CPTu and SDMT on the characterization of a tropical soil site

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ABSTRACT: The stratigraphical profile, the groundwater level and the geo-mechanical design parameters are required for a proper geotechnical site characterization. The piezocone (CPTu) and the seismic flat dilatometer (SDMT) have been used for site investigation worldwide. The base of the interpretation of such tests was elaborated to explain the behavior of conventional soils, and there are limitations to its use for unusual soils. So, identifying unusual soils are relevant and the combination of seismic and penetration tests has been successfully used for this purpose. This paper presents and discusses the applicability of CPTu and SDMT for the geotechnical characterization of a tropical soil site. The site has a residual soil from Sandstone overlaid by a colluvium soil, which were substantially modified by pedogenetic and morphologic process due to climate tropical conditions. CPTu and SDMT were initially interpreted to define unusual soil behavior. Classifications and correlations to estimate geotechnical soil parameters were used and the results were compared to the ones obtained from laboratory tests.

Keywords: In situ tests; tropical soils; CPTu; SDMT

1. Introduction

In a proper site characterization it is necessary to define the subsoil profile, which includes identifying the position of the layers, thickness, soil type and the groundwater table. In addition, it is also necessary to estimate the hydraulic and mechanical parameters of the horizons of interest.

Piezocone (CPTu) and Seismic Dilatometer (SDMT) have been used by the geotechnical community as logging tools for site investigation. Moreover, SDMT allows to determine the shear wave velocity to calculate de maximum shear modulus based on elasticity theory. The other geotechnical parameters can be estimated based on correlations developed mainly for soils from Europe and North America.

Tropical soils are predominantly formed by chemical alteration of the rocks. The main difference observed in tropical soils, with respect to classic sedimentary soils, is the presence of a bonding structure, which generates a cohesive-frictional nature, anisotropy due to relic structure, unstructuring under shear conditions and low influence of stress history [1].

This paper presents and discusses the results of CPTu and SDMT tests carried out at a research site located inland of the state of São Paulo, Brazil. It has a residual soil from Sandstone overlaid by a colluvium soil, which was substantially modified by pedogenetic and morphologic process due to climate tropical conditions. The combination of seismic and penetration tests was done to identify unusual soil occurrence. The applicability of CPTu and SDMT for the geotechnical site characterization according to the traditional approach was presented and discussed. The estimated soil parameters are compared to the available reference values determined based on laboratory and others in situ tests.

2. CPTu

The CPTu in carried out pushing a standard instrumented cone probe into the ground in the standard rate of 20 mm/s by a hydraulic jack and a reaction system. The probe has 60º cone tip, with 10 cm² base area and a 150 cm² friction sleeve located above the cone tip and a transducer to register pore pressure.

The standard CPTu measurements of tip bearing (q_c), sleeve friction (f_s) and pore pressure behind the tip (u_2) are continuously recorded typically every 25 or 50 mm. These three parameters, in various combinations such as friction ratio F_r (= f_s/q_c), are used to delineate site stratigraphy [3]. Several classification charts can be used to describe soil type for engineering applications [4-7].

3. SDMT

The flat dilatometer (DMT) was developed in Italy by Silvano Marchetti. It was introduced in North America and Europe in 1980 and it has been currently used in over 40 countries [8].

The DMT test starts by inserting the dilatometer into the ground. Soon after penetration, the operator inflates the membrane and takes two readings: the A-pressure and the B-pressure by use of the control unit. The A-pressure, required to just begin to move the membrane against the soil ("lift-off") and the B-pressure, required to move the center of the membrane 1.1 mm against the soil [8].

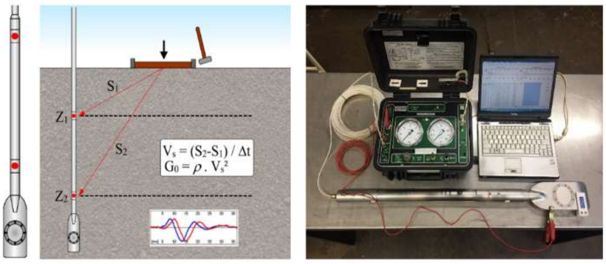
The blade is 95 mm width, 15 mm thickness and it has a circular steel membrane of 60 mm in diameter. The membrane is mounted flush on the blade and kept in place by a retaining ring [8].

