Seismic DMT Test in a Non-Text Book Type Geomaterial

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ABSTRACT: This paper presents and discusses the use of the Seismic DMT test for site characterization of an unsaturated tropical soil which occurs in an experimental research site from Bauru, São Paulo, Brazil. This soil can be considered a non-textbook type geomaterial because of its peculiar behavior which cannot be explained by the principles of classical Soil Mechanics. A compressive site characterization was previously performed at this site. Recently a SDMT test was carried out on this site and the data were interpreted according to the traditional approach as well as to assess soil cementation. It was observed that the SDMT is a useful test for detailed stratigraphic logging, estimation of geotechnical stiffness and strength parameters and to determine maximum shear moduli of the unsaturated tropical soil. These preliminary results encouraged us to continue studding this hybrid test for practical application in geotechnical engineering of tropical soils.

1 INTRODUCTION

In all geotechnical jobs the objectives of a site characterization program are: define the stratigraphic profile and the groundwater level, estimate the geotechnical parameters from each unit and identify the critical ones. It is also an objective to define the geotechnical design parameters and indicate the required in situ and laboratory tests, if necessary.

The rational approach for site characterization relays on in-situ penetration tools coupled in some cases with geophysical techniques. The seismic flat dilatometer test (SDMT) has been used by the geotechnical community as a logging tool for site characterization as well as to determine the shear wave velocity to calculate de maximum shear modulus based on elastic theory. The other geotechnical parameters are estimated based on correlations developed for soils from Europe and North America.

Tropical soils are predominantly formed by chemical alteration of the rock. 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, destructuration under shear conditions and low influence of stress history (Vaughan et al. 1988). Consequently, the principles of the classical Soil Mechanics are not able to well assess the behavior of these materials. As a result, many researchers have been developing models to characterize mechanical behavior of these non-textbook geomaterials.

Tropical soil includes both lateritic and saprolitic soils and there are significant differences between the mechanical behaviors of the mature (lateritic) and young (saprolitic) soils. So, it is necessary to identify their genetic characteristics since their properties are strongly dependent on the degree of weathering.

Recently Cruz (2010) studied several sedimentary and residual soils and developed charts for detecting the presence of cemented structured based on SDMT data. The author plotted the SDMT data on charts G_o/E_D *vs* I_D and G_o/M_{DMT} *vs* K_D for this purpose.

This paper presents SDMT test data carried out at one relatively well-studied tropical research site located inland of the state of São Paulo, Brazil. The data are presented and interpreted according to the traditional approach. The soil cementation is also assessed plotting the SDMT data on the charts suggested by Cruz (2010). The estimated soil parameters are compared to the available reference values determined based on laboratory and others in situ tests. Preliminary findings are presented and briefly discussed.

2 STUDIED SITE

2.1 *Site location*

The Research Group on Geotechnical Engineering from São Paulo State University - Bauru Campus, has two experimental research sites (RS1 and RS2) which are around 300 m apart from each other. These sites are 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 two research sites in Brazil are shown on Fig. 1.

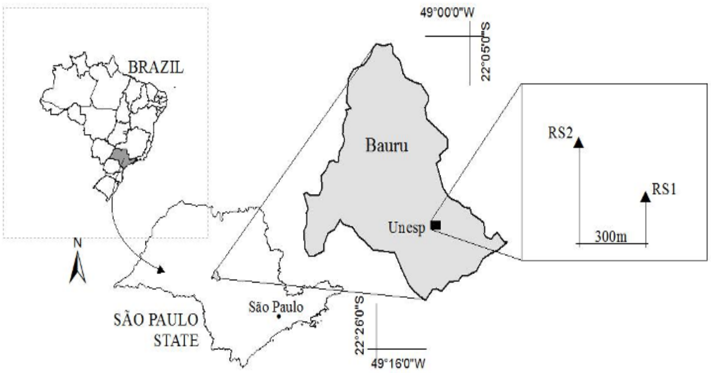

Fig. 1. The location of Unesp-Bauru research sites.

2.2 *Geology*

The soil profiles from both research sites (RS1 and RS2) are quite similar. They are geologically characterized by sandstone rocks from Bauru Group (Upper Cretaceous), which recovers the volcanic rocks from Serra Geral Formation. The volcanic rocks emerge in the direction of the Tiete River. Sedimentary rocks from Marilia Formation are predominant at these sites, which are experiencing weathering processes over tropical conditions. De Mio (2005) emphasizes that these soils exhibit characteristics from the parent rocks, like sequence of layering and modifications on these geological materials by pedogenetic and morphogenetic processes (softening caused by water migration by the fracture zones, recovering by colluvial soils in several phases, among others). 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.

