Proceedings Seventh International Congress International Association of Engineering Geology

5–9 SEPTEMBER 1994 / LISBOA / PORTUGAL

Editors
R.OLIVEIRA, L.F.RODRIGUES, A.G.COELHO & A.P.CUNHA
LNEC, Lisboa, Portugal

OFFPRINT

A.A.BALKEMA / ROTTERDAM / BROOKFIELD / 1994

Dilatometer tests in Brasília porous clay

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Abstract This paper presents results of Marchetti dilatometer tests (DMT) in a soft unsaturated and collapsible porous clay of Brasília, Brazil. Soil parameters were obtained from correlations developed from saturated and sedimentary soils in Europe. DMT data for the porous clay were compared with other in situ and laboratory tests and the results presented a good agreement and repeatibility.

Introduction

The dilatometer was developed in Italy by Marchetti (1980) [9] and consists of a 14 mm thick 95 mm wide and 220 mm long blade (Figure 1) which is driven or pushed into the soil. On one face there is a 60 mm diameter steel diaphragm capable of a lateral expansion of 1 mm under gas pressure. Beneath the membrane there is an electric switch that turns on a buzzer and warns the operator when the expansion reaches 1 mm. The gas pressure is brought from the surface by means of plastic leads. At the start of the membrane expansion the operator records the initial lift-off pressure that displaces the membrane (pressure *A*) and at the end of the 1 mm inflation, the final pressure (*B*). The same procedure is repeated each 20 cm during penetration of the instrument.

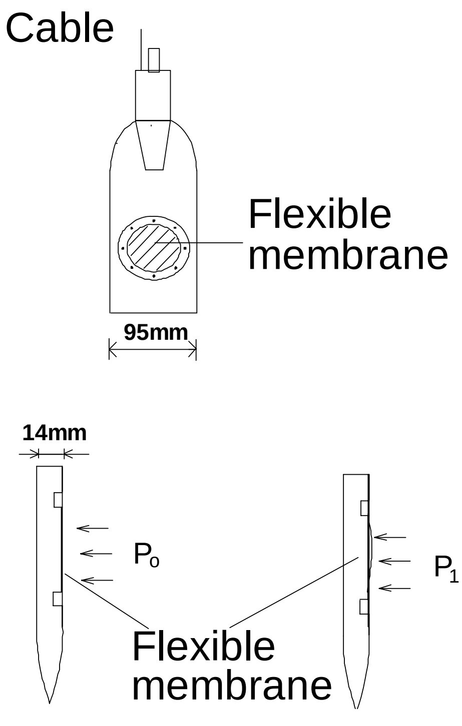

Figure 1 The Marchetti dilatometer

The following p_0 and p_1 values are obtained:

$$p_0 = A + \Delta A \qquad (1)$$

$$p_1 = B - \Delta B \qquad (2)$$

where ΔA and ΔB correspond to membrane stiffness corrections.

Then, the following index parameters are obtained:

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \qquad \text{Material index} \quad (3)$$

$$K_D = \frac{p_0 - u_0}{\sigma'_{vo}} \qquad \text{Horizontal stress index} \quad (4)$$

$$E_D = 34.6(p_1 - p_0) \qquad \text{Dilatometer modulus} \quad (5)$$

where u_0 is the in situ porepressure and σ'_{vo} the in situ overburden effective stress.

Marchetti (*op cit*) proposed a series of correlations based on Italian soils for estimating the soil type, unit weight, the in situ stress ratio K_0, the overconsolidation ratio *OCR*, the undrained strength for clays c_u, the friction angle for sands and the one-dimensional compression modulus *M*. These correlations are based on a limited number of Italian soils, being eight sand deposits and only two clay deposits. Several researchers [2, 3, 5, 7, 8, 10, 13] revalidated these correlations for other sand and clay deposits and concluded that the original Marchetti proposals led to reasonably accurate results. Lunne et al (1989) [7] proposed slight modifications to a few correlations.

