Evaluation of geotechnical parameters by DMT in Portuguese soils
Evaluation des paramètres géotechniques par le DMT dans des sols portugais

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ABSTRACT: Herein are presented the conclusions resulting from three experimental studies performed with Marchetti´s dilatometer on alluvial deposits of three Portuguese rivers. The results are then compared with conventional laboratory and "in situ" tests. A first approach to the use of this equipment on residual soils, by means of a practical study performed on soils of granitic nature, is also described.

RESUME: On presente ici les conclusions obtenues à partie de trois études pratiques realisées en employant le Dilatómetre de Marchetti en des depôts alluviaux de trois fleuves portuguais. Plus L'on etablit des comparaisons des essais traditionels en laboratoire et "in situ". L'on fera aussi la description d'une première approche à l'utilization de ce equipement dans des sols residuels, par moyen d'une étude practique mise en action pour des sols granitiques.

1. INTRODUCTION

This paper presents the results of the first attempt of characterization of Portuguese soils by means of Marchetti's dilatometer (DMT). The study was conceived in order to evaluate its adequacy and efectiveness of DMT to obtain the mechanical properties of both sedimentary and residual soils.

Marchetti´s Dilatometer test consists of the static insertion of a blade which has located an inflating membrane on one of its faces. The membrane is inflated every 20 cm, using a pressurized gas, taking measures of the pressures needed to displace its center by 0.05 mm (reading A) and 1.1 mm (reading B). These two measured pressures are then corrected, taking into account the membrane's rigidity, thus obtaining the pressures P_0 and P_1, respectively.

Marchetti (1980) defined 3 DMT parameters, as follows:

Material Index, $Id = (P_1 - P_0)/ (P_0 - u_0)$ (1)

Dilatometric Modulus, $Ed = 34.7 (P_1 - P_0)$ (2)

Lateral stress index, $Kd = (P_0 - u_0) / \sigma'_v$ (3)

These parameters have been correlated with stratigraphy, unit weight, stress history, resistance and deformability of transported soils.

The main goal to be achieved with the study was to verify in the portuguese territory the consistency of the common correlations established by the scientific comunity for transported soils. Therefore, three comparative studies were made on alluvial deposits of three of the main Portuguese rivers - Tagus, Mondego and Vouga - located on the South, Center and Center - North of Portugal, respectively.

Concerning residual soils there is an evident lack of information about their characterization by means of DMT. So, a first attempt was made in order to purpose some specific correlations by means of some experimental studies performed on granitic residual soils located in northern part of the country.

2. TRANSPORTED SOILS

The geological environments of the studied areas are characterized by considerable thickness (over 30.0 m) of the deposits, which lie over the Cretacic (Mondego and Vouga) and Miocenic (Tagus). The identification and physical characteristics of those soils are resumed in Tables 1 and 2.

Table 1 - Identification tests on transported soils

	Tagus	Mondego	Vouga
Grain size (%)			
< 0.074 mm	95.0 - 98.0	72 - 81	---
< 0,06 mm	---	70 - 80	70 - 82
< 0.002 mm	---	20 - 30	6 - 10
Liquid limit (%)	45 - 75	45 - 55	45 - 60
Plastic limit (%)	18 - 30	30 - 34	25 - 40
Unified Class. *	CH	OL - OH	OL - OH

* ASTM D2487 - 85. Classification of soils for engineering purposes

Table 2 - Physical characterization on transported soils

	Tagus	Mondego	Vouga
Unit weight (KN/m^3)	16.0 - 17.5	14.0 - 15.0	16.0 - 17.0
Moisture content (%)	50 - 70	60 - 100	50 - 70
Specific gravity of solids (KN/m^3)	25.0 - 26.5	26.0 - 26.4	26.0 - 26.4
Void ratio	1.4 - 2.2	1.5 - 3.0	1.2 - 1.8
Organic content (%)	---	9 - 11	---

The mechanical characterization was based upon field vane (FVT), CIU and CK_0U triaxial and oedometer tests. The results were compared with those obtained from Marchetti´s Dilatometer (DMT) which were carried out in the three sites. Table 3 shows the summary of the results of dilatometer modulus, E_D, material index, I_D, and horizontal stress index, K_D.