2.3 *Site Characterization*

Several site characterization programs including SPT, SPT-T, S-SPT, DMT, PMT, SCPT, CH and DH tests were carried out at these two sites. Sample pits were also excavated to retrieve undisturbed and disturbed soil blocks. Soil samples from these blocks were tested in laboratory for soil characterization and determination of mechanical properties and parameters.

The tropical soil profiles at these two sites comprise a sandy soil (RS1 and RS2). The top 13 m has lateritic soil behavior (LA') (horizon B) followed by a saprolitic soil (horizon C) with non lateritic behavior (NA'). The groundwater table was not found up to 20 m depth. The MCT Classification System (Mini, Compacted, and Tropical) proposed by Nogami and Villibor (1981) for tropical soils was used to define and classify the soils with regards to the lateritic behavior.

3 PREVIOUS TESTS

3.1 *Laboratory tests*

Several different types of laboratory test in both saturated and unsaturated soils were performed to obtain reference values for defining geotechnical soil parameters for the experimental research site RS1. Grain size distribution for the soil samples retrieved every meter from one of the SPT tests were defined using dispersant (Fig. 2.g) and with no dispersant (Fig. 2.h) for RS2 site 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 on tropical soil profiles.

The soil retention curve is important information to characterize the behavior of partially saturated soils since soil suction affects strength and stiffness parameters. Fig. 3 presents the drying and the wetting retention curves for a soil sample collected at 1.5 m depth from the RS2 site.

3.2 *SPT, CPT and Seismic data*

The typical soil profile for the RS2 research site was defined based on the SPT tests and it is presented in Fig. 2.a together with SPT N values (Fig. 2.b). This soil profile is quite similar to the one from the RS1 site. N-values from SPT tests increase almost linearly with depth, up to 13 m depth. One SPT test complemented by torque measurement (SPT-T test as suggested by Ranzine 1988) was carried out at this site and the T/N ratio profile is presented on Fig. 2.c. Décourt (1998) proposed a soil classification system based on the T/N ratio which can be used as an index to identify collapsible soils.

