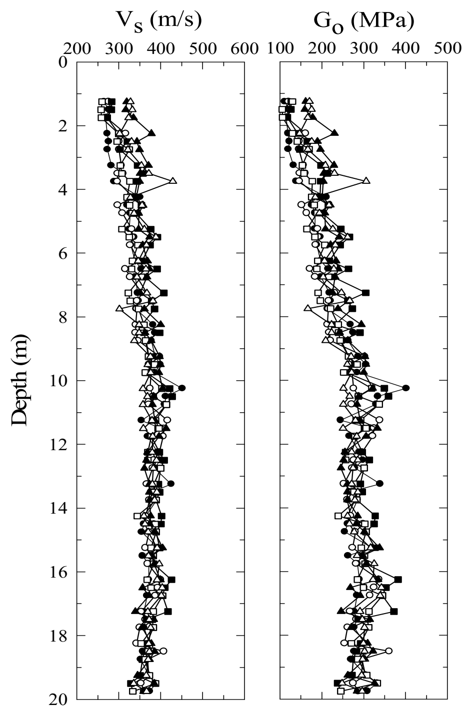

Figure 12: V_S and G_o profiles from downhole tests carried out at the study site.

The maximum shear modulus was calculated by the equation 2:

$$G_O = \rho . V_S{}^2 \quad (2)$$

where V_S is shear wave velocity, and ρ is the soil density, which was determined from undisturbed soil samples collected in sample pits excavated at the site.

Figure 13 e Figure 14 show the G_o/E_D *vs* I_D and G_o/M_{DMT} *vs* K_D charts, respectively, obtained from average values of G_o, I_D, K_D, E_D and M_{DMT}. Three lines and one equation are shown in each chart (Fig. 13 and Fig. 14) to define the limits for the DMT sedimentary international database and upper bounds for cemented structured soils (Cruz, 2010).

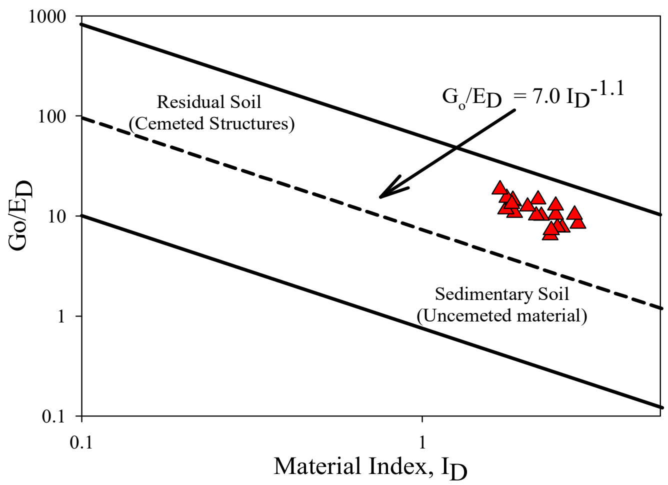

Figure 13: Seismic and DMT data plotted on G_o/E_D vs I_D chart for the study site (adapted from Cruz 2010).

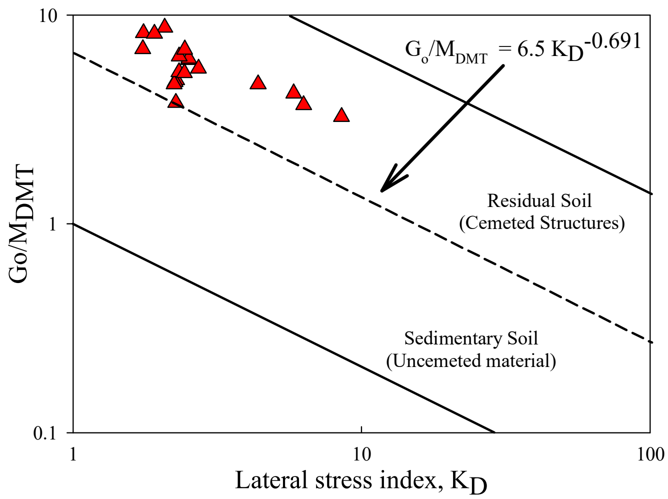

Figure 14: Seismic and DMT data plotted on G_o/M_{DMT} vs K_D chart for the study site (adapted from Cruz 2010).