The DMT interpretation starts by identifying of three intermediate DMT parameters [8]:

– material index: $I_D = (p_1-p_0)/(p_0-u_0)$
– horizontal stress index: $K_D = (p_1-p_0)/(\sigma'_{v0})$

– dilatometer modulus: $E_D = 34.7^* (p_0 - p_1)$

The seismic dilatometer (SDMT) is the combination of the standard DMT with a seismic module for measuring the shear wave velocity (Vs) [9]. The seismic module is a cylindrical element placed above the DMT blade, equipped with two receivers, spaced 0.5 m apart (Fig 1a). Vs is calculated (Fig 1b) by the ratio between the difference in distance from the source and the two receivers (S_2 - S_1) and the delay of the arrival of the impulse from the first to the second receivers (Δt). Figure 1c shows the seismic dilatometer equipment.



(a) (b) (c)

Figure 1. Seismic Dilatometer (SDMT): (a) DMT blade with a seismic module; (b) Schematic representation of the SDMT; (c) Seismic dilatometer equipment (adapted from Marchetti et al. [9]).

4. Study site

CPTu and SDMT were carried out at the University of São Paulo (USP) research site, located in São Carlos, state of São Paulo, Brazil (Fig 2).

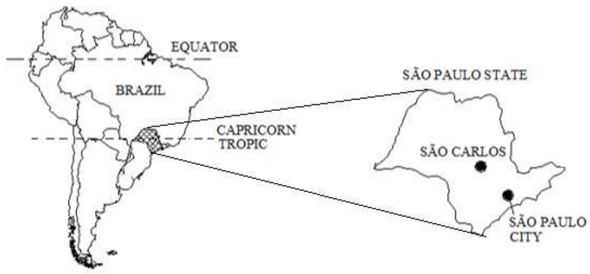


Figure 2. São Carlos, where the studied site is located.

The soil profile (Fig. 3a) at the site can be basically divided in a brown clayey fine sand (Cenozoic Sediment with lateritic behavior - LA') up to about 6 m depth. Under this layer there is a pebbles layer of about 0.5 m thick. The last layer is a residual soil from Sandstone: a red clayey fine sand with non-lateritic behavior - NA'. The MCT Soil Classification System (Mini, Compacted, Tropical) proposed by Nogami and Villibor [11] was used to define and classify the soil with regards to its lateritic behavior. The groundwater level varies seasonally between 9 and 12 m below the ground surface. N_{SPT} values tend to increase with depth (Fig. 3b) and the soil is composed by sand (around 70%), silt (around 5%) and clay (around 25%) as show in Figure 3.c. The void ratio (e) values decrease with depth varying from 1.17 at 1.0 m depth to 0.63 at 9.0 m depth (Fig. 3d).

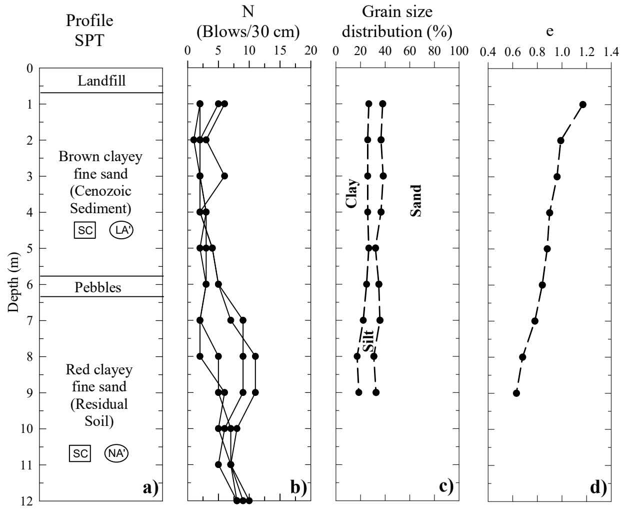


Figure 3. In situ and laboratory tests data (adapted from Machado [10]).