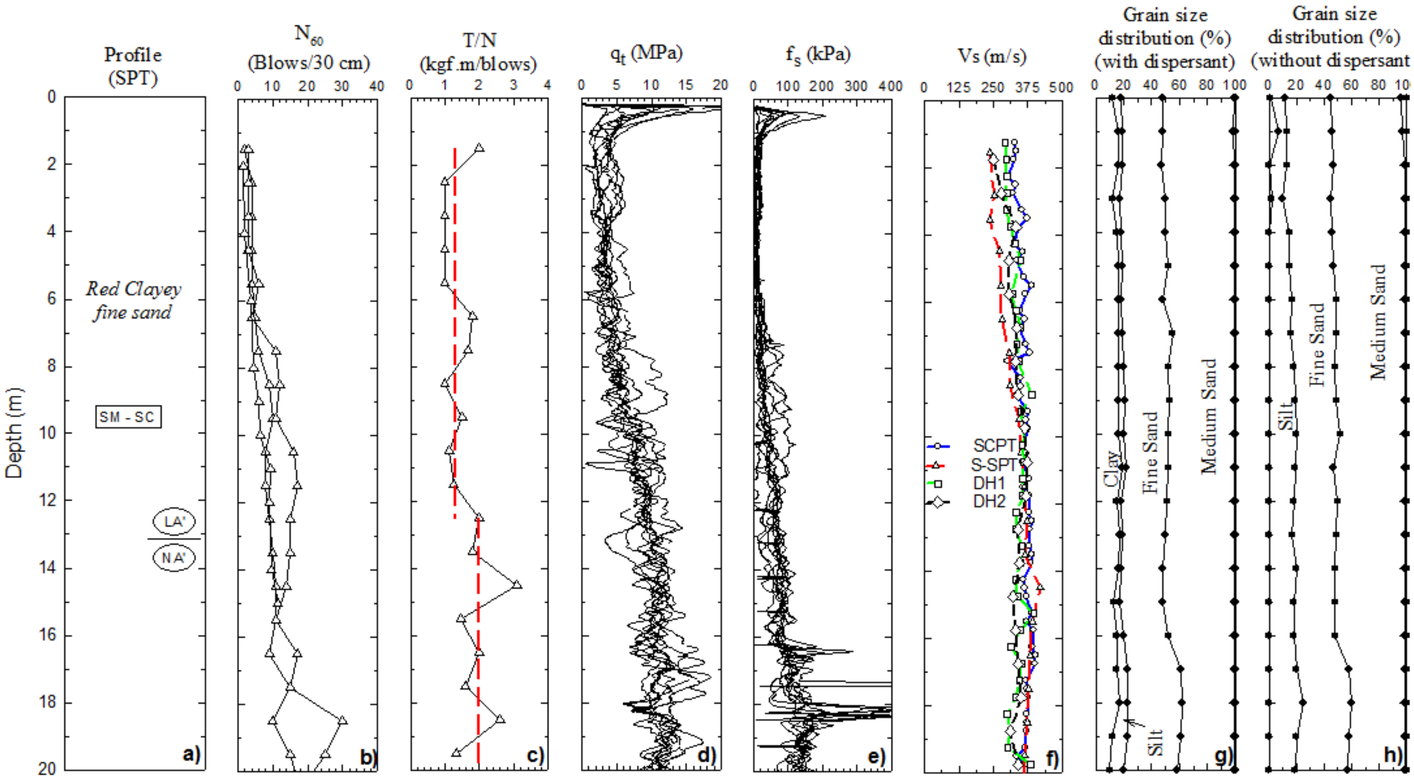

Fig. 2. Synthesis of in situ (SPT-T, CPT and Seismic) and laboratory (grain size analysis) test data for the RS2 site.

It can be observed 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 (Fig. 2.c). The interpretation of MCT classification test data separated lateritic (LA') from non-lateritic (NA') soil behavior almost at the same depth (13 m).

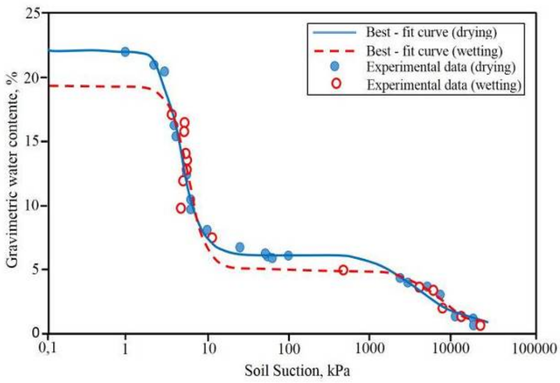

Fig. 3. Soil-water retention curve for one meter depth soil sample for the study site (Fagundes, 2014).

CPT tests were carried out at RS2 site at three distinct locations and at different seasons of the year (Fig. 2.d and Fig. 2.e). It was assumed that measured cone resistance (q_c) was equal to corrected cone resistance (q_t), since the soil is unsaturated and pore pressure was not measured. The cone tip resistance (q_t) and the sleeve friction (f_s) presented higher value at the top 1 m and tends to increase with depth leading to a friction ratio ($R_f=f_s/q_t*100$) between 1 and 3 %. Fig. 2.f shows the variation of Vs values with depth for the RS2 site determined by SCPT, S-SPT (Seismic SPT) and two down-hole tests (DH1 and DH2).

3.3 *DMT data*

One DMT test was carried out at the Bauru RS1 site up to 15 m depth by Giacheti et al. (2006) as well as at two other tropical research sites (USP-São Carlos and Unicamp-Campinas). These test data were interpreted and compared with reference soil parameters for each study site. Fig. 4 presents the DMT data (P_o, P_1, I_D, K_D and E_D) for the Bauru RS1 site.

Giacheti et al. (2006) concluded that the I_D index was able to identify changes and the boundaries of soil layers in terms of DMT soil behavior, but it was unable to separate the boundaries of lateritic and saprolitic soils. They also concluded that this index does not give information about grain size distribution (it has to be confirmed by soil sampling), but identify differences on soil behavior, as pointed out by Marchetti et al. (2001). The estimated total unit weight based on DMT test was quite good especially for Bauru Site.

