DMT experience in Iberian transported soils

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ABSTRACT: For the last ten years DMT has been used successfully, both in Portugal and Spain, in transported soils characterization, with special emphasis on alluvial deposits. These results have been cross-correlated with those from both in situ and laboratory testing, such as SCPTU, FVT, PMT, triaxial and consolidation tests, to test the efficiency of interpretation models in the soils of both countries. In this paper, the general conclusions of ten years of work will be presented, primarily with stress history, shear strength and stiffness parameters. Some comparisons of p_2 (DMT) and u_2 (CPTU) results are also presented

1 INTRODUCTION

The results presented in this paper are part of an extensive program, composed of 47 experimental sites, first located in Portuguese territory and recently enlarged to Spain.. The main goal was to check the accuracy of DMT tests with regards to the universally accepted correlations established for parametrical derivation, and to study other approaches that are being studied in our group (Cruz, 1995; Cruz et al, 1997). From the total amount of experimental sites, 15 were performed in granitic residual soils whose behaviour is quite different from sedimentary transported one. The research on residual soils is presented in another paper in this conference.

Sedimentary experimental sites covered all types of soils from clays to sands, organic to non-organic, stable to sensitive. Over all, 200 tests were performed (plus identification and physical index tests) including 57 DMT, 50 FVT, 40 CPTU, 4 PMT, 6 SCPTU, 2 cross-hole seismic, 9 triaxial and 37 oedometric consolidation tests.

2 STRATIGRAPHY, UNIT WEIGHT AND PORE PRESSURE

One of the basic important features of DMT is its capacity to give information related to the basic properties (identification and physical index) of soils, thus creating a rare autonomy in the characterization field. Analysing the global data set obtained in this research program, one should be tempted to say that DMT can easily take the place of boreholes in general subsurface investigations. Of course, this is not a suggestion to fully substitute boreholes in investigations, but just some of them (perhaps a maximum of 50%). This consideration is mainly due to the following reasons:

a) DMT identifies with accuracy the type soil and the resulting information is easy to correlate with boreholes, thus allowing to create cross sections with the same level of accuracy;
b) DMT shows even higher accuracy to characterise strata with interbedded thin layers, usually undetected in bore-hole information;
c) It is possible to determine the position of water level, and consequently hydrostatic pore pressure (u_0), in sandy environments;
d) Through U_D parameter information on permeability can be obtained;
e) I_D is a numerical way for classification of soils, easier to use than CPTs, which surely opens a new range of possibilities for data interpretation, with special emphasis in statistical analysis and to basic understanding of mixed soils behaviour.

The data analysis that supports these conclusions is presented in the following paragraphs. In the first place, identification of soils based on Marchetti (1980) original correlation, globally represents the geological environment of the experimental sites, confirming the international recognition of his corre-

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lation. In fact, DMT results show good comparisons with borehole information and laboratory identification tests, by means of Triangular and Unified classifications. Additionally, comparisons with CPTU identification results revealed the same level of accuracy for both tests.

The unit weight was evaluated by Marchetti and Crapps (1981) chart and compared with values obtained in laboratory from undisturbed samples. Of course, in sandy soils undisturbed sampling is very difficult, so the results reflect mainly cohesive soils (clays and silts). The final results revealed variations globally less than $1kN/m^3$, and only in a few cases differences of $\pm$ $2kN/m^3$ (Figure 1). Thus, it can be said that results show good accuracy allowing reasonable vertical effective stresses evaluations which makes the test more independent from external needs.

