Flat Dilatometer Testing in Brazilian Tropical Soils

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ABSTRACT: Flat dilatometer tests were carried out at three relatively well-studied tropical research sites in the state of São Paulo, Brazil. Test results are presented and interpreted according to the traditional approach for site characterization of conventional soils. The results were compared to laboratory and others in situ tests. Soil description in terms of grain size distribution had to be confirmed with soil sampling. Correlations to estimate geotechnical parameters have to consider soil genesis. In this manner, some adjustment is necessary, especially for the soils with higher clay content. In tropical soils this approach appears to be an interesting way to achieve all requirements for an appropriate site characterization based on DMT testing.

1 INTRODUCTION

Flat dilatometer test (DMT) has been used by the geotechnical community as a logging tool to estimate geotechnical parameters for most soil conditions. Besides stratigraphic information, the DMT allows the estimative of geotechnical parameters based on correlations developed for soils from Europe and North America.

Tropical soils exhibit a unique mechanical behavior due to their genesis and partially saturated condition. The properties of these soils are very dependent on the degree of weathering and there are only a few DMT data available on tropical soils.

DMT test results from three relatively well-studied tropical research sites in the state of São Paulo, Brazil, are presented and interpreted according to the traditional approach developed for conventional soils. The results were compared to available reference soil parameters determined based on laboratory and others in situ tests. Preliminary findings are presented and briefly discussed.

2 TROPICAL SOILS

Tropical soils are formed predominantly by chemical alteration of the rock and they have peculiar behavior that cannot be explained by the principles of classical soil mechanics.

The term tropical soil includes both lateritic and saprolitic soils. Saprolitic soils are necessarily residual and retain the macro fabric of the parent rock. Lateritic soils can be either residual or transported and are distinguished by the occurrence of laterization process, which is enriching 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 aluminum bonds support a highly porous structure. Saprolitic 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. Differences between the mechanical behaviors of the mature (lateritic) and young (saprolitic) soils have been reported for both natural and compacted condition. For tropical soils it is also necessary to identify their genetic characteristics since their properties are strongly dependent on the degree of weathering.

3 DESCRIPTION OF SITES AND TESTS

3.1 *Sites*

Research sites located at three University *campus*: Unesp (Bauru), Unicamp (Campinas) and USP (São Carlos), in the state of São Paulo, Brazil, were studied (Figure 1). At the site in Bauru, the subsoil is a sandy soil. The top 13 m has lateritic soil behavior. The soil at the Campinas Site has a clayey texture and is composed of two distinct layers: porous lateritic clay overlaying a silty clay of non-lateritic behavior, both derived from weathering of Diabase rock. At the site in São Carlos, the subsoil is clayey fine sand with two well-defined layers; Cenozoic sediments of lateritic behavior overlaying the residual soil derived from sandstone with non-lateritic behavior. The MCT 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.

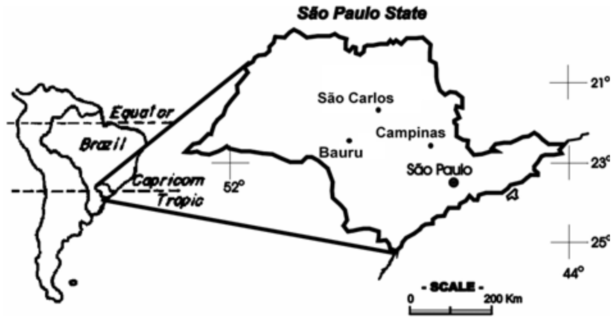

Figure 1. Cities where research sites are located.

3.2 *Tests*

Marchetti (1997) describes the flat dilatometer, which consists of a steel blade with a thin, expandable, circular steel membrane mounted on one face (Figure 2). The blade is connected, by an electro-pneumatic tube, running through the insertion rods, to a control unit on the surface. Marchetti (1997) also describes the test procedure which starts by inserting the dilatometer into the ground. By use of a control unit with a pressure regulator, a gauge and an audio signal, the operator determines the p_o-pressure required to just begin to move the membrane and p_1-pressure required to move it 1.1 mm into the ground. The blade is then advanced into the ground of one depth increment, typically 200 mm, using common field equipment.

According to Marchetti et al. (2001), the primary way of using DMT results is to interpret them in terms of common soil parameters and this methodology ("*design via parameters*") opens the door to a wide variety of engineering applications.

DMT interpretation starts with the calculation of three intermediate parameters (I_D, K_D and E_D). The Material Index $I_D = (p_1-p_o)/(p_o-u_o)$ is calculated to identify soil type, where u_o is the hydrostatic pore pressure. In general, I_D provides an expressive profile of soil type and, in "normal" soils a reasonable soil description (Marcheti et al., 2001). The Horizontal Stress Index $K_D = (p_1-p_o)/(\sigma'_{vo})$ where σ'_{vo} is the pre-insertion in situ overburden stress, provides the basis for several soil parameters correlations and is the key result of the dilatometer test (Marcheti et al., 2001). The dilatometer modulus (E_D) is obtained from p_0 and p_1 by the theory of elasticity and it is found that $E_D = 34.7\ (p_1 - p_0)$. E_D in general should not be used as such, especially because it lacks information on stress history (Marchetti et al., 2001). The strength and deformability soil parameters can be obtained from published empirical correlations.