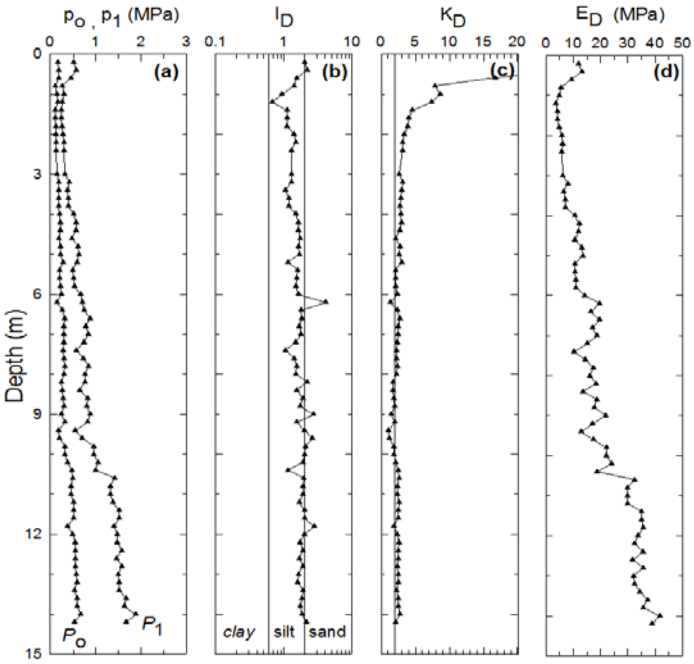

Fig. 4. DMT test data for the Bauru RS1 site.

Ménard PMT tests were carried out right beside DMT test at Bauru RS1 site and the authors observed that DMT Modulus (E_D) was in the same order of magnitude of E_{pmt} up to about 11 m depth. E_{pmt} values were almost half E_D after that depth.

K_o predicted from DMT using Marchetti (1980) correlation basically matched PMT K_o values up to 8 m depth for Bauru RS1 site. DMT K_o curve calculated using Baldi et al. (1986) correlation better matched PMT K_o values below this depth.

Giacheti et al. (2006) estimated strength parameters for the three studied sites. The estimated DMT friction angle based on Baldi et al. (1986) correlation was quite good for the soil below 5 m depth for Bauru RS1 site. The authors also discuss the dynamic behavior of tropical soils from of Go/E_D ratio. Go/E_D ratio was higher at the lateritic soil layer tending to decrease as the soil is less developed.

4 SDMT TESTS

The seismic dilatometer (SDMT) test consists in combine the mechanical flat dilatometer with a seismic module for measuring the shear wave velocity (V_S). The seismic module contains two receivers spaced 0.5 m (Marchetti et al. 2008). The source to generate seismic waves consists of a steel bar placed under the wheel of pushing equipment which is struck by a 2 kg sledgehammer. The source is oriented with its long axis parallel to the axis of the receivers to allow the highest sensitivity to the generated V_S. This type of source is suitable for generating predominantly S waves. When a shear wave is generated at the surface, it reaches first the upper receiver, then, after a delay, the lower receiver. The seismograms acquired by the receivers are amplified and digitized at depth and stored in a laptop placed at the surface. Subsequently, V_S values are determined by the ratio between the difference in distance among the source and the two receivers (ΔS) and the delay of the arrival of the impulse from the first to the second receiver (Δt) (Marchetti et al. 2008).

One SDMT logging test was carried out at Bauru RS2 site in order to obtain first seismic DMT data on this reasonably well-known site. The dilatometer blade and the seismic module were pushed into the ground with a CPT pushing device with the penetration rate of about 20 mm/s. The subsoil at the site is unsaturated and c-pressure was not recorded.

5 TEST RESULTS AND ANALYSIS

SDMT tests data in terms of P_o, P_1, I_D, K_D, E_D and V_S are presented on Fig. 5 for the RS2 site. The I_D, K_D and E_D parameters were calculated using classical DMT correlations.

As SDMT testing does not provide soil samples the soil type can be identified based on the I_D parameter. Total unit weight can be estimated by using the Marchetti and Crapps (1981) chart, which relates I_D and E_D (Fig. 6). The estimation of geotechnical soil parameter for this site will be presented using classical correlation formulae and the maximum shear modulus will be calculated based on the measured Vs values from the seismic DMT data.

5.1 *Soil Classification*

The I_D parameter (Fig. 5.b) shows that the soil from the study site basically behaves as silty soil (silty sand up to 10.2 m depth and sandy silt below this depth). The grain size distribution determined in laboratory using dispersant according to the Brazilian standard (ABNT NBR-7181, 1988) classifies the soil as a clayey fine sand, almost with no silt, as it can be seen in the Fig. 2.g. The I_D index is not a result of a sieve analysis but 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, as pointed out by Marchetti et al. (2001). It is what was observed for this particular site.