Campanella and Robertson [4] interpreted the reasons why the DMT yielded so good results. They employed a special research DMT that has tiny device below the membrane that measures horizontal displacements during inflation and the whole inflation curve can be constructed, as shown in Figure 2. This research apparatus was used in clays and sands and results were compared with selfboring pressuremeter tests at the same depth, with a good agreement. The main conclusions were: the DMT is equivalent to a *poor-boy* selfboring pressuremeter test, with only two points along the expansion curve: the first one, corresponding to p_0, and the final one is p_1, corresponding to a large radial strain of 14%. The dilatometer modulus E_D is calculated as the average slope of the inflation curve between p_0 and p_1.

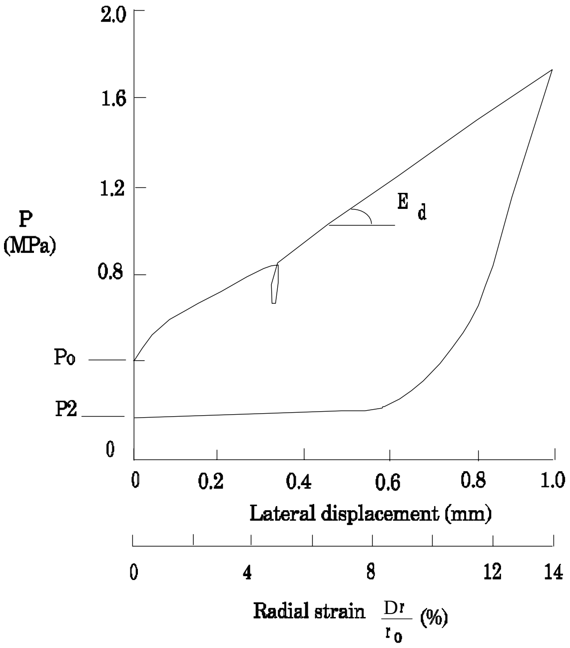

Figure 2 Interpretation of the UBC research DMT (adapted from Campanella & Robertson, 1989, [6])

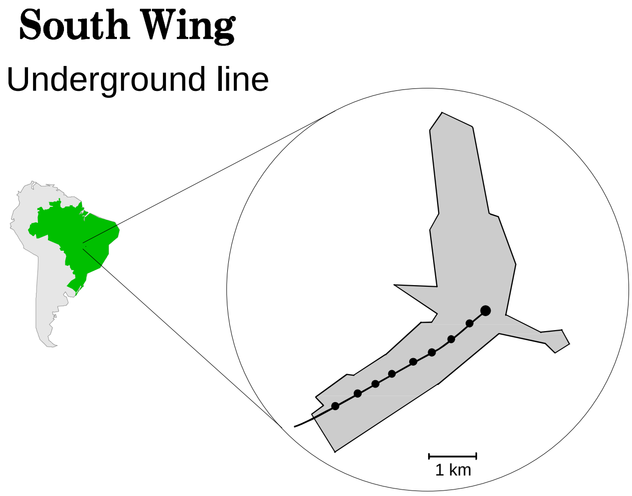

Figure 3 Site location

Site investigation programme

The work described herein is related to the construction of the Brasília Underground transportation system. It encompasses 6.5 km of tunneling employing the *NATM* (New Austrian Tunneling Method) method and over 4 km of cut-and-cover slurry-walls false tunnels. Details about the project and tunneling were published elsewhere (Ortigao and Macedo, 1993 [12])

A field investigation programme was carried out to obtain design parameters. The following in situ tests were used: boreholes and standard penetration tests (SPT), Marchetti dilatometer (DMT), Ménard pressuremeter (PMT), piezocone (CPTU) and horizontal plate loading tests (PLH). Block samples were obtained from test pits for laboratory testing. A series of triaxial and oedometer tests was carried out. This paper presents results of in situ stress ratio K_0, deformation moduli and strength parameters and compares in situ and laboratory test data.