In both charts the plotted data from the study site are above the equation line which separates the DMT sedimentary international database and nearby to the residual soil (cemented structures). It indicates that the bonded structure of the studied unsaturated tropical sandy soils produces G_o/E_D as well as G_o/M_{DMT} that are systematically higher than those measured in sedimentary soils.

The average values of q_c and G_o are plotted in the Schnaid et al. (2004) chart (Fig. 15) based on the data from both CPTs and all seismic tests. It shows that the G_o/q_c ratio for all soils from the study site are higher than those measured in cohesionless soils. In addition, it can be observed in this figure that the lateritic soils present a higher G_o/q_c than the saprolitic soils, which is in accordance with the findings from Giacheti & De Mio (2008).

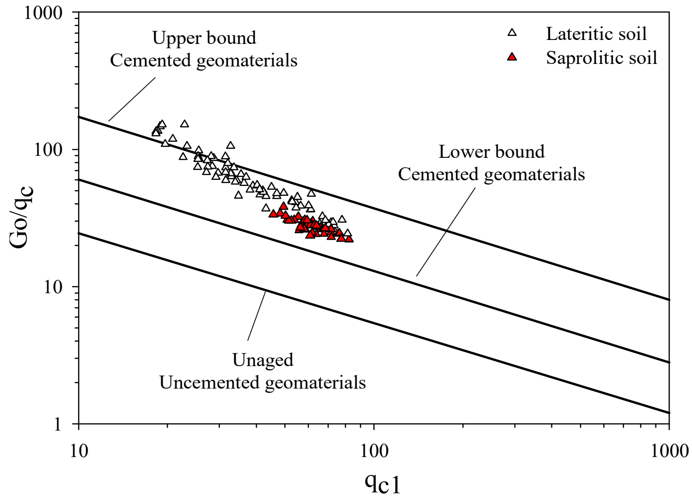

Figure 15: G_o/q_c for lateritic and saprolitic soils from the study site in the Schnaid et al. (2004) chart.

6 CONCLUSIONS

- The I_D parameter classified sand and clay mixtures from the study site as silty soils. This behavior is similar to which were found in the in situ grain size distribution determined without dispersant.
- The estimated geotechnical soil parameters based on classical DMT correlations worked well for the soil below 5 m depth for the study site. The friction angle estimative was much higher for topsoil. The unsaturated soil from the study site has a cohesive-friction behavior, which depends on soil suction. This estimative try to represent it just in terms of the friction angle.
- The average profiles from two CPTs campaings carried out in different seasons indicated that soil suction affected q_c and f_s values up to 4 m depth for the study site.
- The interpretation of CPTs carried out in the different seasons brought the points on Robertson (2012) chart from a contractive (wet season) to a dilative (dry season) behavior, which is in accordance to what was found in unsaturated triaxial tests carried out on undisturbed soil samples from the study site.
- The mechanical behavior of unsaturated tropical soils is directly influenced by soil suction. As a result, in situ soil index and estimated geotechnical parameters based these indexes should con-

sider the influence of soil suction. So, the moisture content profile together with the soil-water retention curve are relevant information for a proper site characterization for the study site.

- The charts from Cruz (2010) and Schnaid et al (2004) indicate that the soil from the study site has an unusual behavior. The bonded structure of unsaturated tropical sandy soils produced G_o/E_D, G_o/M_{DMT} and G_o/q_c, which are systematically higher than those measured in sedimentary soils.
- The test data and their interpretation pointed out the importance of using hybrid tests, like SCPT and SDMT, for the site characterization of unsaturated tropical soils as well as the importance of considering the temporal variability caused by soil suction, since it affects the soil behavior of unsaturated tropical soils.

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