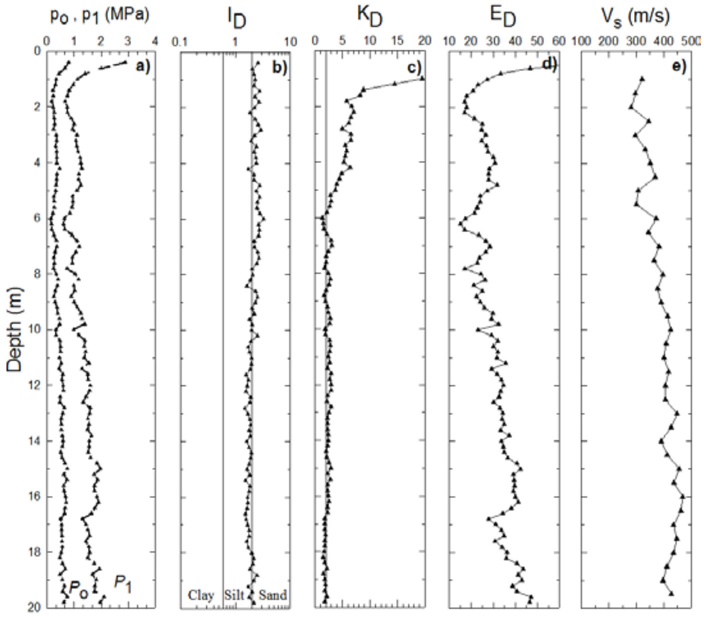

Fig. 5. SDMT test data for the Bauru RS2 site.

The grain size distribution *in situ* has no dispersant (Fig. 2.f) and it behaves more likely as a silty soil, as it was captured by the DMT on the I_D *vs* E_D chart suggested by Marchetti and Crapps (1981). It was also observed in this study that the estimative of the soil total unit weight (γ) using the same I_D *vs* E_D chart (Fig. 6) are in a close agreement with those obtained from undisturbed samples just below 5 m depth (Fig. 7.a). It is worth highlighting that the major goal of the I_D *vs* E_D chart is to estimate total *in situ* geostatic stress and not the total unit weight, as discussed by Marchetti et al. (2001).

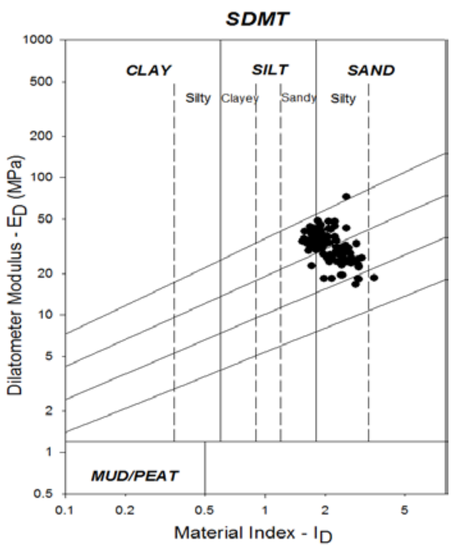

Fig. 6. Bauru site testing data position on the schematic DMT soil classification chart (Marchetti and Crapps, 1981).

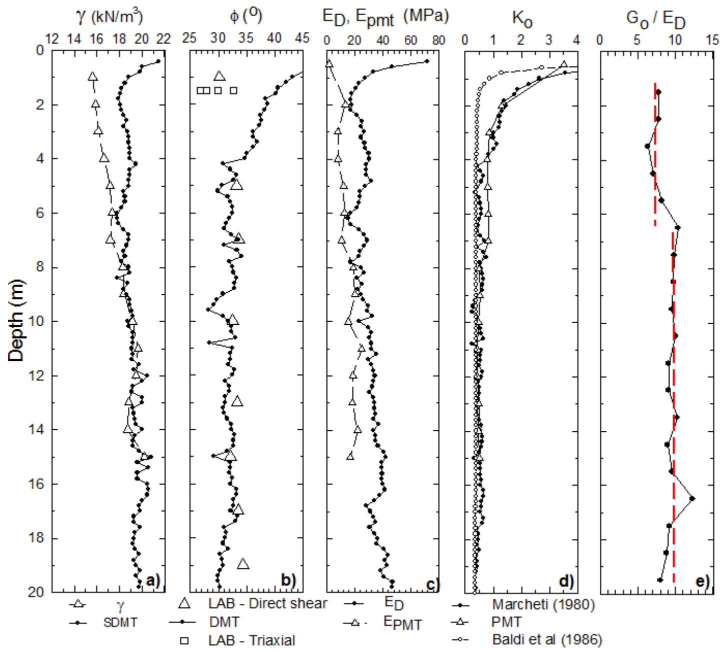

Fig. 7. Estimated parameters from SDMT test for the Bauru site and results from others tests.