Geology and site conditions

Regional geology and the geomorphology have been

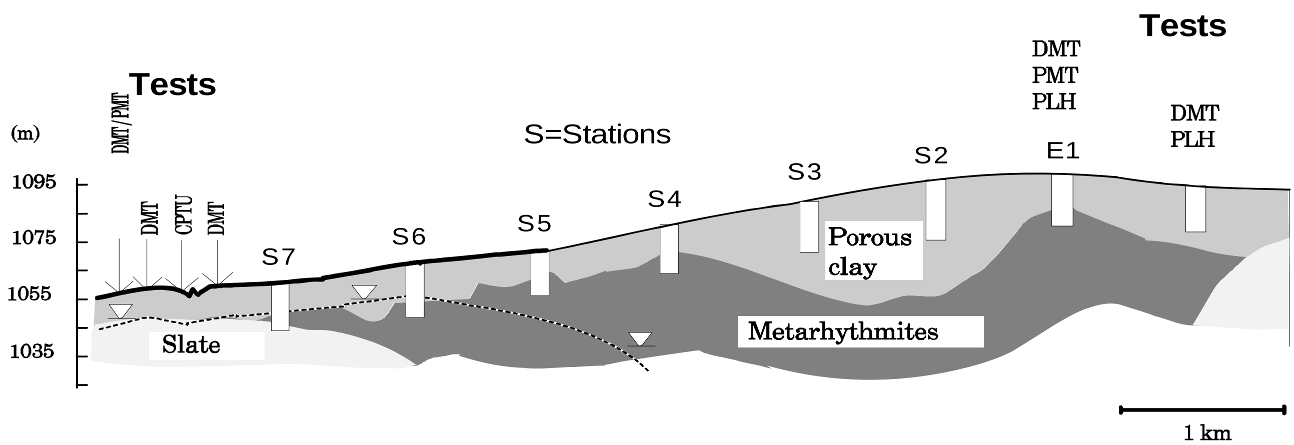

Figure 4 Soil profile along the tunnel, South Wing, Brasília

described by Ortigao and Macedo (1993) [12]. The region is flat, as a characteristic of the central plateau highlands. It is covered by a layer of latosoils and lateritic soils designated here by *porous clay*. It overlies residual soils from slate or a sequence of interlayered siltstones and sandstones, that geologists call *metarhythmites*. These soils are part of the *Paranoah* formation.

Climate alternates from a 6 month rainy season to a very dry Winter, leading to laterization process. Leaching of soluble salts occurs at the top of the porous clay are deposited below. This is responsible for a large amount of pores at the top of the clay layer resulting in high void ratios, low unit weights and high permeability.

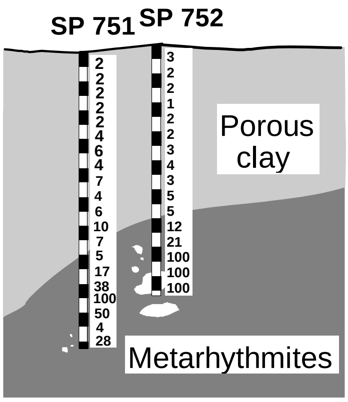

Figure 5 SPT results

This study concentrates at the south wing of Brasília (Figure 3) where the tunnel is now being excavated. Soil profile was initially investigated by 65 mm diameter 20 to 30 m spaced boreholes in which SPT's were carried out at every metre along depth. The porous red clay is 8 to 30 m thick, the SPT blowcount is low, varying from 2 to 3 blows/30 cm.

The water level is generally very deep, except at tip of the south wing (Figure 4), where it can be found at 8 to 10 m depth only. Groundwater observations show high seasonal variation of the water level due to the high permeability of the porous clay.

The bottom of the porous clay is clearly indicated by a sudden rise in the SPT values (Figure 5), as boreholes strike the residual soils below. These residual soils were investigated during excavations and show an inherent anisotropy as a dominant feature. Bedrock characteristics such as bedding and shear planes, are present in the residual soils, therefore they are *structured*. Strength and deformation properties in structured soils vary with direction in relation of bedding and shear planes. Therefore, it is unlikely that in situ tests such as those used for the investigation of the porous clay could be useful in these structured soils.

Characterization of the porous clay

A summary of the laboratory test results on the porous clay is presented in Figure 6. They were carried out on undisturbed block samples.