Table 3 - DMT results on transported soils

Vouga	I_D	E_D (MPa)	K_D
Sands and Silty sands	1.5 - 4.0	5.0 - 15.0	2.0 - 4.5
Sandy silts	0.8 - 1.5	2.5 - 4.0	1.5
Silty clays	0.3 - 0.8	1.0 - 2.0	1.8 - 3.0
Clays	< 0.3	0.5 - 2.0	1.8 - 3.0
Mondego	0.25 - 0.40	0.9 - 1.2	1.3 - 1.8
Tagus	0.15 - 0.25	0.5 - 1.8	1.8 - 2.3

The comparison between DMT results and conventional tests led to the following conclusions:

i) *stratigraphy* - DMT results, based on Marchetti's correlations (1980), show good agreement with data obtained by grain size distribution test; however, in cases of organic soils, I_d values seem to be lower than expected;

ii) *unit weight* - DMT values, based on Marchetti & Crapps (1981) correlation are within the limits of $\pm$ 1KN/m^3;

iii) *coefficient of earth pressure at rest* - DMT results, based on Marchetti's correlation (1980), show good agreement with Alpan's correlation, based on plasticity index, as can be seen in Figure 1;

iv) *undrained shear strength* - DMT results, based on Roque's correlation (1988), seem to agree with the peak values of FVT, after Bjerrum correction, as can be seen in Figure 2; on the other hand, Marchetti (1980) and Lacasse correlations (1988) showed good agreement with residual values of FVT obtained on soils with moisture content higher than liquid limits, as shown in Figure 3; this situation seems to be a consequence of the different criteria in which each correlation is based upon; indeed, Marchetti and Lacasse correlations are established via overconsolidation ratio (OCR), in terms of effective stresses and with P_0 as the main pressure used in the correlations, while Roque's correlation is based on load capacity theories, in terms of total stresses and with P_1, which is less affected by insertion of the blade, being the main pressure used in the correlation;

v) *drained constrained modulus* - DMT results, based on Marchetti's correlation (1980), are fairly consistent with oedometric modulus, E_{oed} (defined as the inverse of coefficient of volume change, m_v) obtained from consolidation tests, as shown in Figure 4.