5.2 *Geotechnical soil parameters*

The strength parameters are amongst the most important information on the geotechnical design. Fagundes and Rodrigues (2015) recently studied the influence of soil suction (s) on the shear strength of the 1.5 m depth soil from the Bauru RS2 site. The authors carried out triaxial tests on undisturbed and compacted soil samples. They concluded that the variation of shear strength with increasing suction for the compacted soil is much greater than for the undisturbed soil (Fig. 8.a and Fig. 8.b). The friction angle (ϕ') values for the undisturbed soil varied from 26.8^o for the saturated condition and 32.7^o for the higher suction value with an average value equal to 29.3^o. The intercept of cohesion increased with suction from zero on the saturated condition to 3 kPa (s = 50 kPa), to 11 (s = 200 kPa) and to 34 (s = 33 MPa) for the undisturbed soil.

Giacheti et al. (2006) presented reference friction angle for this site determined using direct shear tests under consolidated drained condition (CD) on undisturbed soil samples up to 19 m depth at its natural soil condition, as show in Fig. 8.b. The ϕ angle varied from 30.1^o to the soil from 1 m depth to 34.4^o to the one from 19 m depth. The average value is equal to 32.8^o. The correlation suggested by Marchetti (1997) is used to estimate the friction angle (ϕ') values along depth based on DMT test results, where the ϕ' angle is depend from K_D value, as the following equation:

$$\phi' = 28 + 14.6 \log K_D - 2.1 \log^2 K_D \qquad (1)$$

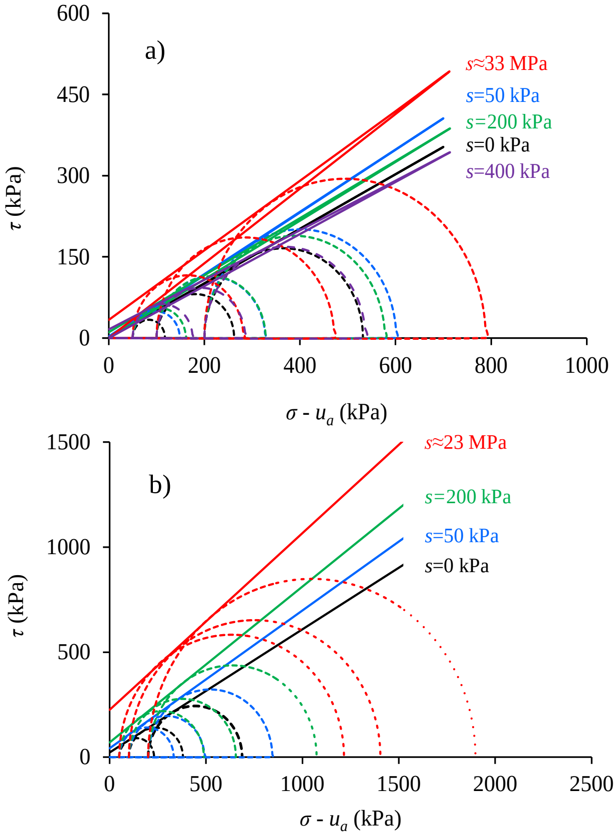

Fig. 8. Mohr circles and Coulomb failure envelopes for 1.5 m depth soil from RS2 site (a) undisturbed and (b) compacted (Fagundes and Rodrigues, 2015).

Fig. 7.b allows comparing the assumed reference ϕ' angle (lab – direct shear and triaxial tests) and the estimated ϕ' angle via DMT test. The estimated DMT friction angle was reasonable below 5 m depth.

The average estimated ϕ' angle was equivalent to the average measured ϕ' angle of about 33^o. For the 5 m topsoil the ϕ' angle was determined just for samples collected at 1.0 m depth by direct shear test (RS1 site) and 1.5 m depth by triaxial test varying suction (RS2 site).

These values are also plotted on Fig. 7.b. The estimated ϕ' angle based on DMT test data was much higher than the determined both by the triaxial and direct shear tests. Fagundes and Rodrigues (2015) showed an increase on the intercept of cohesion with suction for 1.5 m depth soil sample (Fig. 8). Bezerra (2014) monitored the water content and indirectly the soil suction by the retention curve with depth at the RS2 site and observed significant changing on both during the seasons of the year up to 4 m depth. This unsaturated soil has a cohesive-friction behavior and the estimative of the shear strength based on DMT data represent it just in terms of the friction angle. It could justify the higher DMT ϕ' angle for the top 5 m depth.