5. Test results and discussion

Six CPTus and six DMTs (four of them with seismic measurement - SDMT) were carried out at the site in March 2016 and in April 2017. (three CPTus and three DMTs in each test campaign). Soil sampling was also carried using a helical auger to collected samples to determine the water content profiles (Fig 4a) in each campaign. Soil suction was estimated using water content data and a Soil Water Retention Curves (SWRC) determined by Machado [10] from undisturbed soil samples collected at 2, 5, and 8 m depth (Fig. 4b). They were determined by suction-plate and pressure-chamber techniques.

The soil water content varied from 16% to 20% between 1 to 8 m depth (Fig. 4.a), resulting in soil suction values lower than 20 kPa (Fig. 4b). Deliberately both test campaigns were carried out in end of the wet season to have lower soil suction influence on the test data.

5.1. CPTu

Six CPTus were carried out at the site. They were pushed into the ground with a multi-purpose pushing device with the penetration rate 20 mm/s. The u_2 values were recorded by using the slot filter filled with grease [12] in four tests and with the porous element saturated with glycerin in two tests. The slot filter was used because the porous element can be desaturated by suction during penetration before reaching the groundwater table. The slot filter technique is easier to prepare and useful to get additional information for stratigraphic logging, as well as to assist the definition of the groundwater table [13].

Figure 5 presents the tests data in terms of q_t, F_r and u_2 for both test campaigns. The CPTus carried out in both campaigns present similar q_t and F_r profiles, mainly bellow 2 m depth, which indicates lower soil suction on the CPTus carried out in the wet season [12, 15]. The soil was classified based on the I_c, the soil behavior type index (Figs. 5d and 5e). The average CPTus data were plotted in Robertson´s [7] charts (Fig 6). Figure 6 shows sand-like-dilative (SD) soils up to 1.0 m depth. The soil was classified as transitional (TD) between 1.0 to 2.2 m depth, and as a clay-like-dilative soil below 2.2 m depth (Fig. 6). It is interesting to note that almost all the soils present a dilative behavior at large strains.

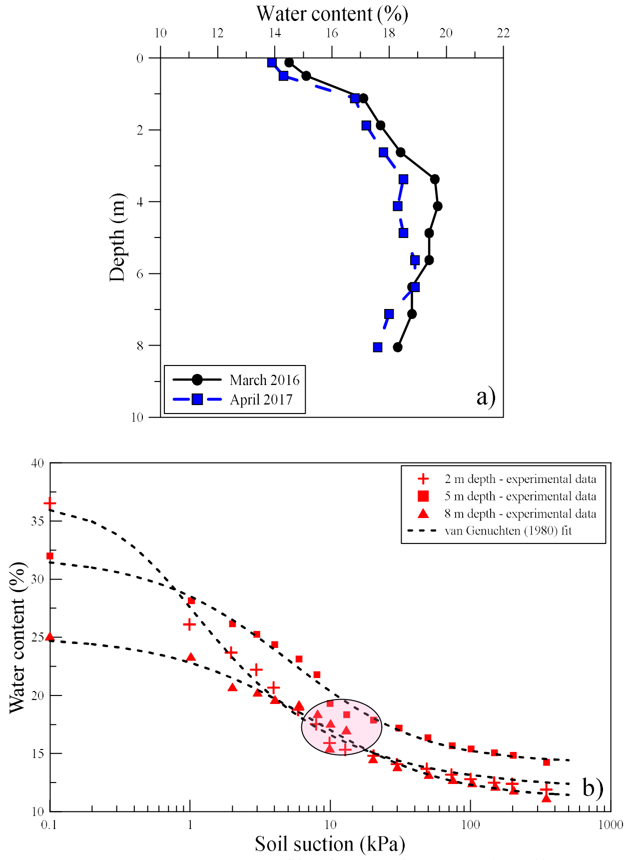


Figure 4. a) Water content profiles for March 2016 and April 2017 campaigns (adapted from Rocha [14]), b) Soil water retention curves for soils collected at 2, 5 and 8 m depths (adapted from Machado [10]).

