Portuguese experience in residual soil characterization by DMT tests

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Keywords: Marcheti Flat Dilatometer, Residual Soils

ABSTRACT: The mechanical behaviour of residual soils, products of rock weathering have significant deviations from conventional transported soils, for which Classical Soil Mechanics models have been developed. In situ tests are very useful for deriving geomechanical parameters, both for stiffness and strength property evaluations, and of these DMT test has been proving very useful for the characterisation of these soils. For the last decade the dilatometer test has been systematically incorporated in research programs for residual soils, which are very common in the North of Portugal.

In this paper, the at rest earth pressure coefficient (K_0), shear strength parameters (c' and ϕ') and stiffness parameters (G_0, E and M) of these soils will be evaluated. A first approach to the interpretation of an alternative dynamic insertion procedure of the blade for the most compacted or less weathered horizons of these residual soils will also be described.

1 INTRODUCTION

The first campaign of DMT tests performed in Portugal, 10 years ago, in the context of a MSc thesis (Cruz, 1995), had the main goal to evaluate the adequacy of international established correlations, in Portuguese soils. From the geological point of view, the Center and South of Portugal are dominated by sedimentary environments, while North region lies on residual soil massifs with special emphasis on granitic type. The collected data for residual soil will be presented herein, while of another paper presented elsewhere in this conference discusses sedimentary soils for this region.

Due to the presence of a cemented structure, residual soils show a quite different behaviour from sedimentary soils and thus classical soil mechanic theories have some limitations in the interpretation of geotechnical parameters. Being aware of that, the authors establish a large scale research work in order to adapt DMT evaluations to residual soils, which included 15 site experimental programmes carried out between Porto and Braga, with a total of 40 drillings with SPT tests, 36 DMT tests, 22 CPT(U) tests, 4 PMT tests, 5 DPSH tests, and 10 triaxial tests.

2 GENERAL IDENTIFICATION

Granitic residual soils (saprolitic) of North region of Portugal are the result of mechanical and chemical weathering, by means of arenization and hydrolysis of feldspar minerals, respectively. The resulting soils can be globally characterized as non-plastic sandy silts to silty sands, systematically classified as SM or SC, according to Unified Classification. In the context of this work, these soils had 15 to 35% of non-plastic fines, void ratios varying from 0.5 to 0.8, and saturation degrees ranging from 50 to 100%.

3 ANALYSIS OF RESULTS

3.1 *Stratigraphy and unit weight*

One of the basic important features of DMT is its ability to give information related to the basic properties (identification and physical index) of soils, thus creating a rare autonomy in the field characterization. In the course of this research, the overall data set have shown the same level of accuracy of that found in Portuguese sedimentary soils (Cruz et al, 2005) and thus, revealing no need for specific approaches for residual soils.

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3.2 *Strength properties*

As previously described, residual soil behaviour are deeply marked by the presence of a cemented structure, represented by the development of both cohesive intercept (c') and shear strength angle (ϕ'), according to Mohr – Coulomb criterion. This reality takes the following implications for deducing the strength parameters by DMT:

i. Cohesion intercept it is not considered in the basic DMT data reduction.
ii. Shear strength angle derived with recourse to the formulae considered for sedimentary soils, represents the overall strength instead of the parameter on its own, and thus giving higher values than reality.

However, as DMT is a two-parameter test, it is reasonable to expect the possibility of deriving both c' and ϕ', and so it was tried by Cruz et al (2004) as explained in the following paragraphs. According to basic DMT reference (Marchetti, 1980), K_D profiles follow the classical shape of OCR profiles and present typical patterns as function of typified behaviours:

i. Normally consolidated (NC) soils tend to present values around 2.
ii. Low to medium over-consolidated (OC) soils show K_D higher than 2, and generally decreasing with depth until reaching the NC value.
iii. NC soils affected by cementation or aging show K_D profiles stable with depth and higher than 2.

The K_D profiles within the present study show a general tendency to remain stable with depth, showing values significantly higher than 2, namely ranging from 5 to 15. Thus, following the above mentioned assumptions, Cruz et al (2004) concluded that K_D clearly reflects the effects of cementation, although the range of results was too narrow to feel c' variations. However, OCR (which is a numerical amplification of K_D) can be taken as reference parameter, since it represents the cemented structure, as it is presented in the following paragraph.