Atterberg limits are: liquid limit LL =50-80%, plastic limit PL =35-50% and water content w =35-55%. The clay fraction, *i.e.*, the percentage of soil particles less than 2 μm lies between 70 and 55%. The percentage of fines, *i.e.*, less than 60 μm in diameter, varies from 70 and 80%.

The average unit weight of the porous clay γ is 15 kN/m^3, except at the top where severe leaching took place even lower values can be found. The void ratio is close to e =1.7 and the degree of saturation is low above the water level, about 60-80%.

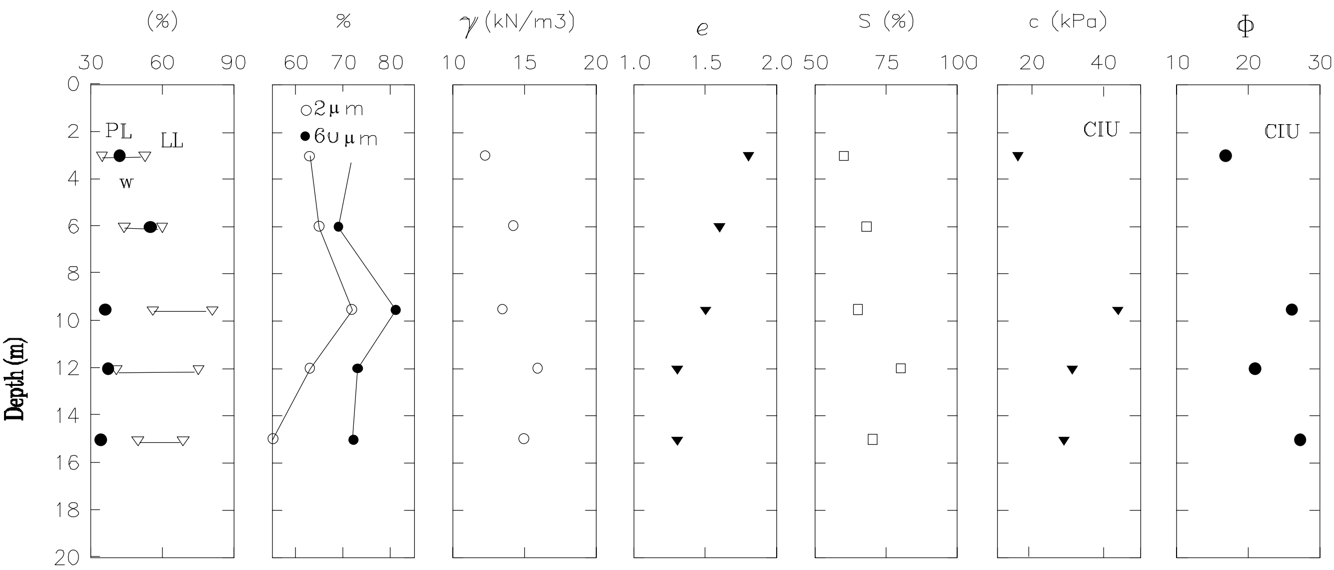

Figure 6 Summary of laboratory test data

Undrained triaxial tests on unsaturated and saturated samples were carried out. Strength of the unsaturated clay can be represented by the following Mohr-Coulomb's parameters: cohesion *c* from 20 to 40 kPa and friction angle ϕ in the 25-28^{o} range. These parameters can be regarded as effective strength parameters because measured porepressures were very low in *CIU* tests on unsaturated samples.

Local experience with construction on this clay has proved that it is collapsible. Low rise buildings on shallow foundations tend to crack one to two years after construction. Good practice is to adopt deep foundations consisting of small diameter bored piles, even for just one story building.

DMT testing programme and results

Five DMT boreholes were carried out in the south wing of Brasília, with some 20 to 30 tests per working day. The small size and portability of the equipment and the use of a local drilling rig led to high productivity and low cost per test. Data were processed by a computer program and plotted as indicated in figure 7 to figure 8. The results indicate a good repeatability in the porous clay. K_0 value is close to 0.6, the friction angle varies in the range of 20 to 27 degrees and the cohesion is around 20 kPa. It is remarkable that the DMT correlations yield both cohesion and friction angle for this clay, which presents a drained behaviour due to its high permeability.