DMT tests were carried out at each site in order to obtain pioneering data for this type of test in these reasonably well-known sites. One field logging with the DMT was carried out in each research site pushing the dilatometer blade into the ground with a heavy truck-mounted penetrometer at a penetration rate of about 20 mm/s. The calibration procedure to obtain ΔA and ΔB pressures, necessary to overcome membrane stiffness, was done before each profile. A-Pressure and B-Pressure were recorded every 200 mm during all the tests and p_o and p_1 pressures were calculated. The subsoil at all the sites is mostly partially saturated, so C-Pressure was not recorded.

A comprehensive site characterization program including SPT, SPT-T, CPT, SCPT and Cross-hole tests were carried out at each site. Ménard Pressuremeter Test (PMT) was also carried out at the Bauru Site. Sample pits were excavated to retrieve disturbed and undisturbed soil blocks in all the sites. These blocks were tested in the laboratory to characterize the soil and to determine mechanical properties.

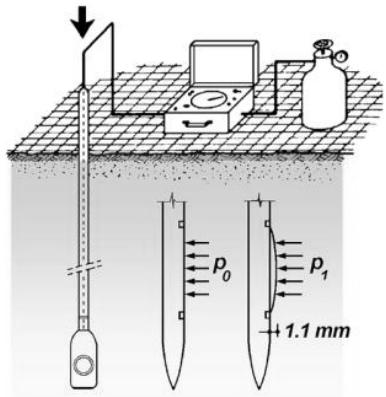

Figure 2. General layout of the dilatometer test (*www.marchetti-dmt.it/pagespictures/testlayout.htm*).

4 TEST RESULTS AND DISCUSSION

DMT tests results in terms of p_o, p_1, I_D, K_D and E_D are presented in Figures 3, 4 and 5, respectively for Bauru, Campinas and São Carlos sites. Grain size distribution and stratigraphic characterization based on various SPT soundings carried out at the sites to identify and classify the soils are also presented.

As DMT testing does not provide soil samples, 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 (Figure 6). The I_D, K_D and E_D parameters were interpreted using classical or standard empirical correlations. The derived geotechnical parameters were then compared to reference laboratory ones from tests on undisturbed block samples or from those obtained via in situ tests. This comparison allowed establishing preliminary bases to interpret DMT tests on these soils.

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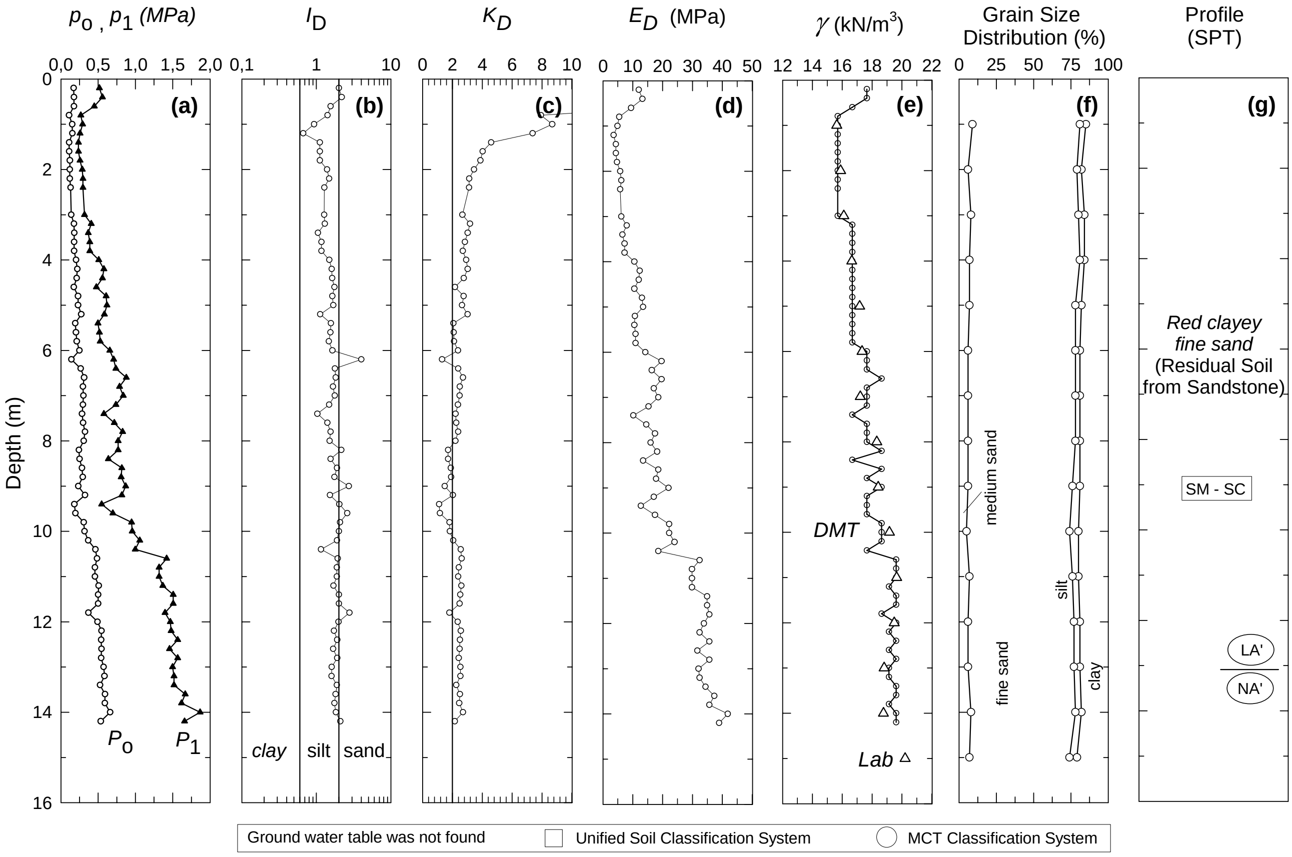