PMT tests were carried out at the Bauru RS1 Site and they will be used to compare deformability (E_{pmt} and E_D) and coefficient of lateral earth pressure parameters estimated using the SDMT test data from RS2 site. The soil profiles on these sites were assumed to be the same.

Dilatometer Moduli (E_D) are plotted together with Ménard PMT moduli (E_{pmt}) on Fig. 7.c. It can be observed in this figure that E_D is always higher than E_{pmt} values. Giacheti et al. (2006) presented E_D similar to E_{pmt} up to about 11 m depth and E_{pmt} was almost half of E_D after that depth. These authors as well as Ortigão et al. (1996) explained the low PMT moduli with soil disturbance. An interesting and more appropriate comparison in terms of soil deformability would be with the DMT constrained modulus (M) derived from the original correlation proposed by Marchetti (1980) with laboratory values from oedometer tests. Unfortunately there are no oedometer tests for this site to be used as reference values.

The SDMT test data can also be used to estimate the coefficient of lateral earth pressure (K_o). The original correlation suggested by Marchetti (1980) was elaborated for clayey soils. Marchetti (1985) suggested a K_o chart for sands. This chart estimates K_o for a given value of cone tip resistance (q_c) and K_D. Baldi et al. (1986) updated it converting into the following equation for sandy soils:

$$K_o = 0.376 + 0.095\ K_D - 0.0017\ q_c/\sigma'_{vo} \quad (2)$$

Fig. 7.d presents K_o curves estimated based on SDMT test results using Marchetti (1980) and Baldi et al. (1986) correlation plotted together with the K_o values interpreted based on PMT test results. 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 from DMT data using Marchetti (1980) correlation better matched PMT K_o values. Below 8 m depth the K_o from PMT test data assumed almost a constant value equal to about 0.5. This value could be estimated using Jaky (1948) formula for a friction angle (ϕ) of 30^o. DMT K_o curve estimated using Baldi et al. (1986) better matches the reference K_o values from 8 to 20 m depth, pretty much the same presented by Giacheti et al. (2006) for the RS1 site.

Shear wave velocity from the SDMT test and total unit weight determined with undisturbed soil samples collected in a sample pit excavated at the RS1 site were used to calculate maximum shear moduli (Go). The Go/E_D values *versus* depth are shown on Fig. 7.e. The criteria to select E_D to calculate this ratio was averaging three E_D values over 0.6 m intervals. Two average Go/E_D ratios can be seen on this Fig 7.e: 7.5 from 1 to 6 m and 12.7, bellow 6 m depth. Giacheti et al. (2006) presented higher Go/E_D values which tend to decrease with depth indicating that this ratio tends to increase with soil evolution. It is not observed with the presented SDMT data. The reason is the higher E_D values determined on the top 6 m depth than those determined at the RS1 site.

5.3 *Cementation*

Tropical soils have a bonding structure associated to their genesis. Interpretation charts were elaborated by Cruz (2010) for detecting the presence of cemented structures on soils based on DMT and SDMT in situ test data as well as DMT calibration experiment carried out inside an artificially cemented block samples prepared in a large chamber (CemSoil box).

Fig. 9a and Fig. 9b show the Go/E_D *vs* I_D and Go/M_{DMT} *vs* K_D charts, respectively, suggested based on the findings on the research conducted by Cruz (2010). Three lines and one equation are shown in each chart (Fig. 9a and Fig. 9b) to define the limits for the DMT sedimentary international database and upper bounds for cemented soil (CemSoil data).

In both charts the plotted SDMT data from Bauru RS2 site are above the equation line which separates the DMT sedimentary international database and nearby to the residual soil from Portugal and bellow the limit bound defined by the CemSoil data. It indicates that the bonded structure of studied tropical sandy soils produces Go/E_D as well as Go/M_{DMT} that are systematically higher than those measured in sedimentary soils. It was not possible to identify the difference on Go/E_D for lateritic and saprolitic soils as shown by Giacheti et al. (2006) based on DMT and seismic test data, Giacheti and De Mio (2008) based SCPT and the Go/q_c ratio and by Rocha (2013) with S-SPT test and the Go/N_{60} ratio. These ratios were used to assess cementation and they indicated that the lateritic soils have higher ratios than the saprolitic ones.