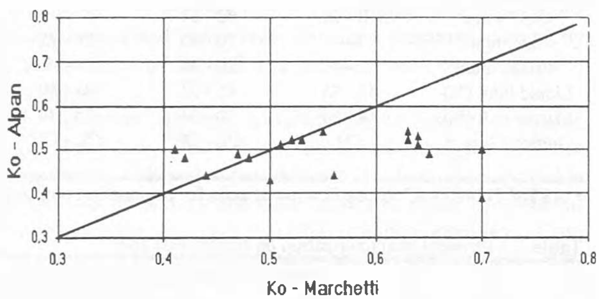

Figure 1 - Coef. earth pressure at rest

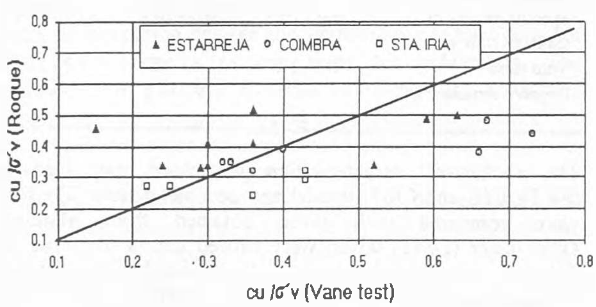

Figure 2 - Peak undrained resistance on transported soils

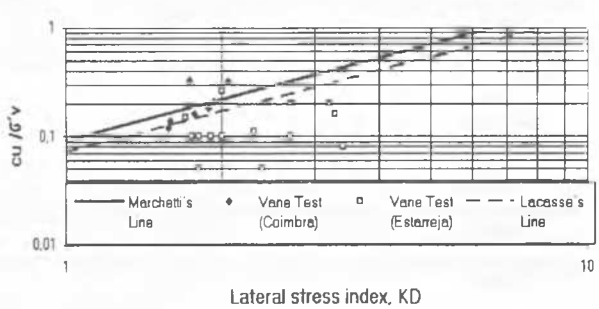

Figure 3 - Residual undrained resistance on transported soils

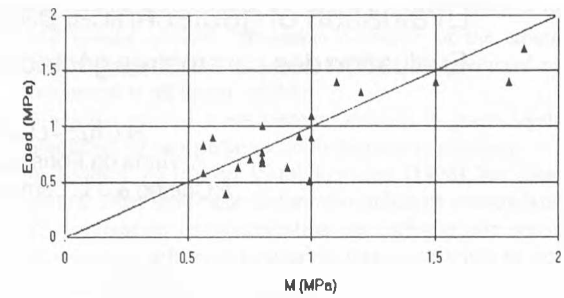

Figure 4 - Drained constrained modulus

3. RESIDUAL SOILS

The behaviour of residual soils is hardly explained by classical soil mechanics when solely taken into account. Indeed, the existence of an inherited cemented structure leads to stress-strain relations different from those exibited by transported soils. These differences are mainly due to the presence of a cohesion intercept, c', revealing shear strenght increment related to cementation, and the existence of two yield points, the first corresponding to the loss of cementation resistance and the second corresponding to an overall plastic yield of the soil (Vaughan *et al*, 1988).

Expectedly, DMT correlations, which were established from tests in transported soils, do not fit on residual soils, except for the stratigraphy and unit weight as they do not depend on cemented structure.

This problem will be discussed below, based on the results obtained from a study performed on two granitic residual (saprolitic) soils belonging to the same geological complex and located nearby the city of Porto. It is recognized that there is a lack of significative experimental data and so the presented correlations need to be confirmed by other experimental sites with different geological environments and weathering degrees.

The results of identification and physical characterization of the studied soils are presented in Tables 4 and 5, while Table 6 shows the mechanical results obtained from triaxial tests, cone penetration tests (CPT) and Pressuremeter tests (PMT and SBPT). The similarities between both sites are evident.

The DMT parameters, I_D, E_D and K_D are presented in Table 7.

Table 4 - Identification tests on residual soils

	Porto	Maia
Grain size (%)		
< 0.074 mm	15.0 - 40.0	37.0 - 40.0
< 0,06 mm	15.0 - 35.0	---
< 0.002 mm	2.0 - 8.0	---
Liquid limit (%)	28 - 40	30 - 40
Plastic limit (%)	18 - 30	15 - 25
Unified Class.	SC - SM	SC - SM

Table 5 - Physical characterization on residual soils

	Porto	Maia
Unit weight (KN/m^3)	18.0 - 20.0	18.0 - 19.5
Moisture content (%)	15 - 25	20 - 24
Specific gravity of solids (KN/m^3)	26.2 - 26.6	26.6
Void ratio	0.6 - 0.8	0.7 - 0.75
Degree of saturation (%)	70 - 100	70 - 85

Table 6 - Mechanical tests results

	Porto	Maia	Testing procedure
Coef. of earth pressure at rest	0.36 - 0.38	--	SBPT
	0.35 - 0.40	--	Triaxial with bishop rings
	38		SPT(*)
Eff. shear	--		(N_1) 60
strength	44 - 45	42 - 44	CPT (*)
parameters:	--	--	q_c, σ'_{v0}
	40 - 47	--	SBPT (*)
ϕ'(°)	--	--	(sands)
c' (KPa)	37	--	PLT
	7	--	(D=120;60;30cm)
	37 - 38	37	Triaxial tests(**)
	9 - 12	--	(CID;CK_0D)
			(100 mm)

*results obtained by means of correlations for granular soils
** undisturbed block samples

Table 7 - DMT results on residual soils

	Porto	Maia 1	Maia 2
I_D	1.5 - 2.2	1.2 - 2.1	1.2 - 2.1
E_D (Mpa)	20 - 30	10 - 30	20 - 30
K_D	7.0 - 11.0	5.5 - 7.0	4.5 - 8.0

3.1. Stratigraphy and unit weight

The results of stratigraphy and unit weight seems to be consistently staded by conventional classification charts developed for transported soils.

3.2. Coefficient of earth pressure at rest, K_0

The determination of the coefficient of earth pressure at rest, K_0, on granular soils was established by Baldi *et al* (1986) using DMT and CPT tests, acording to the following correlation:

$$K_0 = C_1 + C_2 K_D + C_3 q_c/\sigma'_v \quad (4)$$

where C_1 = 0.376, C_2 = 0.095, C_3 = 0.00172, qc is te cone resistance of CPT and σ'_{v0} is the vertical effective stress at rest.

Campanella and Robertson (1991) making use of the theory of Durgonuglu and Mitchell (1975) pointed out a mean to evaluate K_0 using solely the K_D value. The resulting diagram can be seen in Figure 5.