Figure 3. DMT test results; total unit weight, grain size distribution and SPT profile for Bauru Site.

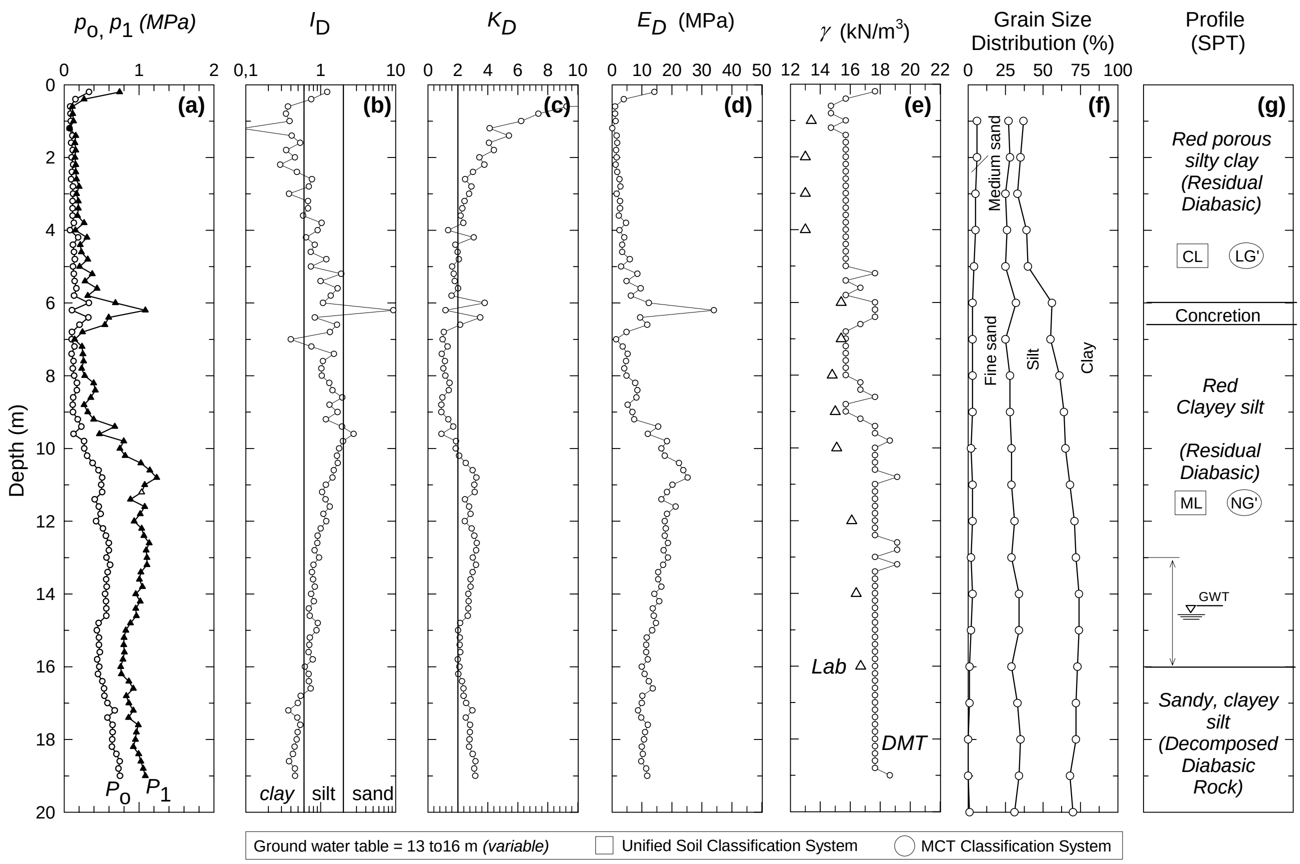

Figure 4. DMT test results; total unit weight, grain size distribution and SPT profile for Campinas Site.