6 CONCLUSIONS

This paper presented and discussed one of the first SDMT test carried out in a Brazilian tropical soil and the initial experience on the interpretation of this test in a “non-classical” geotechnical materials. The conclusions are:

- The I_D parameter was not appropriate to identify the grain size distribution since mixtures of sand and clay were identified as silty soils. The *in situ* grain size distribution determined with no dispersant is in fact a silty soil, closer to the behavior captured by the DMT using the classical I_D *vs* E_D chart.
- It was also observed that the I_D parameter was unable to separate the boundaries of lateritic and saprolitic soils. The soil description in terms of grain size distribution for tropical soils has to be confirmed with soil samples, as already suggested by Giacheti et al. (2006). The samples can also be used to help identifying genetic characteristics of the soils.
- The estimated total unit weight based on SDMT data for this site was good enough for its major objective: the estimative of total stresses on a soil mass.

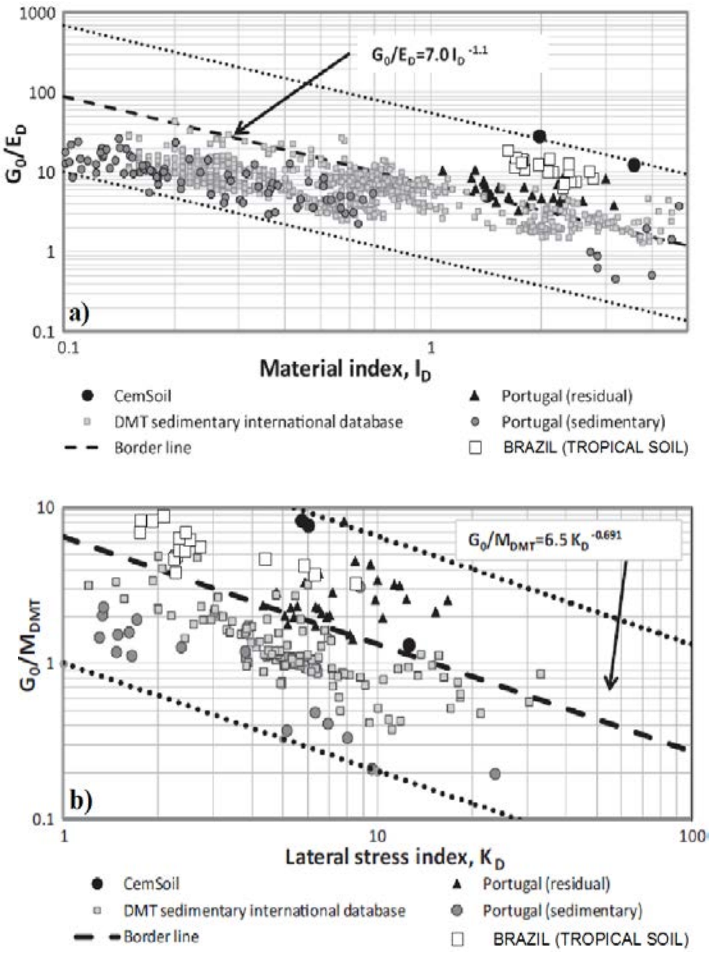

Fig. 9. SDMT tropical sandy soil data plotted on Go/E_D *vs* I_D chart (Fig. 9a) and Go/M_{DMT} *vs* K_D chart (Fig. 9b) (adapted from Cruz, 2010).

- The estimated DMT friction angle based on Marchetti (1997) correlation worked well for the soil below 5 m depth. The estimate was much higher for top soil. This unsaturated soil has a cohesive-friction behavior and the estimative of the shear strength based on DMT data try to represent it just in terms of the friction angle.
- Significant differences were observed between Dilatometer (E_D) and Ménard Pressuremeter (E_{pmt}) modulus. The E_D values were always higher than the E_{pmt} values for this site.
- The better prediction of K_o values from DMT data was made using Marchetti (1980) correlation up to 8 m depth. Below this depth the DMT K_o values estimated by Baldi et al. (1986) correlation were better.
- Both charts from Cruz (2010) indicate the presence of cemented structures for all the soils from Bauru RS2 site. The bonded structure of unsaturated tropical sandy soils produce Go/E_D as well as Go/M_{DMT} which are systematically higher than those measured in sedimentary soils. It was not possible to identify the difference on Go/E_D for lateritic and saprolitic soils as shown by Giacheti et al. (2006) based on DMT and seismic test data for the Bauru RS1 site.

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