Machado [10] carried out triaxial tests on undisturbed samples collected in this site. Santos et al. [16] interpreted and discussed such data and pointed out that these soils have a contractive behavior in the drained triaxial tests and no dilation during failure. This behavior is quite different than what was observed based on the CPTu data interpretation. The CPTu test interpretation considers that clays have undrained cone penetration and sands and gravels have fully drained cone penetration. The partially drained cone penetration probably occurred in study site which can be explained considering the soil characteristics, due to its intermediate permeability, in the range of 10^{-5} to 10^{-8} m/s [17]. So, inappropriate soil classification and geotechnical parameters estimation can occur in this site. The CPT data interpretation could be better adjusted in soils like that by using different penetration rates, as suggested by [18, 19].

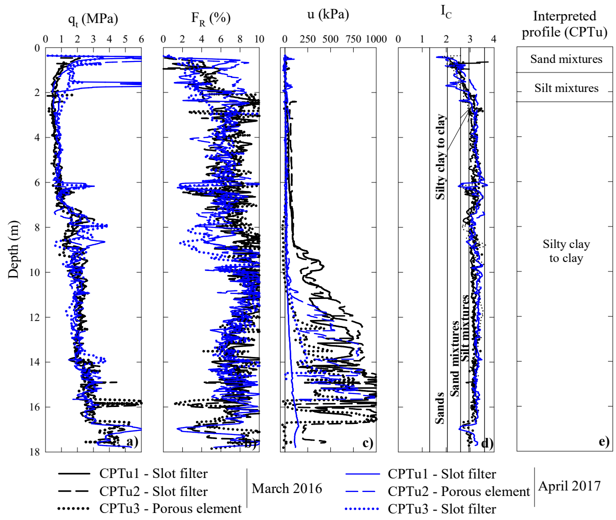


Figure 5. CPTu tests data and interpretation for both campaigns.

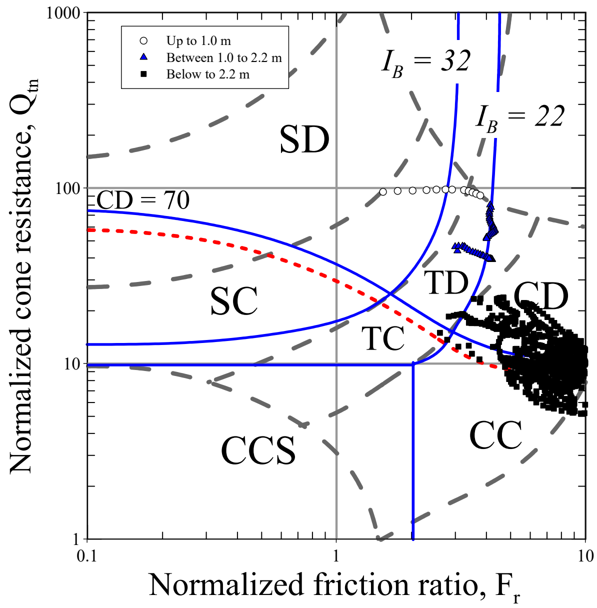


Figure 6. Average CPTu data from the study site in the normalized CPT soil behavior from Robertson [7]. The symbols are: CCS: Clay-like Contractive – Sensitive. CC: Clay-like Contractive. CD: Clay-like Dilative. TC: Transitional Contractive. TD: Transitional Dilative. SC: Sand Contractive. SD: Sand Dilative.

Robertson [7] suggests the seismic cone (SCPT) as a useful tool to identify unusual geomaterials, such as the tropical soils. The author proposed the use of a modified normalized small strain rigidity index (K^*_G), the small strain rigidity index (I_G) and normalized cone resistance with a variable stress exponent (Q_{tn}). The I_G is defined by equation 1 and K^*_G by equation 2:

$$I_G = \left(\frac{G_0}{q_n}\right) = \left(\frac{G_0}{q_t - \sigma_v}\right) \quad (1)$$

$$K_G^* = \left(\frac{G_0}{q_n}\right).(Q_{tn})^{0.75} \quad (2)$$

where G_0 is the maximum shear modulus and σ_v is the vertical stress.