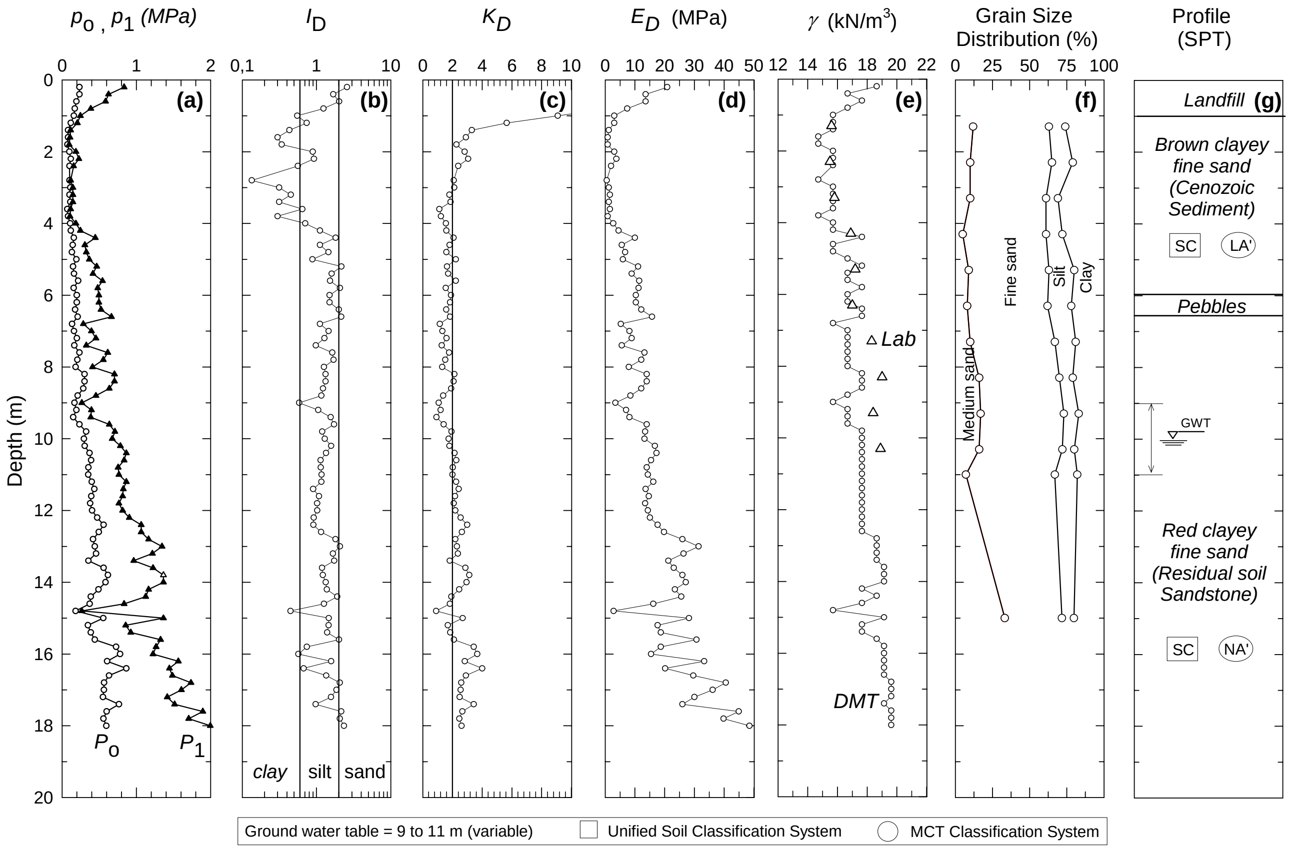

Figure 5. DMT test results; total unit weight, grain size distribution and SPT profile for São Carlos Site.