Even tough the concept of overconsolidation ratio does not have the same meaning for sedimentary and residual soils, the presence of a naturally cemented structure gives rise to similar behaviour. In fact, preconsolidation stress (designated as virtual preconsolidation stress) now represents not the maximum past stress, but the break of cementation yeld locus, and the ratio with vertical rest stress is called 'virtual over-consolidation degree (vOCR)', thus differentiating it from the one physically sustained in the process of sedimentary soils generation with 'stress memory'. This concept, as previously designated, has the same meaning as the established terminology: "vertical yield stress = σ'_{vy}"; which corresponds to other established more general concept: "yield stress ratio = YSR". Thus, the OCR derived from the DMT test on residual soils (vOCR) reflects the strength resulting from the cemented structure, normalised in relation to the effective vertical stress. Moreover, it should be pointed out that OCR evaluation is I_D and K_D dependent (that is P_0 and P_1 dependent), allowing to be confident on the determination of both angle of shear resistance and effective cohesive intercept.

In soils with the mechanical complexity of residual soils it is useful to get information from distinct sources. Thus, the pair DMT+CPT(U) tests has been adopted frequently. Following the same pattern as for OCR, another approach was also considered to deduce c' based on this combination, since M/q_c ratios has been used with success to determine OCR in granular soils (Marchetti, 1997). The available data show M/q_c values situated in the frontier NC/OC (10-12), frequently tending to OC (12 to 15), which must be interpreted as an effect of the matricial cementated structure. It is also clear that the increase with depth is substantially higher with M than with q_c.

Figure 1 illustrates representative evolution of K_D, vOCR and M/q_c with depth, obtained in the present study. The results clearly show the sensitivity of vOCR and M/q_c to variations in soil condition and the lack of it with K_D.

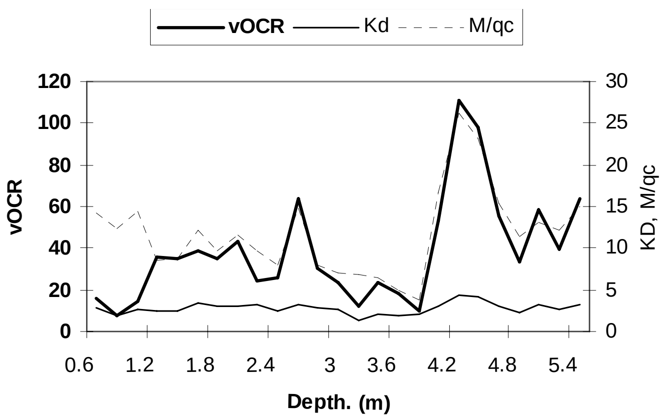

Figure 1. Representative K_D, vOCR, and M/q_c profiles.

The comparisons of these 3 parameters with triaxial testing confirmed that convergence with c' is greater with vOCR (DMT) and M/q_c than with K_D (Figures 2, 3 and 4), as it was expected. In the same figures it is also represented the correlations with c'/σ'_{v0} (true values of this latter multiplied by 100 to be represented in the same scale).

On the other hand, comparing c' with preconsolidation pressure, σ'_p, obtained via DMT, the relation between them is represented by 0,011, which is lower of those pointed out by Mayne & Stewart

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(1988) and Mesri et al (1993), for overconsolidated clays (0.03 to 0.06 and 0.024, respectively), which could be explained by a stronger overconsolidation effect.