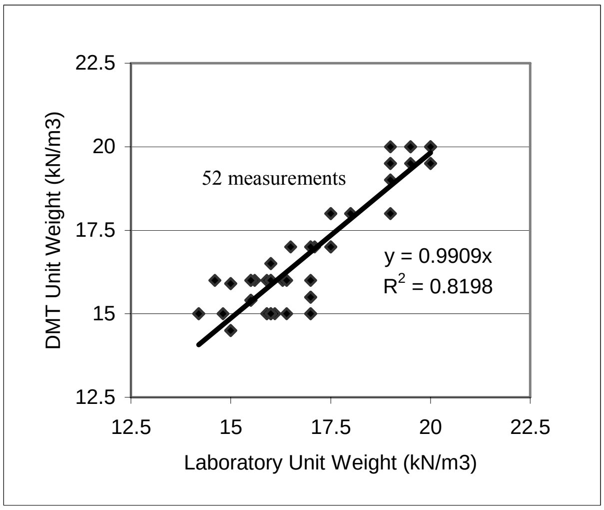

Figure 1 - Unit Weight comparisons

Although DMT cannot measure pore pressure directly, the value of pressure P2 (Luttenegger, 1988) and consequent Pore Pressure Index, U_D, can be used to derive important information of the strata, as pointed out by ISSMGE TC16 report (Marchetti, 2001):

a) Determination of water level in sandy environments;
b) Discerning free from non-free draining layers.

Besides DMT tests, the data collection of this work include piezometric measurements and CPTU (u_2 type) which allowed to outline some conclusions. In fact, direct comparisons of P_2 and u_2 revealed a general parallel increasing pattern, although with some scatter for low values (Figure 2).

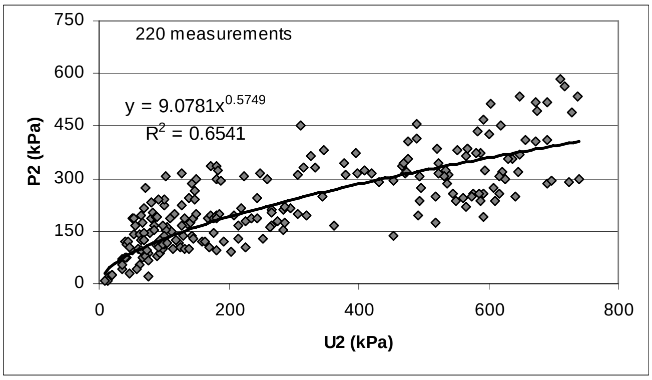

Figure 2 - P_2 (DMT) - u_2 (CPTU) comparing results

In fine grained soils with I_D lower than 0.9, when plotting the ratio P_2/u_2 against I_D reveal a clear drop-down of the ratio with increasing I_D is revealed, approaching gradually a lower level of 0.5 (Figure 3a). In sandy soils, the overlap of P_2 and u_0 profiles can be easily recognized, confirming the efficiency of the parameter to detect the depth of water table. The general plot shows a distribution that could be useful to interchange P_2 and u_2, mostly in silty soils.

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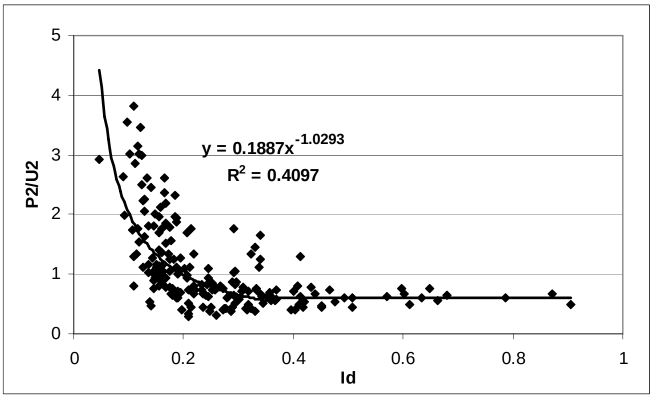