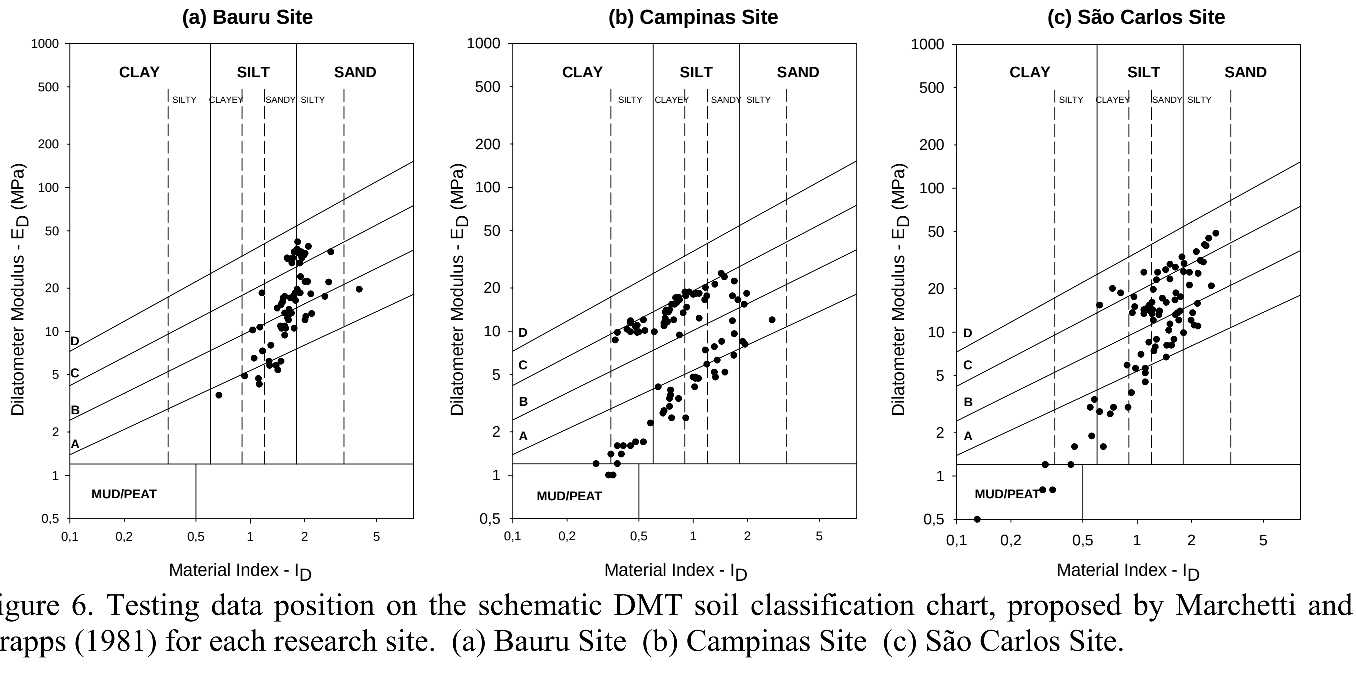

Figure 6. Testing data position on the schematic DMT soil classification chart, proposed by Marchetti and Crapps (1981) for each research site. (a) Bauru Site (b) Campinas Site (c) São Carlos Site.

4.1 *Bauru Site*

4.1.1 *Soil classification*

For the Bauru Site the I_D parameter indicates that the soil basically behaves as a sandy silt up to 9.2 m depth and silty sand between 9.4 to 14.2 m depth (Figure 3.b). The soil texture determined based on grain size distribution is a clayey fine sand, as can be seen in the Figure 3.f.

As pointed out by Marchetti et al. (2001), the I_D is not a result of a sieve analysis but it is a parameter that reflects mechanical behavior and this parameter indicates that a mixture of clay-sand would generally

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be described as silt. This is what happened for this particular site.

Results from Standard Penetration Test with Torque Measurements (SPT-T) indicates that T/N ratio for the top 13 m is almost constant within an average value of 0.7, defining the boundaries of two different layers at that depth (Giacheti et al., 1999). MCT classification system separated lateritic (LA') from non-lateritic (NA') soils at the same depth (Figure 3.g). CPT tests carried out at this site also indicate that cone tip resistance (q_c) and friction ratio (R_f) are different at the same two layers identified by MCT and SPT-T tests. Unfortunately DMT test stopped at a depth of 14.2 m , so no conclusion can be drawn regarding this aspect because there are not sufficient testing data in the non-lateritic soil layer (below 13 m depth).

Total unit weight (γ) of the soil estimated, based on material index I_D and dilatometer modulus E_D using Marchetti and Crapps (1981) chart (Figure 6.a) are in close agreement with those obtained from undisturbed samples, as presented in Figure 3.e. DMT testing results, for this particular site, were able to estimate soil density.

4.1.2 *Geotechnical soil parameters*

PMT tests were carried out at the Bauru Site quite close to the DMT test. Figure 7.b 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 after 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.

Another interesting application of DMT test is to estimate the coefficient of lateral earth pressure (K_o). Original correlation proposed by Marchetti (1980) was developed for clayey soils. Marchetti (1985) prepared a K_o chart for sand. Such chart provides K_o for given values of cone tip resistance (q_c) and K_D. Baldi et al. (1986) updated this chart and it was converted into the following algebraic equation for sandy soils:

$$K_o = 0.376 + 0.095\ K_D - 0.0017\ q_c/\sigma'_{vo} \qquad (1)$$

Figure 7.b presents K_o curves estimated based on DMT test results using Marchetti (1980) original correlation and Baldi et al. (1986) correlation (equation 1) as well as K_o values interpreted based on PMT test results. K_o from PMT is equal to 3.5 at 0.5 m of 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 results using Marchetti (1980) correlation closely matched PMT K_o values. Below 8 m depth, K_o interpreted based on PMT test results assumed an almost constant value equal to about 0.5, which could be computed by Jaky (1948) formula for a friction angle (ϕ) of 30°. DMT K_o curve calculated using Baldi et al. (1986) better matches the other part of the soil profile, between 8 to 14 m depth.