This diagram shows the possibility of relating q_c/σ'_v with K_d, by the following expression:

$$q_c/\sigma'_v = 33\ K_D \quad (5)$$

The CPT and DMT tests performed in Porto experimental site showed results that differed considerably from this expression. The corresponding relation is presented below:

$$q_c/\sigma'_v = 8.4\ K_D \quad (6)$$

If constant C_2, the only value from equation (4) that turns to reflect the q_c - K_D dependency. is modified according by:

$$C_2 = 0.095 * 8.4 / 33 = 0.024$$

the resulting K_0 values will range within the limits 0.35 - 0.50, which are consistent with those obtained from SBPT and triaxial tests.

The same process was applied in Maia, obtaining a relation between q_c/σ'_v and K_D equal to 12.5 which leads to a C_2 value of 0.035. The resulting K_0 values range within the limits 0.4 - 0.5. Unfortunatly, no data from SBPT tests are available so it is not possible to confirm the results, although they are with in the expected limits.

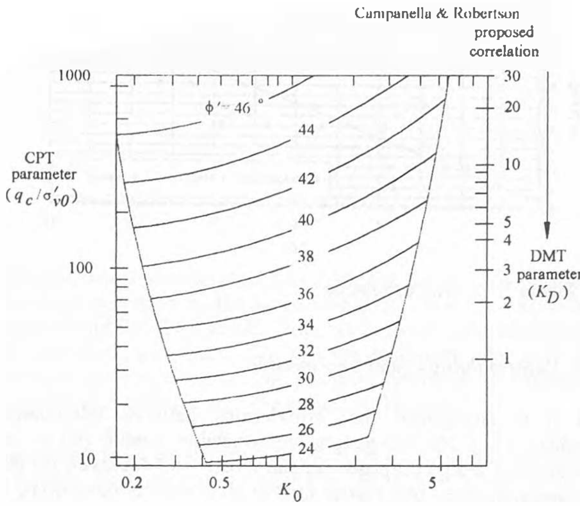

Figure 5 - Proposed chart for predicting peak friction angle (ϕ'_{ps}) from DMT and CPT, for uncemented, unaged, silica sand - Durgunoglu and Mitchell (1975) - Marchetti (1985) bearing capacity theory (Campanella e Robertson, 1991).

3.3. Contribution of cementation on effective cohesive strength

While values of I_D and E_D in both places are more or less alike, K_D values differ considerably as can be seen in Table 7. The correponding friction angles, ϕ', evaluated using the diagram of Figure 5 (K_D axis) are within the limits of 40° - 42° (Porto) and 38° - 40° (Maia), which are between than those evaluated by SPT and CPT tests, fairly near the SBPT results and higher than triaxial tests. These late values congregate with an effective cohesion intercept which cannot be negligenciated, so it seems that this discrepancy can be explained in the fact that K_D reflects not only friction angles but also the effective cohesion due to cemented structure.

If this is valid, since it is easy and allowed to evaluate ϕ' by triaxial tests, even with remoulded samples (Vaughan et al, 1988), then it is possible to sub-divide K_D values into the contributions of friction and cohesion. A way of doing this can be sequenced as stated below:

i) determination of ϕ' (triaxial);
ii) determination of K_0 using corrected Baldi's correlation as explained in 3.2;
iii) evaluation of K_D, based on Figure 5, as would be obtained if there were only friction contribution (which will be called equivalent K_d, K_{Deq});
iv) the difference between K_D and K_{Deq}, (called here K_{Dc},)will translate cementation contribution.

The evaluation of cohesion by means of triaxial tests - recognized as the most fundamental tool for shear strength evaluation - in residual soils is, however, very difficult because they easily loose cimentation resistance during the sampling process. So, in the present study this evaluation was carried out using the expression shown below, based on Mohr - Coulomb failure criterium:

$$\sigma' \text{tg}\ \phi'(K_D) = c' + \sigma' \text{tg}\ \phi'(t) \quad (7)$$

where $\phi'(K_D)$ means the friction angle calculated from K_D and $\phi'(t)$ means the friction angle evaluated by triaxial tests.

The regression line between K_{Dc} and c' can be seen in Figure 6, and the corresponding equation is:

$$c' = 0.83\ K_{Dc} \quad (8)$$

The amount of data is not statistically significative to draw definitive correlations, but our intention is solely to point out a trend for further investigation about characterization of residual soils by DMT.