Figure 3a - Variation P_2 / u_2 with I_D in fine grained soils

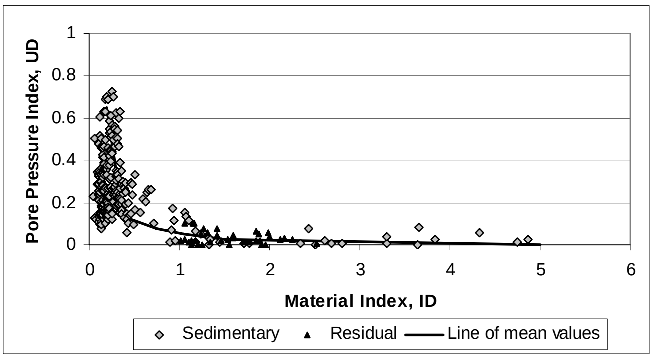

Figure 3b - Variation of U_D with I_D

As for the Pore Pressure Index, U_D, evaluations, Figure 3b presents the globally obtained data, with the black line representing the evolution of mean values for each interval of soils defined by Marchetti (1980) and represented by I_D. From these data the following conclusions can be outlined:

a) Data reflects fully undrained behaviour for soils with $I_D < 0.35$, meaning clayey soils.

U_D, within this interval decreased globally from a maximum of 0.65 to 0.25.

b) Fully drained behaviour ($U_D = 0$) was identified for soils with $I_D > 1.8$, meaning sands to silty sands
c) Partially undrained behaviour (transition curve) for the intermediate soils, showing U_D decreasing from 0.25 to 0, with increasing I_D.
d) The obtained values fit well with data from Benoit (1989)

3 STATE OF STRESS AND STRESS HISTORY

In the course of this research, it was not possible to experimentally determine K_0, namely through Self-Boring Pressuremeter testing and/or K_0 triaxial testing, so the main comparisons are limited to some empirical correlations applied to fine grained soils. DMT data was derived from Marchetti correlation (1981) and then compared with evaluations proposed by Mayne & Kulhawy (1982), and confirmed, in clays by recent research (Lunne et al., 1990), as refered by Mayne (2001):

$$K_0 = (1 - \sin\phi') \, OCR^{\sin\phi'}$$

The shear strength angle of clays was derived through IP (Kenney, 1967) and OCR derived from dilatometer. The results of the obtained correlations are presented in Figure 4, where the results of K_0 deduced from plasticity index and OCR (Brooker & Ireland, 1965) were included. It results clear that there is no gap between both correlations and showing essentially 1:1 proportion.

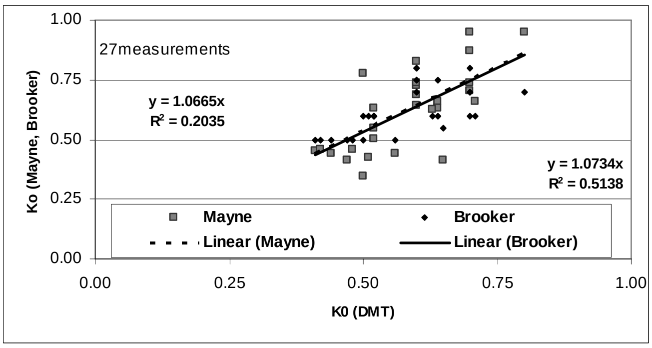

Figure 4 - K_0 comparisons

Stress history was analysed by comparing OCR(DMT) with oedometric consolidation test results, which generally fit together. It should be remembered that the work covered a narrow band of OCR values (1-3), corresponding to normally to slightly overconsolidated soils.

4 ANGLE OF INTERNAL FRICTION, ϕ'

The determination of friction angle throughout DMT is a very difficult task since there is a strong dependency of K_0, whose evaluation in sandy soils is very problematic. Various methods have been proposed, which can be summarized as follows (ISSMGE TC 16):

a) Method 1a - Iterative method (Schmertmann, 1983); it is based on K_D and thrust penetration of the blade (directly determined or through q_c from CPT tests), which can be applied to both K_0 and ϕ'.
b) Method 1b - Based in CPT and DMT tests performed side by side (Marchetti, 1985), the method first derives K_0 from q_c and K_D through Baldi's correlation (1986) and then recours to the theory of Durgonuglu & Mitchell (1975) to estimate ϕ' from K_0 and q_c.
c) Method 2 - Based on the definition of a lower bound (Marchetti, 1997), this method does not procure the precise value of the parameter, but just a safe value; it depends solely on K_D.