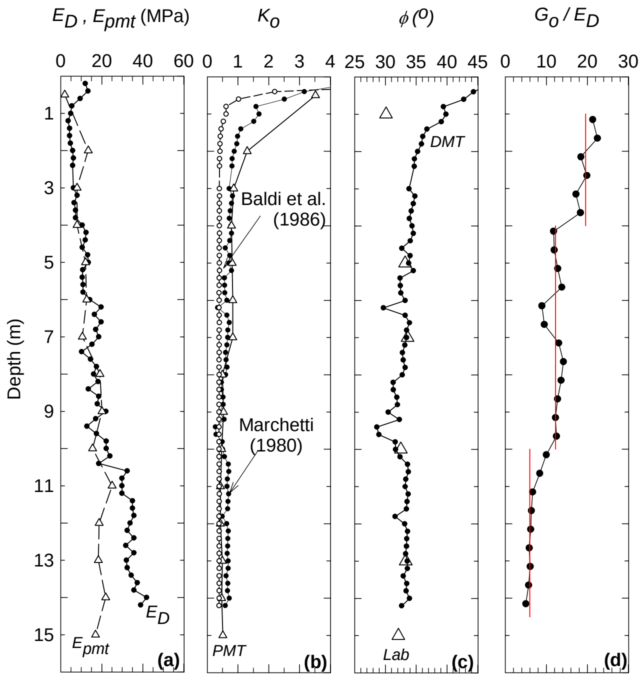

Figure 7. Estimated parameters from DMT test for the Bauru Site and results from other tests.

The reference friction angle for this site was determined by direct shear tests under consolidated drained condition (CD) on undisturbed soil samples at its natural soil content. The correlation adopted to estimate friction angle (ϕ) based on DMT test results is presented by Marchetti (1997), where the ϕ is obtained from K_D by the following equation:

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

Figures 7.c presents the comparison of reference (lab) and predicted (DMT) friction angles. The estimated DMT friction angle was quite good for the soil below 5 m depth. In this case, average estimated ϕ angle was equal to the average measured ϕ angle of about 32°. For the 5 m topsoil, the ϕ angle was determined just for the sample collected at 1 m depth and it was 30°. The interpretation of DMT test results yielded to a ϕ angle 8° higher than the measured one.

Shear wave velocity determined with cross-hole seismic tests and total unit weight determined with undisturbed soil samples collected in a sample pit excavated at the site were used to calculate maximum shear modulus (Go) based on elastic theory.

The Go/E_D values *versus* depth are also presented at the Figure 7.d**.** The criteria used to select E_D to calculate this ratio was averaging three E_D values over 0.6 m intervals. It is interesting to note at the Figure 7.d that Go/E_D ratio tends to decrease with depth, which indicates that Go/E_D ratio tends to increase with soil evolution. Three average Go/E_D ratios were presented; between 1 to 4 m depth it was 20, between 4 to 10 m depth it was 12 and between 10 to 14.5 m depth it was 6 (Figure 7.d).

4.2 *Campinas Site*

4.2.1 *Soil classification*

The I_D parameters for this site are presented in Figure 4.b. The top 6 m red porous silt clay, which is classified as LG soil at the MCT classification system, presented an I_D of silt clay or clayey silt. DMT was able to identify the concretion at 6 to 6.5 m depth and classified it as a sand material. The layer between 6.5 to 16 m depth is a clayey silt, residual soil from dibasic rock, and it was described by the DMT as different materials, changing from the upper to the lower part as a sandy silt, to silt and to clayey silt. The last layer, a sandy clayey silt (decomposed Diabasic rock), was identified by DMT as a silty clay.

For this site, the I_D parameter was not able to describe the soil based on the grain size distribution but the DMT response identified soils with distinct behavior. Marchetti et al. (2001) already emphasized that the I_D is not to describe the soil in terms of grain size distribution since this parameter reflects mechanical behavior. The DMT test results identified layers with distinct behavior at this site but the DMT was not able to separate the boundaries of lateritic and saprolitic soils.

The estimated total unit weight (γ) for the Campinas Site using Marchetti and Crapps (1981) chart (Figure 6.b) based on DMT data was much higher (γ between 16 to 20 kN/m^3) than the values obtained in the laboratory (γ between 13 to 16 kN/m^3), as can be seen in Figure 4.e, especially for the red porous silty clay layer.

4.2.2 *Geotechnical soil parameters*

DMT constrained modulus (M) derived from the original correlation proposed by Marchetti (1980) is compared with laboratory values from oedometer tests (Figures 9.a_2). The oedometer tests were carried out with undisturbed soil samples at natural soil content up to a maximum load of 800 kPa. It can be seen in Figure 9.a_2 that the original Marchetti's correlation is quite promising for the soil from Campinas Site since M estimated from DMT is in relatively close agreement with M determined based on oedometer, basically for all testing data.

The correlations for drained materials were preferentially adopted to estimate strength parameters for the unsaturated red porous silty clay from the Campinas Site, which has high void ratio and high permeability. This approach was also assumed by Cunha et al. (1999) to interpret DMT tests for a porous clay from Brasilia. The reference friction angle was determined with consolidated undrained triaxial tests (CU) carried out on undisturbed soils samples at the natural moisture content. Figures 8.b presents the comparison of reference (lab) and predicted (DMT) friction angles. The estimated DMT friction angles using Marchetti (1997) correlation (equation 2) were higher than those obtained from triaxial tests. The red porous silty clay layer presented an average friction angle equal to 30.5^o based on triaxial tests and the estimated DMT friction angle has an average value equal to 34.5^o. This difference is even higher for the clayey silt layer, where the triaxial average friction angle was 20.2^o and the average predicted DMT friction angle was 32.5^o.