Figure 9 presents the results of several boreholes together. Several and allow the following conclusions. K_0 is high at the first two metres of depth and then decreases and lies in the 0.5-0.7 range, slightly decreasing with depth. The one-dimensional compression modulus *M* varies from a value around 5 MPa at the ground level and increases with depth reaching 20 MPa at 15 m depth. Values of E_D increase from zero at the ground level and reach 15 MPa at 15 m depth.

Figure 10 compares strength parameters from all boreholes plotted together. The repeatability is remarkable. The friction angle lies in a narrow

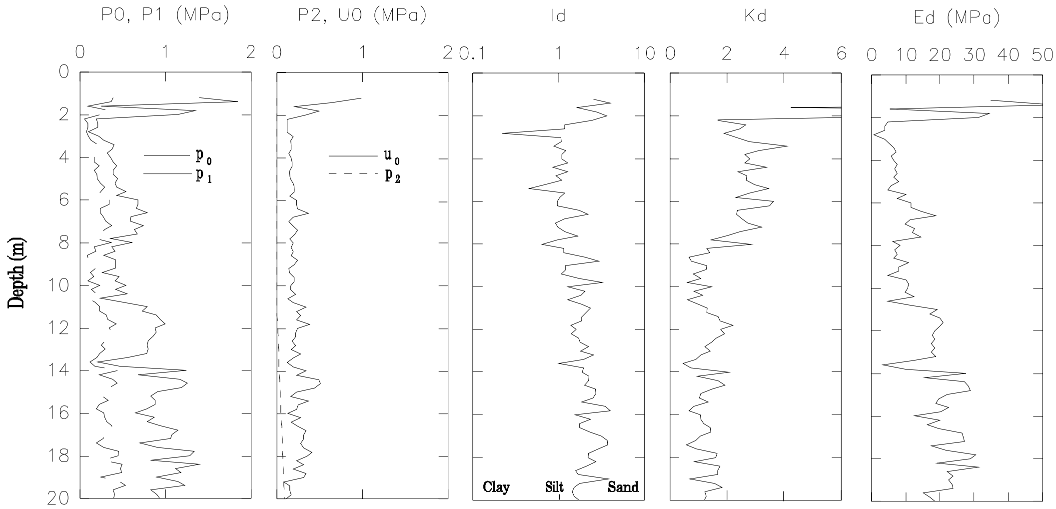

Figure 7 Typical results from DMT test (SP608)

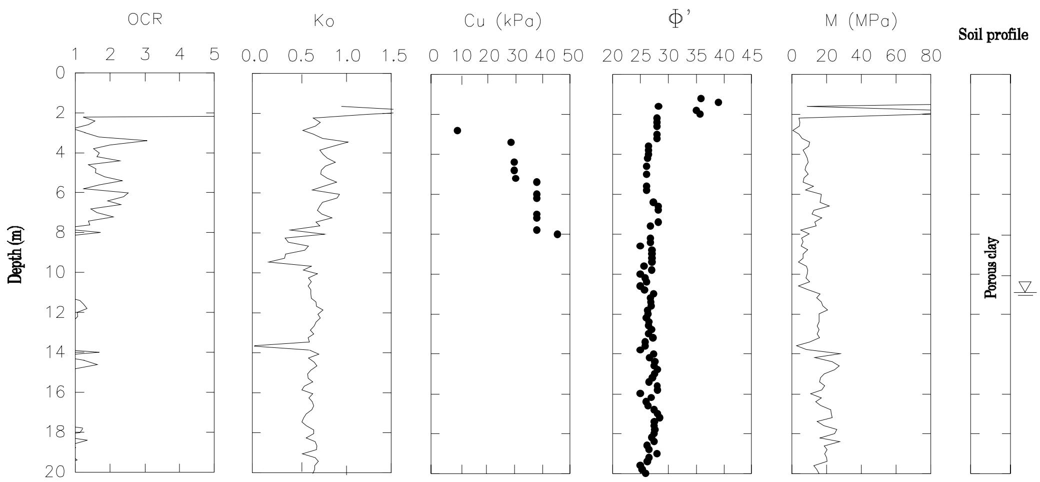

Figure 8 Typical results from DMT test (SP608)