Robertson [7] demonstrated that soils with K^*_G lower than 330 are likely young and uncemented. Moreover, soils with K^*_G higher than 330 tend to have significant microstructure (cemented/bonding and ageing).

Figure 7 presents I_G *vs* Q_{tn} chart and the average data for the studied site. I_G was calculated considered the average G_0 values determined by the SDMTs (Figure 8d). It indicates that the porous bonded structure of tropical sandy soils caused by oxide and hydroxide of aluminum produced K^*_G values higher than 330.

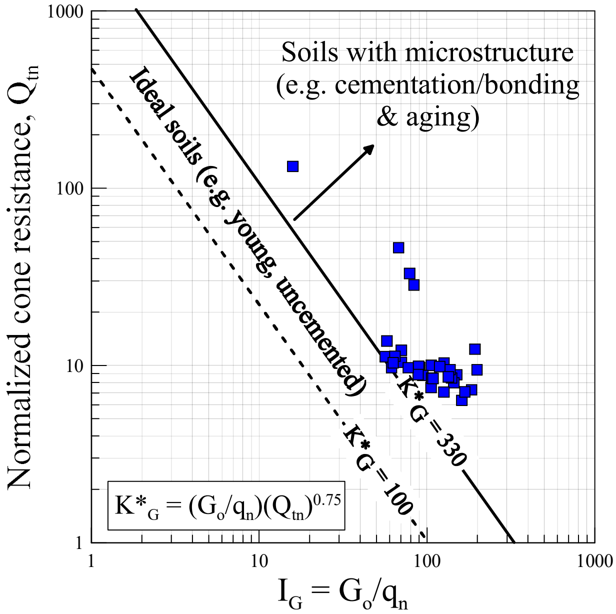


Figure 7. Average CPT and seismic data from the site plotted on Q_{tn} *vs* I_G chart from Robertson [7] to identify soils with microstructure.

According to Robertson [7], the proposed 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. Therefore, the conventional empirical correlations for CPTu data interpretation was not used for the cone tests carried out in this site.

5.2. SDMT

Six DMTs, four of them with seismic (SDMT), were carried out at the site. The dilatometer and the seismic module were pushed into the ground with the same CPT pushing device. Figure 8 presents the tests data in terms of I_D, K_D, E_D and Vs. I_D, K_D, E_D were calculated by Marchetti's equations [20]. The soil behavior type was defined based on the I_D parameter (Fig. 8a) by using Marchetti & Crapps´ chart [21] (Fig. 9).

It can be observed in Figure 8a and Figure 9 that the soil from the study site behaves like a silty sand up to 3.5 m depth and as a silt below this depth. The grain size distribution determined in laboratory using dispersant according to the Brazilian standard [22] classifies this soil as a clayey sand (Fig. 3.c). According to Marchetti et al. [8], the material index (I_D) is not a result of a sieve analysis; it reflects the mechanical response of the soil to the DMT membrane expansion.

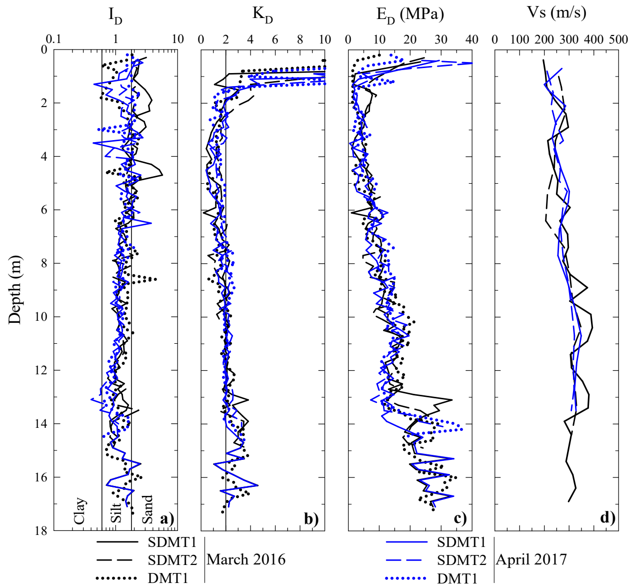


Figure 8. SDMT data for the study site.