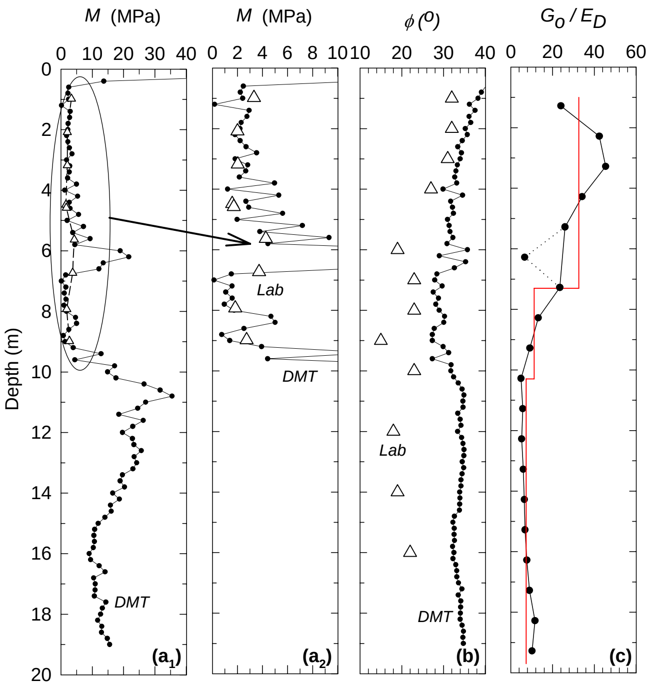

Figure 8. Estimated parameters from DMT test for Campinas Site and results from other tests.

Seismic piezocone test results from the Campinas Site allowed calculation of maximum shear modulus (Go). The Go/E_D values *versus* depth are also presented at the Figure 8.c and this ratio was calculated using the same criteria already presented for the Bauru Site. It also can be seen in Figure 8.c, that lateritic soil layer achieves a higher Go/E_D ratio, which decreases with depth and follows the same trend of Go/E_D ratio observed for the Bauru Site. Three average Go/E_D ratios were calculated for the Campinas Site. This ratio was 33 between 1 to 7 m depth (the lateritic soil layer), 11 between 7 to 10 m depth and 7 between 10 to 19.5 m depth.

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4.3 *São Carlos Site*

4.3.1 *Soil classification*

At the Cenozoic sediment, between 1 to 6 m depth, the I_D parameter identified two distinct soils at this layer (Figure 5.b); a clayey soil (clayey silt or silty clay) between 1.0 to about 4.0 m depth and a silt material (silty sand or sandy silt), between 4.0 to 6.0 m depth. DMT test was not sensitive to the stone line, which was identified by the SPT and some CPT tests between 6.0 to 6.5 m depth. The I_D parameter identified the residual soil; red clayey fine sand as a soil that behaves as silt; sometimes it is more a sandy silt and other times it is more silty sand.

At this particular site the DMT response was not able to identify exactly the changes in the soil behavior since it did not separate the boundaries of lateritic and saprolitic soils. It is also interesting to point out that at the site in São Carlos, Robertson et al. (1986) classification chart identifies the red clayey fine sands (residual soil from sandstone), as clays with a SBT=3 (Giacheti et al., 2003). DMT identified this material as silty soils. Marchetti et al. (2001) affirmed that the I_D is not a result of a sieve analysis but it is a parameter that reflects mechanical behavior and a clayey sand can behave as a silty soil.

Total unit weight of the soil estimated based on material index (I_D) and dilatometer modulus (E_D) using Marchetti and Crapps (1981) chart (Figure 6.c) are in reasonable agreement with those obtained from undisturbed samples, as presented in Figure 5.e, especially for the Cenozoic sediment (up to about 6 m depth).

4.3.2 *Geotechnical soil parameters*

DMT constrained modulus (M) derived from the original correlation proposed by Marchetti (1980) is compared with laboratory values from oedometer tests. The oedometer tests were carried out with undisturbed soil sample at natural soil content up to a maximum load of 800 kPa. It can be seen in Figure 9.a_2 that the original Marchetti's correlation is promising for the clayey fine sand from the São Carlos Site since M estimated from DMT is in relatively close agreement with M from oedometer tests for the samples collected at 1.4, 3.0, 7.0 and 8.4 m depth. Just for the samples collected at 4.6 m depth, M from DMT was almost twice M from oedometer test.

Machado (1998) carried out a comprehensive laboratory study on the soil from the São Carlos Site considering its unsaturated condition. Drained triaxial tests (CD_{sat}) over saturated soil samples as well as multistage triaxial tests with controlled suction were carried out on undisturbed block samples colleted at 2, 5 and 8 m depth. It was concluded that the soil behaves as cohesive-frictional material with the cohesion varying with suction. Friction angle was not dependent on suction and it can be assumed equal to effective friction angle determined based on consolidated drained triaxial test results. Figures 9.b presents the comparison of reference (lab) and predicted (DMT) friction angles. Machado (1998) considered an average ϕ angle equal to 30^o for the Cenozoic sediment and the average estimated DMT ϕ angle for this layer was about 32^o. For the residual soil, measured ϕ angle was 26^o at 8 m depth and estimated ϕ angle was around 30^o, based on Marchetti (1997) correlation (equation 2).