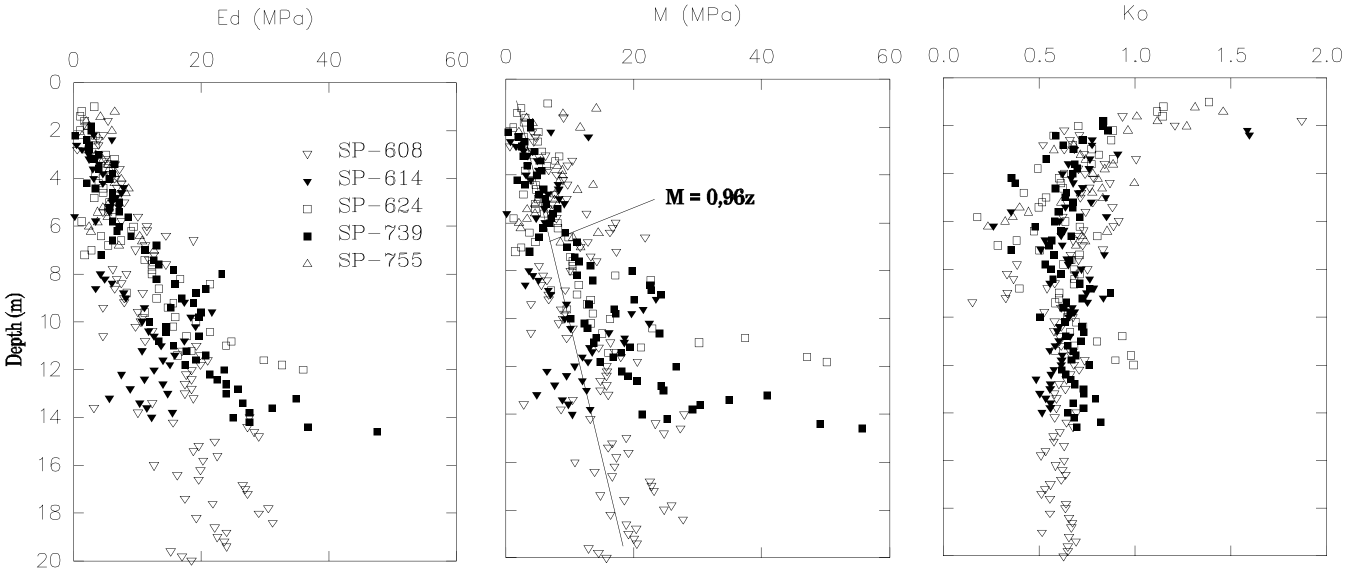

Figure 9 Deformation moduli and K_0 *from several DMT's in the porous clay*

range from 25 to 28 degrees and does not vary with depth. Cohesion data is scattered but seems to increase with depth , as shown in this figure.

Spurious results were obtained for *OCR* and will not be presented here.

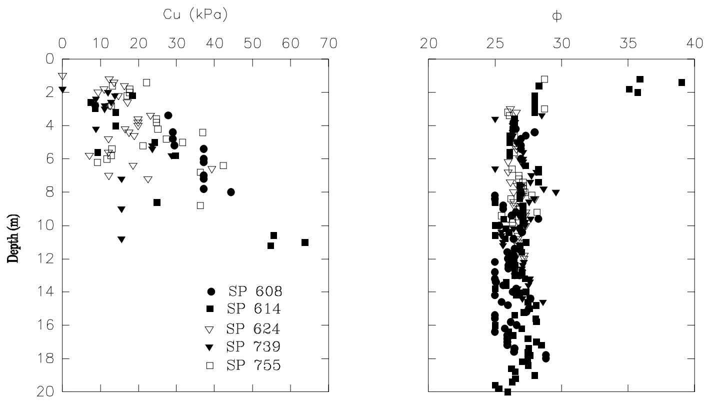

Figure 10 Strength parameters from DMT in the porous clay

Additional in situ tests

The in situ testing programme included horizontal plate loading tests (PLH), Ménard Pressuremeter tests (PMT) and piezocone testing (CPTU). A brief description is given below.