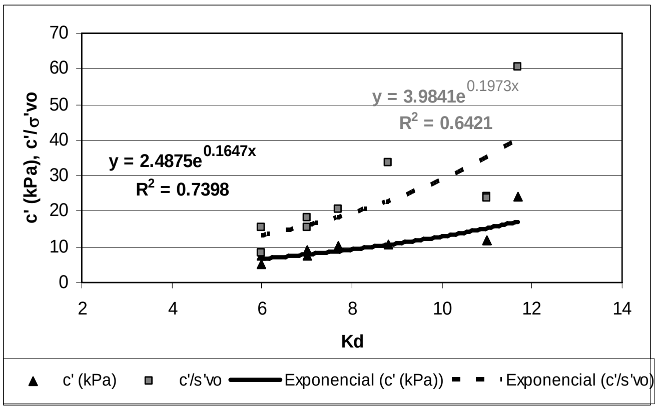

Figure 2 c' and c'/σ'vo (x100) - K_D correlations

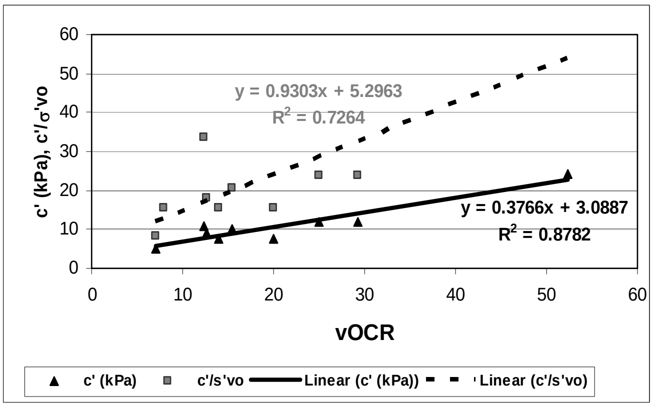

Figure 3 c' and c'/σ'vo (x100) - vOCR correlations

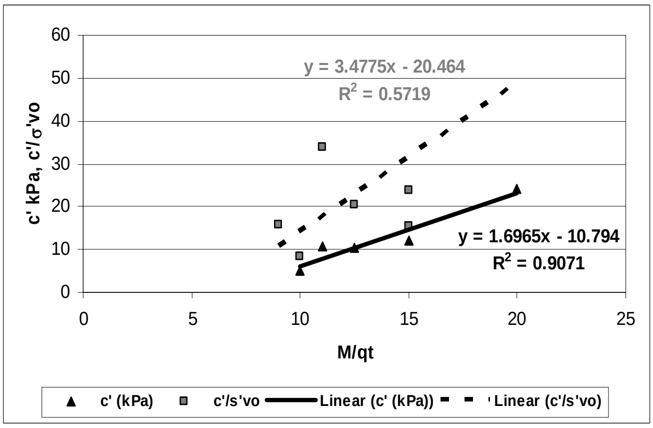

Figure 4 c' and c'/σ'vo (x100) - M/q_t correlations

Once c' is obtained, it is reasonable to expect that it can be used to correct the over-evaluation of ϕ', when sedimentary formulae is considered. Thus, taking the difference between ϕ'_{DMT} (represents the global strength) and $\phi'_{triaxial}$ (represents ϕ', uniquely) and comparing it with c', it becomes clear (Figure 5) the good correlation between them (Cruz et al, 2004). Of course, the data is not enough to validate a proper correlation, but it seems to indicate the adequacy of the method for these evaluations.

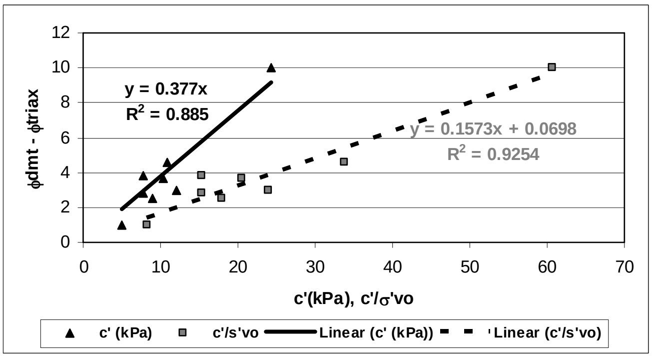

Figure 5 (ϕ'_{DMT} - ϕ'_{TRIAX}) - c' and c'/σ'vo (x100) correlations

4 STIFFNESS PARAMETERS

The determination of stiffness parameters in sedimentary soils has been obtained with considerable success with M (Marchetti, 1980), mainly because of the following reasons:

i. M is a parameter that includes information on soil type (I_D), overconsolidation ratio (K_D), as well as dilatometer modulus (E_D). Note that in residual soils cementation structure is also represented by K_D, as explained before.
ii. E_D represents a ratio between applied stress and resulting displacement.
iii. DMT insertion creates a lower level of disturbance than usual penetrometers (Baligh & Scott, 1975).

In this context, M_{DMT} was cross checked with $M_{0(CPTU)}$ (Lunne and Christophersen, 1983), whose results showed respectively values generally between 10 and 70 MPa (DMT) and lower than 40 MPa (CPTU). This is probably justified by the smaller disturbance degree caused by DMT insertion and also because its known higher sensitivity (than q_c) to stiffness variations. Finally, the triaxial tests performed clearly converge with the DMT test.