The first method is very complex and demands for the measurement of a penetration force which normally is not available, so it hasn't been considered. The second method needs both CPT and DMT results, not always available. The third one, although not so accurate as the other two, has the advantage of being easy to apply. Its expected deviation makes only a small difference in final calculations of bearing capacity for day-to-day problems. The global results obtained by the latter, were plotted against reference ϕ' (CPTU) evaluated by Robertson & Campanella chart (1983) and presented in Figure 5.

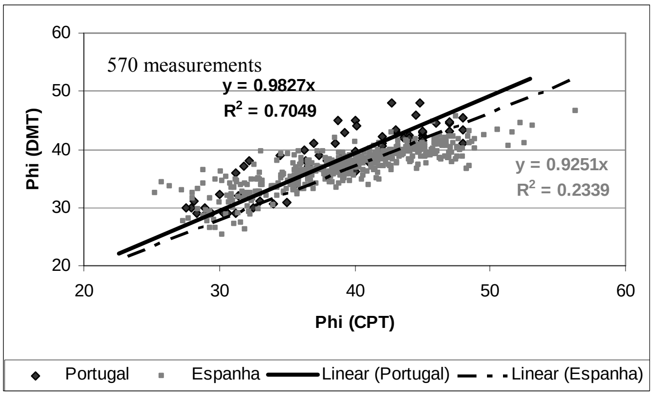

Figure 5 - Marchetti lower bound determination of ϕ' compared with CPTU results

As it can be observed Spanish data shows ratios DMT / CPT lower than the Portuguese and smaller than 1 in both cases. Statistical analysis performed on the ratio ϕ' (DMT) / ϕ' (CPTU) revealed results

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expressed by 0.95 $\pm$ 0.1, globally within the interval 0.76 to 1.33.

5 UNDRAINED SHEAR STRENGH

The undrained shear strength of fine grained soils is one of the best correlated parameters from the dilatometer test. In this scope, the calibration of the parameter was strongly based on Field Vane Tests (FVT), as it is the reference test in Portugal and Spain. The final results (with Bjerrum correction to FVT results) revealed some interesting aspects that will be discussed below.

The most often applied correlation to derive undrained shear of fine grained soils is the one established by Marchetti (1980), which is obtained via OCR, derived from K_D as an input parameter. Several researchers concluded that obtained results by this approach correlates well with corrected field vane test values. On the other hand, since s_u determination is dependent on the test type, Lacasse and Lunne (1988) proposed different correlations related to FVT, triaxial and simple shear tests. The differences between this latter and Marchetti's derived values are represented by parallel trends, so they are very similar.

A completely different approach is given by Roque et al. (1988) who have proposed a determination based on load capacity theories. In this case s_u would be dependent of P_1 parameter (instead of P_0, used on K_D determination), horizontal total stress (derived from DMT, through K_0) and a factor (Nc) depending on the plasticity of soils. This latter may be the weakest point of this formulation since its subjectivity can be significant (reference values for this parameter are just 5, 7 and 9, respectively for non-plastic, intermediate and plastic clays).

It is relevant to emphasize that, as concluded by Lutenegger (1988) the gap between reference values and DMT's increases with increasing I_D, which is certainly linked to partial drainage that arise and becomes significant with increasing silt and/or sand components.

The overall results, when first plotted altogether revealed significant scatter, showing difficult interpretation. However, when divided in two groups, organic and non-organic soils, the results showed quite different trends, as it is presented in Figure 6.