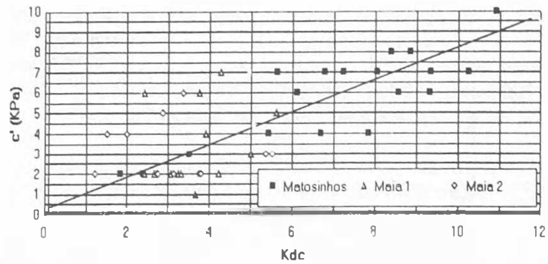

Figure 6 - c' - K_{Dc} correlation

3.4. Deformability - reference moduli

As it is recognized that correlations between dilatometer modulus (E_D) and the general deformability moduli (E) to be adopted for design purposes depend mostly and decisively on the stress-strain levels that matter for the serviceability conditions, it is common to establish these correlations with a reference moduli which stands to be the maximum dynamic shar modulus, G_0, (evaluated for seismic cross-hole tests, CH). This modulus is undoubtfully independent of those levels and also from secondary state factors such as OCR, fabric, being solely dpendent on void ratio, effective stress state and interparticle structure (Jamiolkowski *et al*, 1988; Jamiolkowski and Robertson, 1989; Baldi *et al*, 1989). The former moduli can be evaluated from this late by means of complementary test results such as high quality triaxial tests, which will define the non-linear constitutive laws (such as those from Seed and Idriss, 1970) but it will not be discussed here. It is solely object of this paper to give the obtained correlations between G_0 (CH) and E_D (DMT) introducing the dependency of these moduli with an effective stress state parameter which was introduced by Baldi *et al* (1989), expressed by:

$$p_{0N} = P_0^{(DMT)} / \sqrt{\sigma_v' \cdot p_a} \qquad (9)$$

where p_{0N} is the expansion pressure and p_a is the atmosferic pressure considered equal to 1kpa for adimensionlization purposes.

The Figure 7 shows the values obtained and the correspondent correlation between G_0 and E_D, including the reference purposals for natural and remoulded sands tested in laboratory (deducted from published results from Baldi *et al*, 1989).

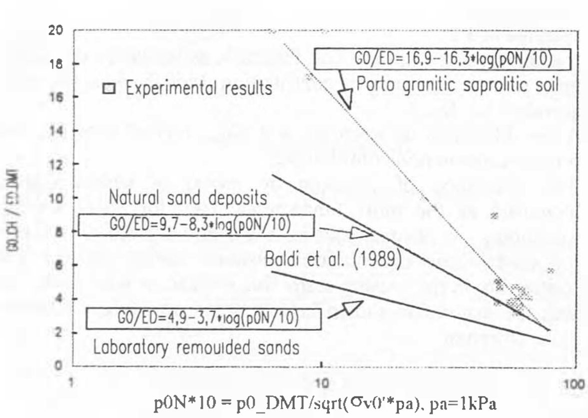

Figure 7 - Correlation between G_0 (CH) and E_D (DMT). Reference proposals from Baldi *et al.* (1989)

The expression deducted for the correlation between experimental results obtained in saprolitic soils from Porto granite is the following:

$$G_0 / E_D = 16.7 - 16.3 \log_{10} (p_{0N}) \qquad (10)$$

which presents a higher gradient of dependency than Baldi's purposals, with high values for the smallest values of the normalized expansion pressure, revealing a strong nonlinearity degree which is most pronounced for low effective confinement stresses (which are associated with ground zones, more dominated by structural cementation than at rest stress states).

4. CONCLUSIONS

1. DMT correlations established for transported soils seems to fit when applied to the same type of soils in Portugal.

2. In some of the conditions described we found it possible to evaluate both peak and residual undrained resistance of sedimentary soils.

3. The tentative characterization of residual (saprolitic) soils by DMT showed encouraging possibilities for the evaluation of coefficient of earth pressure at rest as well as the shear stregth parameters mainly in what concerns the identification of the effective cohesion parcel due to the cemented structure which characterizes this type of soils.

4. For deformability evaluation purposes it is recommended to correlate the dilatometer modulus (E_D) with the reference maximum shear modulus (G_0 from cross-hole tests). The proposal correlation between G_0 / E_D and p_{0N} presents high gradient of dependency reflecting the importance of structuring effects on residual soils.

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