A different approach was established by Viana da Fonseca et al. (2001), based on studies performed in two of the locations within the scope of this paper, where the dilatometer modulus, E_D, was correlated with the maximum shear modulus, G_0, and deformation modulus at 10% of shear strain, $E_{s10\%}$. The respective relations are represented as follows:

$$G_0 / E_D = 16.7 - 16.3 \log (P_{0N}) \quad (1)$$

$$E_{s10\%} / E_D = 2.35 - 2.21 \log (P_{0N}) \quad (2)$$

These relations are higher than the ones proposed by Baldi et al. (1989) for sedimentary soils. In addition, the second correlation was between the correlations defined by these authors for the NC and OC behaviours of sedimentary soils.

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5 COEFFICIENT OF EARTH PRESSURE AT REST, K_0

Even though the evaluation of coefficient of earth pressure at rest through in situ or laboratory testing is very controversial, due to the level of disturbance induced by penetration/installation of equipments and sampling processes, the fact is that this parameter is often needed for design purposes, and so even a rough experimental estimation is better than only an empirical one. Once more, the usefulness of combining CPT(U)+DMT became evident.

Baldi (1986) proposed the following correlation to derive K_0 in granular sedimentary soils, which was taken as a starting point for this purpose:

$$K_0 = C_1 + C_2 \cdot K_D + C_3 \cdot q_c/\sigma'_v \quad (3)$$

where:

$C_1 = 0.376$, $C_2 = 0.095$, $C_3 = -0.00172$

q_c represents the CPT tip resistance and σ'_v stands for the effective vertical stress, which can be derived from DMT results.

Taking into consideration the q_c/σ'_v relation equal to 33 K_D, established by Campanella & Robertson (1991) for non-cemented sandy soils, it is clear that this ratio is not representative of the studied soils. Thus, Cruz et al. (1997) and Viana da Fonseca et al. (2001) proposed to correct C_2 constant of expression (3) as follows:

$$C_2 = 0.095 * [(q_c/\sigma'_v) / K_D] / 33 \quad (4)$$

Although available data on K_0 is very rare, the analysed data reflects the local experiment (0,35 – 0,5). It should be noted that direct application of Baldi's correlation would lead to much higher values, usually greater than 1.

6 DMT WITH DYNAMIC INSERTION

The static insertion of DMT blade can be a significant limitation testing heterogeneous grounds as it is the case of rock weathering profiles where residual soils are presented. Deriving stiffness parameters of compacted soils have had to rely on dynamic penetrometers which are not suited for this type of determination. Taking into consideration that DMT induces a horizontal deformation (while the penetration is vertical) it can be expected, at least, some preservation of the intrinsic characteristics of natural soils. In that sense, a specific research is going on, to find out the real efficiency of parameter evaluation under dynamic insertion. The research work consists in performing pairs of dynamic and static push in DMT tests (1.0 to 1.5 m apart), both in granitic residual soils and reference earthfill made by soils of the same nature. SPT and DPSH tests were also performed to create some basic reference.

The available data (3 sites, which include ISC'2 experimental site – www.fe.up/isc-2) are discussed in the following paragraphs.

The mechanical behaviour of the tested soils can be summarized by the results of SPT, DPSH and PMT tests. Table 1 shows the basic data obtained, including the data related to the number of blows (SPT hammer) needed to penetrate the soil with DMT blade. This results show a very similar strength profile in the case of V.Conde and Gaia's sites, while the ISC'2 site is clearly weaker.

Table 1 – Mechanical characterization of test sites

Site	N(60)	$N_1(60)$	N_{20DPSH}	N(60)/pl	$N_1(60)$/ Epm	N_{20DMT}
ISC2	8 - 25	10 - 25	5 - 15	5 - 15	0.5 - 1.5	12 - 20
V.Conde	20 - 35	25 - 35	---	10 - 15	1.5 - 2.5	15 - 30
Gaia	25 - 30	20 - 35	---	10 - 20	1.5 - 3.0	20 - 30

Typical profiles. The superficial level of ISC2 experimental site (1.5-2.0m) is characterized by an earthfill composed by identical grain size distribution of the granitic residual soils involved in this work (sandy silt to silty sand). As it will be explained below, results from the earthfill showed completely different behaviours, although there was an insufficient amount of data to be relied on for correlations. Therefore, another pair of tests was performed in a silty-sand to sandy silt reference earthfill (10m high) with insufficient level of compaction which allowed both dynamic and static insertion.