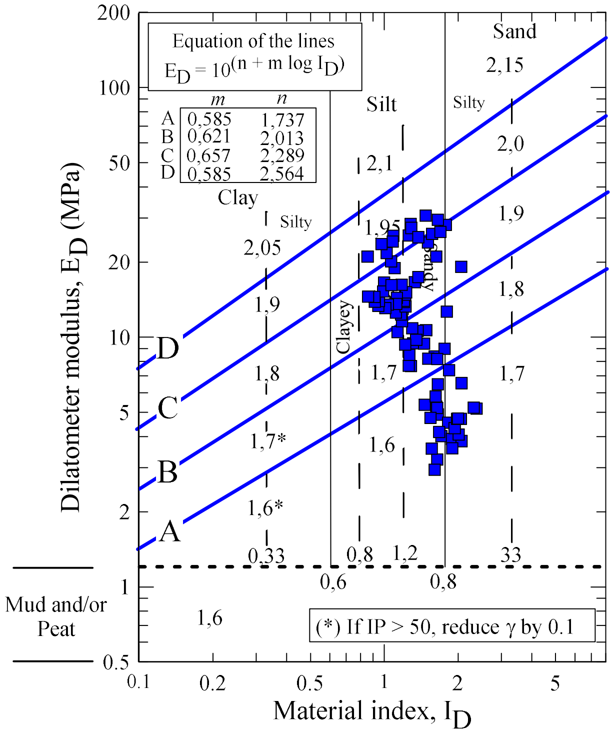


Figure 9. Average SDMT data from the site plotted in the Marchetti & Crapps´ soil classification chart [21].

SDMT data can also be interpreted using the SBT fundamentals, as previously presented in the CPTu interpretation. Robertson´s [23] chart presents the approximate boundary between dilative and contractive behavior at large strains for soils with little or no microstructure. Figure 10 presents this chart together with the plotted average SDMTs data. It is possible to observe in this figure that practically all the soils from the study site presents drained and contractive behavior. It is in a better agreement to what was observed in the drained triaxial test data carried out by Machado [10], so a tentative geotechnical parameters estimative was done, presented and discussed.

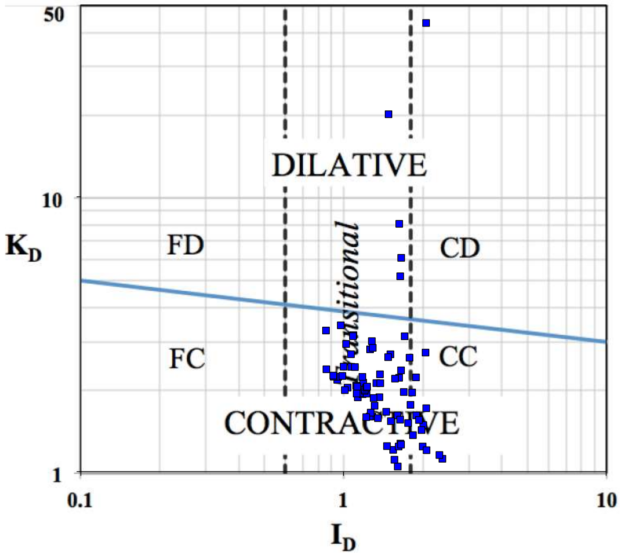


Figure 10. Average SDMT data from the site plotted in the DMT-based soil behavior type (SBT) chart.