Horizontal plate loading tests were carried out in 1.5 m by 1.5 m wide test pits used for block sampling. A 300 mm square steel plate was jacked on the pit walls. Details of the testing procedure and analysis of results is given by Ortigao (1993) [11]. These tests yielded Young's moduli E_i at the beginning of loading and E_{ur} at an unload-reload cycle.

Ménard pressuremeter testing was carried out in two boreholes. Testing techniques conformed with standard procedures (*eg*, Baguelin al [1]). The following soil parameter were obtained: the pressuremeter modulus E_m and the limit pressure p_{lim}. In addition, an unload-reload cycle in the beginning of the test allows the determination of the unload-reload modulus E_{ur}. The corresponding shear moduli G_m and G_{ur} were obtained assuming elastic conditions.

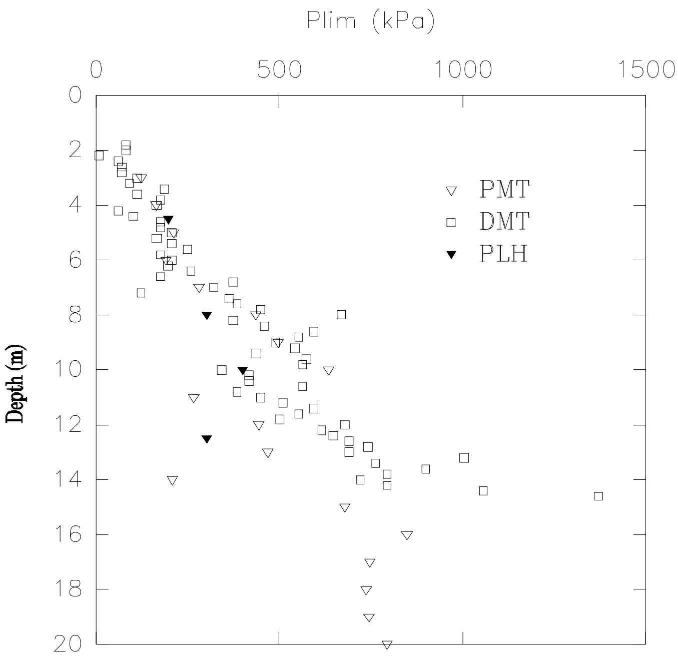

Figure 11 Limit pressure p_{lim} *from PMT, DMT and PLH*

Interpretation of results

Results from different in situ tests were compared with each other and with laboratory test data. The following observations can be made:

- **The limit pressure p_{lim}**

The limit pressure is usually defined for PMT only. However, Robertson and Campanella [4] DMT interpretation allows the adoption of an equivalent p_{lim} for the DMT equal to p_1. Additionally, it is also possible to obtain p_{lim} from PLH similarly to the procedure used for PMT. Results are compared in figure 11. There is a reasonable agreement of p_{lim} values from different tests. This match is explained because p_{lim} is obtained for very large deformation, or *macrodeformation* range, and beyond any influence of soil disturbance by any insertion method.

- **Young's modulus *E***

Young's moduli from all in situ tests are plotted in figure 12. An arbitrary value of 0.33 for Poisson's ratio was employed to obtain *E* from PMT's and PLH's. Due to non-linearity in soil behaviour, secant modulus depends of the strain or stress level. This should be considered when comparing moduli from different tests and a reference strain level should be obtained for each test. As an example, Jamiolkowski et al [5] have shown that in normally consolidated sands the DMT corresponds to triaxial tests moduli at a strain of 0.1%. Equivalent comparisons for clays are not known to the author.

Results plotted in figure 12 show that E_m (PMT) is less than E_D (DMT), which in turn are in the same order of magnitude of a few E_i (PLH) data. Soil disturbance during borehole drilling and probe insertion is an explanation for the low PMT's moduli. Nevertheless, an equivalent soil disturbance would be expected in PMT's and PLH's, but the moduli from these tests are rather different.