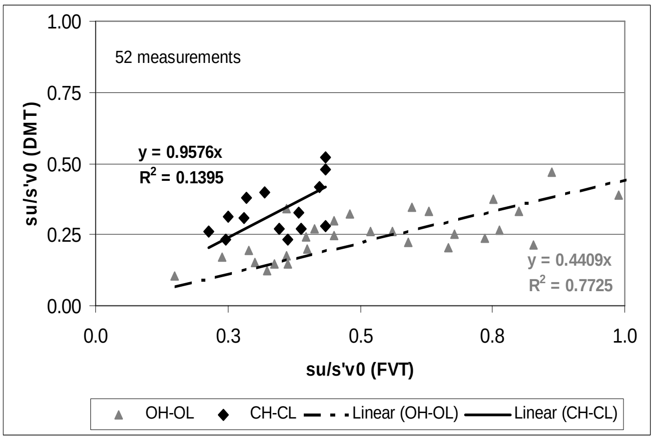

Figure 6 - S_u (DMT) for organic and non-organic soils, compared with FVT

In the non organic cases it is quite clear that results confirm the international experience with the values from Marchetti's correlation being comparable to FVT results. The same conclusion can be applied when the results are compared with those from triaxial tests (Figure 7).

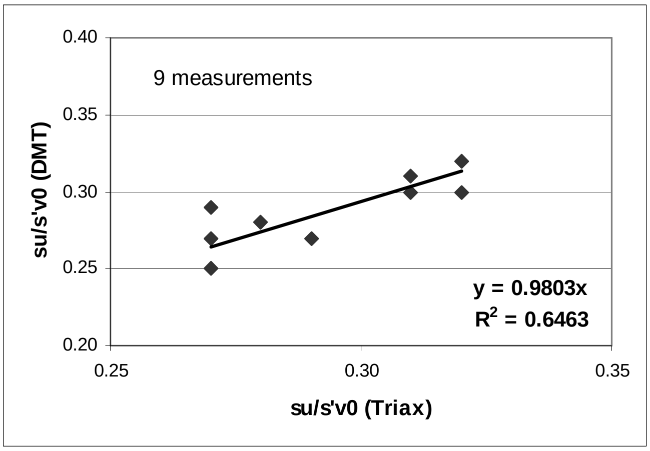

Figure 7 - Results from Marchetti's correlation, compared with triaxial testing

In the case of organic soils, Marchetti´s correlation tends to be too low when according FVT results, while Roque's seem to reproduce them better (Figure 8). More than that, the ratio s_u/σ'_{v0} (DMT) / s_u/σ'_{v0} (FVT) seems to increase with increasing OCR_{DMT} (Figure 9). OCR lower than one, represented in the same Figure, belong to a soft soil layer under an earthfill, whose consolidation was not yet complete. It should be referred that oedometric consolidation tests showed similar values.