Figure 11 presents the estimated geotechnical parameters based on the DMTs carried out at the study site by using classical Marchetti's equations and reference values determined via laboratory tests by Machado [10]. It was observed that the soil unit weight (γ_n) estimative by using the correlation suggested by [24] (equation 3) was in a reasonable agreement with those determined from undisturbed samples by Machado [10] (Fig. 11a) mainly between 2 and 6 m depth.

$$\frac{\gamma_n}{\gamma_w} = 1.12.\left(\frac{E_D}{P_a}\right)^{0.1}.(I_D)^{-0.05} \tag{3}$$

where:

p_a is atmospheric pressure
γ_n is soil unit weight
γ_w is water unit weight

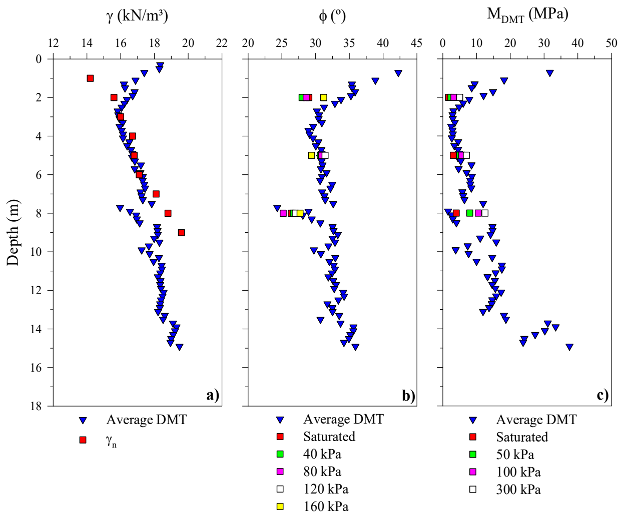


Figure 4. Estimated geotechnical parameters from DMTs carried out at the study site and reference values determined by Machado [10].

The reference shear strength parameters were also determined by Machado [10] via saturated and unsaturated multiple stage CD triaxial tests carried out on undisturbed samples collected at 2, 5 and 8 m depth. The axial translation technique was used to apply suction to the soil samples [25] and they were equal to 40, 80, 120 and 160 kPa. The author concluded that the friction angle (ϕ') values varied from 29º for the saturated condition and 31.2º for the higher suction value with an average value equal to 29.6º for 2 m depth soil sample (Fig. 11b). The ϕ' values varied from 31.2º for saturated condition to 29.4º for 160 kPa suction value, with an average value equal to 30.7º for 5 m depth soil sample (Fig 11b). The ϕ' values varied from 26.9º for the saturated condition to 27.7º for the 160 kPa suction value with an average value equal to 26.7º for the sample collected at 8 m depth (Fig. 11b). The cohesion intercept (c) was equal to zero at 2.0 m depth for the saturated condition and it increases with both depth and soil suction, as show in Table 1.

Table 1. Cohesion intercept (c) values for different depths and soil suction determined via triaxial tests (adapted from Machado [10]).

	Soil suction (kPa)				
Depth (m)	0	40	80	120	160
2	0.0	14.9	21.1	23.1	30.1
5	10.5	26.7	29.6	36.1	43.9
8	26.4	44.6	57.6	51.9	53.4

It can be observed in Figure 11b that the estimated DMT friction angle values were in a reasonable agreement with those determined via triaxial tests, mainly for the soil samples collected at 2 and 5 m depth, with an average value of about 31º. The estimated values are higher than the reference ones for soil sample collected from 8 m depth. Such differences are caused by the fact that the estimated DMT ϕ' values incorporates the component of cohesion as an increase in friction angle, since it assumes the evaluated soils behaves exclusively like a sand.

One of the major applicability of the DMT is for settlement prediction by using the constrained modulus determined by this test: the M_{DMT} [26]. It can be considered a reasonable "*operative modulus*", a relevant parameter for foundations design in "*working conditions*". The average M_{DMT} value is equal 3.8 MPa between 1 to 6 m depth, 9.5 MPa between 6 to 10 m depth, 21.1 MPa between 10 to 14 m depth and 31.3 MPa below 14 m depth. These values are in good agreement with the reference ones determined by saturated and unsaturated (suction values of 50, 100 and 300 kPa) oedometer tests carried out by Machado [10], as shown in Figure 11c.