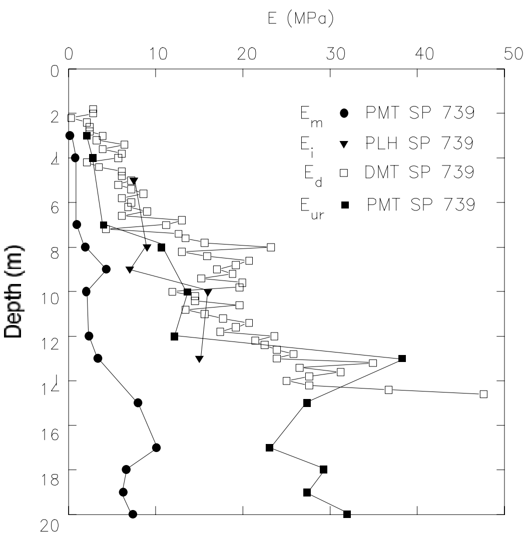

Figure 12 Young's moduli E *from PMT, PLH e DMT*

- **Strength parameters**

The average value for the friction angle ϕ=26º given by the DMT's, with remarkable repeatability, (Figure 13) is reasonably close to a few available laboratory test data. It is pointed out that ϕ given by the DMT was based on correlations for sands. On the other hand, laboratory data for the porous clay was obtained from *CIU* triaxial tests in total stresses. However, due to the low level of saturation, these values seem to agree. Field behaviour of the porous clay can be regarded as *drained* due to its high amount of pores and high permeability.

Cohesion given by the DMT correlations present a lot of scatter. Only a few laboratory reference data for the porous clay are available. Therefore, it is at least premature to state conclusions for this parameter, despite that DMT indicates the same order of magnitude of triaxial test data. Notwithstanding, at low stress levels and for unsaturated conditions it is possible to take into account a cohesion value to express a c-ϕ behaviour. At high stress levels and for saturated conditions it is advisable to disregard cohesion.

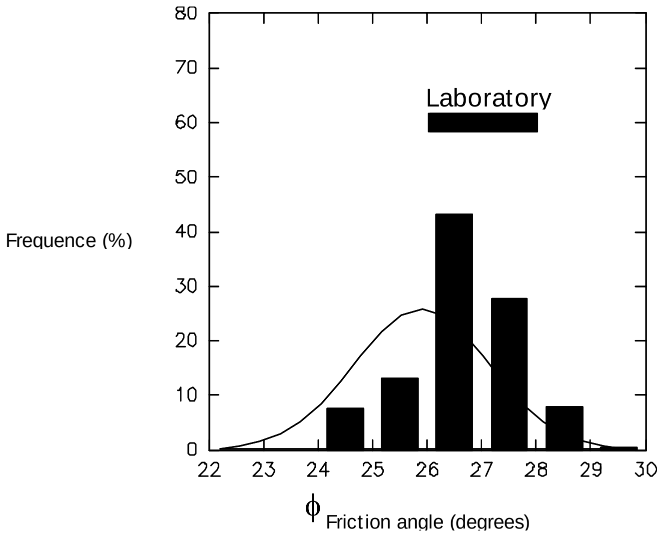

Figure 13 Gauss

Conclusions

Main conclusions from in situ tests in Brasília porous clay are: there is no useful correlation between SPT's and deformation moduli. The SPT index is not at all sensitive to the low stiffness of the porous clay. The time consuming PLH tests, yielded results that agree with other tests. PMT's have shown very low moduli that seem to be affected by soil disturbance.

The DMT led to excellent results: very good repeatability, reasonable agreement with laboratory test data, very easy deployment and operation, low cost and high productivity.

Acknowledgments

The in situ testing programme was sponsored by the Brasília Metro Company and was carried out by Bureau Ltd, São Paulo, (PLH), Geomecânica SA, Rio de Janeiro (CPTU and DMT), Geotécnica SA, Rio de Janeiro, (PMT) and the laboratory tests by the University of Brasília. Support from Lucia Alves and Alejandro Far during the preparation of this article is appreciated.

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