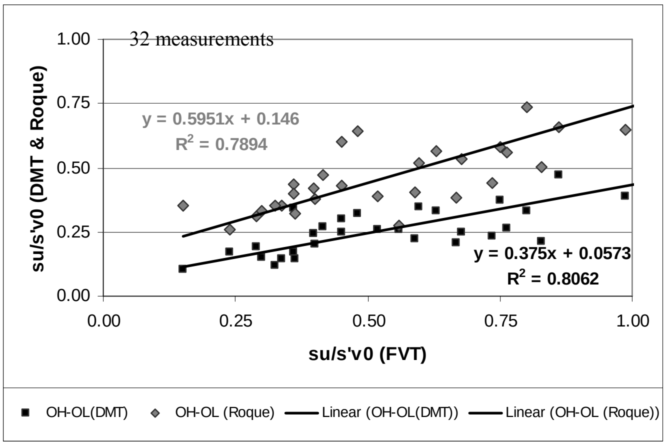

Figure 8 - Results from Marchetti's and Roque's correlation, compared with FVT

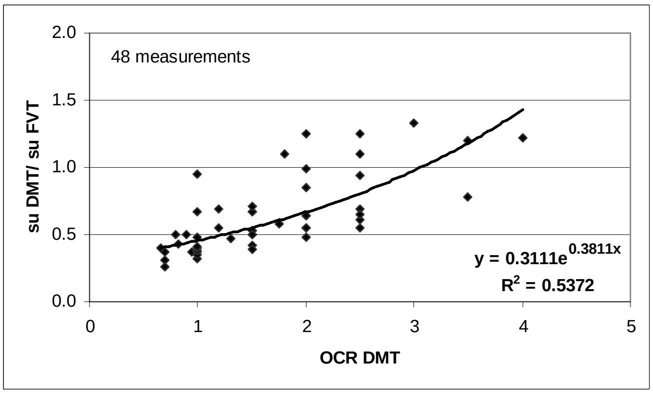

Figure 9 - Ratios S_u (DMT) / S_u (FVT) versus of OCR

The trend expressed in Figure 9 may be a consequence of the different considerations of OCR in each s_u evolution.

6 STIFFNESS PARAMETERS

In terms of stiffness parameters of soils, DMT results are classically interpreted for the purpose of getting constrained modulus, M, (Marchetti, 1980), equivalent to E_{oed} ($1/m_v$), which is based on the 3 intermediate parameters (I_D, E_D, K_D). Thus this calculation not only depends on the stress-strain relationship (E_D) but also the type of soil (I_D) and overconsolitation ratio (K_D). This is, undoubtedly, the main reason for the widely recognized high accuracy of the parameter, when applied to all types of transported soils.

More recently, with the increasing use of seismic measurements to determine small-strain modulus, some attempts have been made to correlate DMT parameters with G_0 through calibrations based in cross-hole tests and seismic SCPTU. Particularly, the works of Jamiolkowski et al (1985) Sully & Campanella (1989), Baldi (1989), Tanaka & Tanaka (1998), and the well documented method by Hryciw (1990) should be pointed out as references..

6.1 *Constrained Modulus, M*

In the present research, 37 oedometer tests were performed to calibrate M_{DMT}, with the results confirming the already known high accuracy of the parameter, as it is shown in Figure 10. Statistical analyses show 1.04 $\pm$ 0.27 for this comparison.

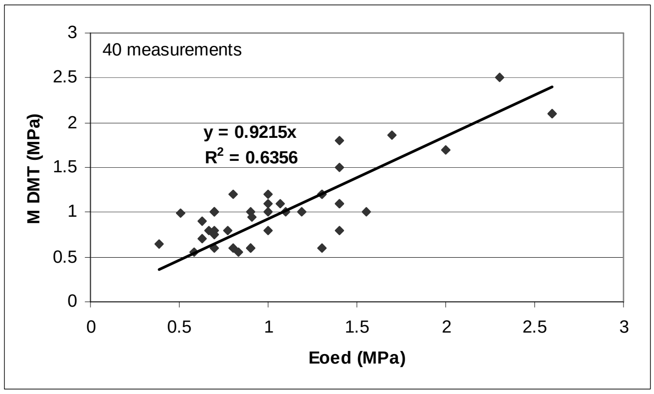

Figure 10 - Comparison between M_{DMT} and E_{oed}

On the other hand, DMT results were also compared with CPTU data, through M and q_t. The resulting correlations are presented in Figure 11.