The seismic dilatometer (SDMT) is also a useful tool to identify unusual geomaterials. According to Robertson et al. [27], Schnaid & Yu [28], Schnaid et al. [29] and Cruz [30], seismic and penetration test data can be directly used to evaluate the possible effects of stress history, degree of cementation and ageing for a given profile. So, G_0/q_t, G_0/M_{DMT} and G_0/E_D ratios provides a measure of the ratio of the elastic stiffness (maximum shear modulus – G_0) to ultimate strength (q_t, M_{DMT} and E_D) and may therefore be expected to increase with sand age and cementation/bonding, primarily because the effect of these on G_0 is stronger than on q_t, M_{DMT} and E_D [29].

Cruz [30] studied several sedimentary and residual soils and proposed charts for detecting the presence of cemented structures (cementation/bonding and aging) based on SDMT data plotting, for example, the G_0/E_D *vs* I_D chart. This author demonstrated that soils with G_0/E_D

higher than 12 tend to have significant microstructure (cemented/bonding and ageing). Figure 12 shows this chart, with three lines and one equation to define the limits for the DMT sedimentary international database and upper bounds for cemented soil. All the average SDMT data from the study site are plotted above the line which separates the DMT sedimentary international database and in the range where the residual soils (cemented structures) are. It indicates that the bonded structure of the studied tropical sandy soil produces G_0/E_D that are systematically higher than those measured in sedimentary soils.

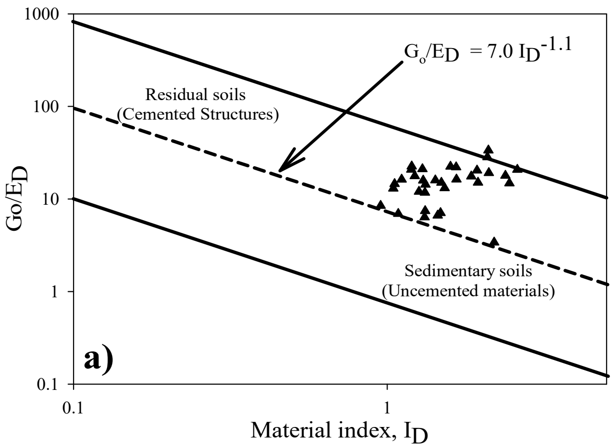


Figure 5. SDMT tropical sandy soil data plotted on G_0/E_D *vs* I_D chart proposed by Cruz [31].

6. Conclusions

- The soil profile was classified as red clayey fine sand based on tactile-visual identification. The I_c index and I_D parameter identified this soil (mixtures of sand, silt and clay) as clays and silts, respectively. The soil identification in terms of grain size distribution must be confirmed collecting soil samples for the study site.
- The CPTu data interpretation classified the study soil as a clay with a dilative behavior, which is not in accordance to what was found based on CD triaxial tests carried out on undisturbed soil samples.
- The complexity on the stratigraphic logging and estimative of geotechnical parameters for the soils from the study site can be associate to their cohesive-frictional behavior, unsaturated condition and to a possible partially drained penetration at the CPTu standard penetration rate.
- The estimated geotechnical soil parameters (friction angle and constrained modulus) and soil unit weight based on SDMT data and correlations worked relatively well for the study site.
- Cruz's chart [30] and Robertson's chart [7] indicate that the soil from the study site has an unusual behavior. The cemented structure of the tropical sandy soil produced K^*_G and G_0/E_D, which are systematically higher than those in sedimentary soils.
- The test data and their interpretation pointed out the importance of using hybrid tests, like SDMT, for the site characterization of tropical soils.

Acknowledgement

The authors thank the São Paulo Research Foundation - FAPESP (Grant # 2015/16270-0), the National Council for Scientific and Technological Development - CNPq (Grant # 446424/2014-5) for supporting their research and the Coordination for the Improvement of Higher Education Personnel (CAPES) for the scholarship granted to the first author.

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