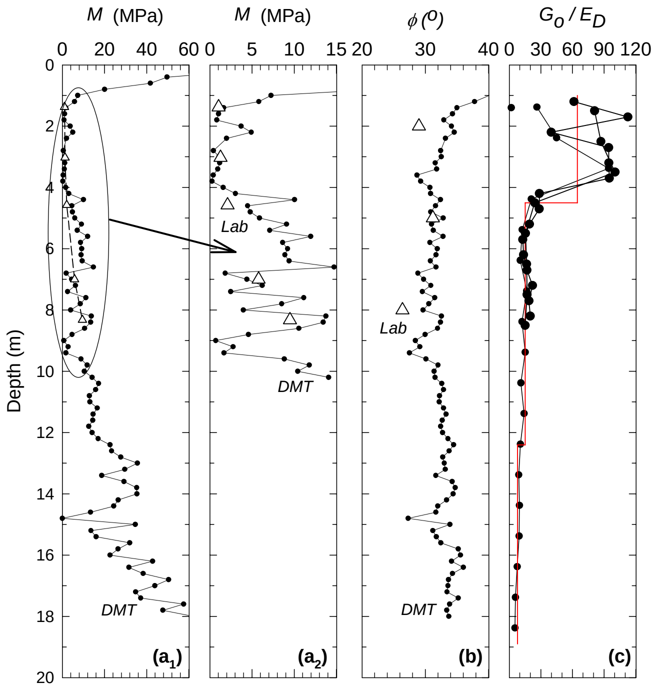

Figure 9. Estimated parameters from DMT test for São Carlos Site and results from other tests.

Seismic piezocone and cross-hole test results from the São Carlos Site allowed calculation of maximum shear modulus (Go) up to about 19 m depth. Shear wave velocities (Vs) calculated with the SCPT tests were in close agreement with Vs calculate with cross-hole seismic tests for this site (Giacheti et al, 2006). The Go/E_D ratio *versus* depth is presented at the Figure 9.c and this ratio was calculated using the same criteria already presented for the Bauru Site. It can be seen in this figure that the lateritic soil has a higher Go/E_D ratio (with some scatter) also for this site, and it tends to decrease with depth, following the same trend of Go/E_D ratio observed for the Bauru and Campinas sites. Three average Go/E_D ratios were calculated for São Carlos Site: 65, between 1 to 4.5 m depth; 15, between 4.5 to 12.5 m depth and 8, between 12.5 to 19 m depth.

5 FINAL REMARKS

This paper presents pioneer DMT tests carried out at three experimental research sites in Brazil and the initial experience and interpretation on this test with "non-classical" geotechnical materials.

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The I_D parameter 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. The I_D parameter was not appropriate to identify soil texture since mixtures of sand and clay or sand, silt and clay were identified as silt or silty soils. For tropical soil, the soil description in terms of grain size distribution has to be confirmed with soil samples, which can also be used to help identifying genetic characteristics of the soils, since they affect soil behavior. At the moment, in Brazil, SPT has been currently used together with DMT to provide samples. Another option is to use a soil sampler from the direct-push technology. DMT can govern the depths from where to recover samples and the same equipment that pushes the probe can also push the soil sampler.

The estimated total unit weight based on DMT test was quite good for the Bauru Site, reasonable for the São Carlos Site and inadequate for the Campinas Site.

At the Bauru Site DMT Modulus (E_D) was similar to PMT modulus (E_{pmt}) up to about 11 m depth and E_{pmt} was almost half E_D after that depth. It is interesting to note that the lateritic soil layer ends close to this depth (between 12 to 13 m depth), based on MCT Classification System, SPT-T and CPT test interpretation. For this site, K_o predicted from DMT using Marchetti (1980) correlation basically matched PMT K_o values up to 8 m depth. Below this depth, DMT K_o curve calculated using Baldi et al. (1986) correlation better matched PMT K_o values, which could be estimated using Jaky (1948) formula.

DMT constrained modulus (M) derived from the original correlation proposed by Marchetti (1980) seems to be quite promising for the São Carlos and Campinas Sites.

The estimated strength parameters for the studied soils assumed drained expansion of the DMT membrane even for clayey soils, because their high permeability and unsaturated condition. The estimated DMT friction angle based on Baldi et al. (1986) correlation was quite good for the soil below 5 m depth in the Bauru Site, reasonable for the São Carlos Site and has to be adjusted for the Campinas Site.

Findings from research on the dynamic behaviour of tropical soils have shown that lateritic soils behave differently from saprolitic soils. Go/E_D ratio was calculated for all the sites and it was higher at the lateritic soil layer tending to decrease as the soil is less developed. It follows the same trend of Go/q_c presented by Schnaid et al. (1998), Giacheti et al. (1999) and Giacheti et al. (2006) for tropical soils. Relating low strain modulus to an ultimate strength parameter or a high strain modulus appears to be an interesting approach to help characterize tropical soils since the low strain modulus from seismic tests reflects the weakly cemented structure of lateritic soils while the penetration or a higher strain modulus breaks down all cementation.

6 ACKNOWLEDGEMENTS

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