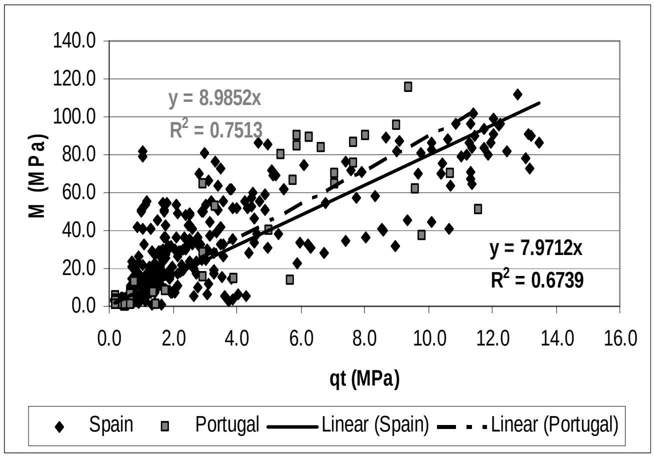

Figure 11 - M/qt correlations

Analysis of data shows a small difference between Portuguese and Spanish ratios of M/q_t, respectively 9 and 8. The M/q_t relation has been as a useful tool for the definition of OCR in granular soils, given the higher sensitivity of M parameter to variations with consistency, when compared to the tip resistance, q_t. Marchetti (1997) suggested that values between 5 and 10 correspond to normally consolidated soils, whereas values between 12 and 24 correspond to overconsolidated soils. Thus, the presented results have only local meaning, which clearly correspond to normally consolidated soils.

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6.2 *Initial or Dynamic Shear Modulus, G_0*

The reference work in this subject shows two different approaches for calibration of DMT results in terms of G_0 determination. The first approach correlates E_D with G_0 (Sully & Campanella, 1989, Tanaka & Tanaka, 1998, etc), being E_D the DMT parameter that relates stress and strain. However, Hryciw (1990), pointed out that correlations based on ED would be affected by the strain DMT working level being too high to be related with small-strain behaviour. Thus, he proposed a new method for all types of soils, developed from indirect method of Hardin & Blandford (1989), which substitutes the variables σ'_0 and void ratio (e) for K_0, γ e σ'_{v0}, all derived from DMT.

During the present work, in two cases it was possible to have seismic data together with DMTs. These campaigns were developed in an alluvial deposit (clayey and sandy) where 6 DMT, 6 SCPTU and 2 cross-hole seismic tests were performed, and the analysis was conducted to get comparisons following both approaches.

The results of the first approach show a local trend for G_0 to increase with both E_D and M (and also q_t from CPTU) with the first one showing less scatter (Figure 12). The general ratio G_0/E_D (=R_G) for clays would be around 7.0 which is close to Tanaka & Tanaka's (1998) results (R_G = 7.5), while for sands (silica's) would be around 1.9 ± 0.6, close to Jamiolkowski (1985) and Baldi's (1986) results (2.2 ± 0.7 and 2.7 ± 0.57, respectively). The comparison of R_G with K_D, in turn, was found inconclusive, confirming Hryciw (1990) observations. However, a relationship was found between that ratio and I_D, which indicates its decrease with the presence of silty fraction (or sandy). In fact, a significant drop of R_G is observed as the soil goes from clay to silty clay. The results are shown in Figure 13.

The comparison of Hryciw proposal with seismic data showed a set of results overlapping those presented by the same author, which seems to indicate the adequacy of the method for this particular case (Figure 14). Using the same error definition used by Hryciw ($G_{0predicted} - G_{0observed} / G_{0observed}$) it comes out that 62% of the total data points reveal an error less than 25% and 93% less than 50%, which is very similar to Hryciw's results.