Tables 2 and 3 include a representation of analyzed data, through the mean values of parametrical ratios (always static/dynamic), in terms of basic, intermediate and derived geotechnical parameters.

Table 2 – Statistics on basic and intermediate parameters

Site	P_{0S}/P_{0D}	P_{1S}/P_{1D}	I_{DS}/I_{DD}	E_{DS}/E_{DD}	K_{DS}/K_{DD}
ISC'2	1.42	1.24	0.85	1.20	1.42
V. Conde	1.26	1.10	0.86	1.10	1.23
Gaia	1.28	1.15	0.89	1.13	1.25
ISC'2 earthfill	0.84	0.77	0.85	0.74	0.84
Reference earthfill	0.79	0.75	0.82	0.71	0.80

Table 3 – Statistics on geotechnical derived parameters

Site	γ_S/γ_D	ϕ'_S/ϕ'_D	M_S/M_D	OCR_S/OCR_D
ISC'2	1.01	1.04	1.37	1.74
V. Conde	1.00	1.02	1.15	1.40
Gaia	1.02	1.03	1.18	1.48
ISC'2 earthfill	0.95	0.98	0.71	0.68
Reference earthfill	0.97	0.97	0.71	0.69

The main considerations that can be outlined from these analyses are the following:

i. Dynamic insertion of DMT blade is responsible for an important loss of bonding in residual soils which leads to decreasing stiffness and strength properties. With the exception of I_D, all DMT parameters analysed have presented smaller values for the tests performed with dynamic insertion.
ii. The opposite behaviour is found in earthfills. Dynamic insertion seems to create a densification of the soil, since all DMT parameters analysed have shown higher values with dynamic insertion.
iii. I_D intermediate parameter increases with dynamic insertion, both in residual and earthfill soils, which means that soil type will be classified coarser than reality.
iv. The rates of variation of unit weight (Marchetti and Crapps, 1981) and angle shear resistance (Marchetti, 1997) are very small, thus showing the low sensitivity of these two parameters to dynamic insertion.
v. M and OCR work as an amplification of E_D and K_D, inducing higher sensitivity to variations. The respective results confirm the conclusions presented before where it was shown that the cemented structure could be assessed with OCR.
vi. There is a clear tendency of correlation between N_{20DMT}, N_{20DPSH} and N_{60}. The trends in these three parameters can be expressed by the following ratios:

N_{20} (DPSH) = 0.58 N_{60}
N_{20} (DMT) = 1.58 N_{20} (DPSH)
N_{20} (DMT) = 0.88 N_{60}

These results suggest that N_{DMT} could be used as a control parameter after applying some normalization to friction reducers.

For what we expressed in preliminary considerations, the possibility of using dynamic insertion in DMT seems to enlarge its field of application making it easier to overcome rigid layers interbedded in soft soils, and increases the range in depth of in situ characterization. In fact, the data suggest that DMT could be used as a static and dynamic testing tool.

7 CONCLUSIONS

Ten years of practice with DMT in residual soils showed a very high standard which can be defined by the following conclusions:

i. Information on stratigraphy and unit weight evaluations revealed itself accurate enough for test and design needs to similar levels of confidence as in sedimentary soils.
ii. The results of the test detect the presence of cementation structures, typical of residual soils
iii. When performed together with CPT(U) tests, it makes possible cross-checking and access to some parameters that would be impossible to get from each of the tests on their own. In this context, DMT + CPT(U) tests have provided reasonable estimations of lateral earth pressure coefficient in the regional granitic complexes.
iv. Being a 2-parameter test, strength parameters (c' and ϕ') can be derived. A method for that evaluation was proposed, needing further research for accurate correlations.
v. Because DMT is a loaddisplacement test, and also can represent numerically both type of soil and cemented structure, it can provide better quality results of stiffness parameters than those obtained by other current in-situ tests, such as penetration tests.
vi. Because the DMT deforms the soil horizontally, it is reasonable to expect some quality of results, even with dynamic insertion. In fact, some research performed on the subject showed interesting possibilities of exploring it as a dynamic tool, enlarging the field of application to compacted soils (N_{SPT}<50, as reference). This may create some chances of using the test in compaction control.

As a final comment, DMT has proven to be very versatile, providing accurate data for design applications, both in residual and sedimentary soils. Dynamic insertion may also provide reasonable quality in results, since the first signs seem to point out that it can be used over a wide range of soils.

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