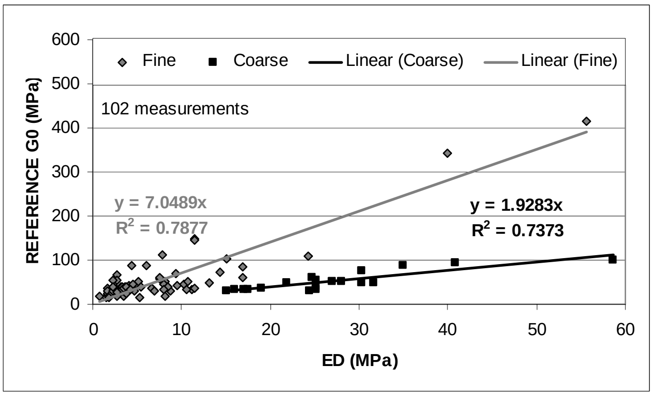

Figure 12 - Comparison between reference G_0 and E_D

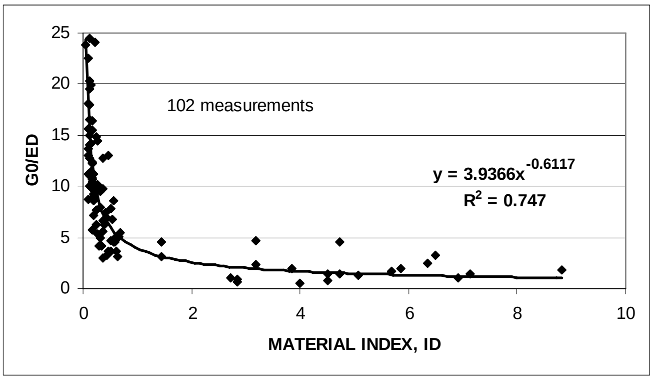

Figure 13 - Comparison between G_0 /E_D and I_D

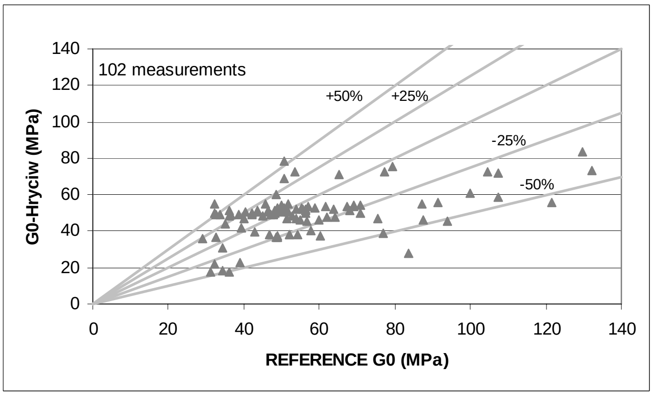

Figure 14 - Comparison between G_{0DMT} (Hryciw method) and Reference G_0

7 CONCLUSIONS

The work presented herein, performed along the last 10 years in Portugal and Spain, involved a great variety of laboratory and in-situ tests and fundamentally aimed to test and improve the quality of DMT correlations to derive geotechnical parameters. Based on the overall analysis the following conclusions are presented below:

a) DMT gives accurate definition of soil stratigraphy, unit weight following the general patterns described in the references.

b) P_2 correlates well with u_2 from CPTU, and the ratio between them seems to decrease with increasing I_D
c) Earth pressure coefficient at rest, K_0, deduced from DMT was confirmed to be reliable both by ϕ' and OCR correlations (Mayne, 2001) and for I_{PS} (Brooker & Ireland, 1965).
d) Shear strength angles deduced from DMT (Marchetti, 1997) matches with CPTU solutions (Robertson & Campanella, 1983), with DMTs being slightly lower.
e) Undrained shear strength, showed two patterns, according to the major or minor percentage of organic content, which seem to lower s_u(DMT)/s_u(FVT) ratios; in this case, Roque's data seem to overpredict the peak FVT value, while Marchetti's correlation tends to underpredict residual FVT values.
f) Constrained Modulus, M, derived from DMT reveals its excellency, confirming the international comments on the subject.
g) Small strain modulus, G_0, seems to correlate well with E_D, presenting rates similar to Tanaka & Tanaka's data for clayey soils and to Jamiolkowski and Baldi´s data for silica sands. Nevertheless, it was also clear that G_0/E_D decreases with increasing I_D. Another approach on this subject was evaluated through Hryciw's method, and results confirm previous data.

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