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Piezocone tests in residual soils: A Portuguese experience in granitic soils.

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ABSTRACT: The general mechanical evolution of massifs throughout weathering is mainly governed by an increasing porosity of rock material, the weakening of mineral grains and the existing bonding between grains is progressively loss. In this process, weathering degrees W_1 to W_3 are represented by sound rock where the macro-fabric plays the major influence, W_4 and W_5 represent the transition behaviour, where micro and macro fabrics have similar influence, towards a residual soil-mass where the relict macrofabric is no longer present (residual soil), with a residual interparticle cementation structure always remaining, sometimes mixed with suction effects commonly present in natural profiles. Due to this structure these materials cannot be modelled by the classical theories of Soils Mechanics, which creates several difficulties on the interpretation of in-situ test results. In the last two decades several Portuguese institutions dedicated specific frameworks to study and characterize this kind of residual massifs (in granitic environments), which are quite common in the North and Centre of Portugal. In this paper, CPTu tests performed in the granitic formations of Porto and Guarda metropolitan areas are analyzed and compared with other geotechnical tests available in Porto Geotechnical Map, which were then calibrated by the results obtained in IPG experimental site (Guarda, Portugal). In this process more than 20,000 tests were involved, including laboratory (triaxial, shear box and oedometers) and in-situ (PMT, DMT, CH and permeability) techniques

1 INTRODUCTION

Residual soils strength characterization it is not an easy task, due to its cohesive-frictional nature as well as disturbance effects related with both sampling and installation of in-situ devices. The sampling problems and the discontinuous information related to laboratory tests leave an important role to in-situ testing on routine analysis. Piezocone penetration tests are among the most widely used in in-situ characterization, offering obvious advantages over other routine in-situ tests, such as sustainable correlations with geotechnical parameters at low cost, rapid procedures, continuous recording, high accuracy, repeatability and possibility of automatic data logging. References on the subject applied to transported sedimentary soils are widely known. However, the application of these current correlations to obtain parameters of residual soils usually leads to erroneous estimations of strength and stiffness parameters. In fact, one of the main characteristics of residual soils is related to the presence of a bonding structure, which generates a cohesive intercept in Mohr-Coulomb failure criterion and the development of more than one yield stress locus and when the sedimentary procedures are applied to residual environments, certain available correlations overestimate the respective geotechnical parameter, as a result of the bonding structure influence in final determinations (Rodrigues 2003, Viana da Fonseca 1996, Cruz 2010). As a consequence of this, it is fundamental to be sure that any correlations with in-situ test parameters respond properly in these soils. The study presented herein aims to contribute to the evaluation of adequacy of CPTu current correlations to determine the geotechnical design parameters, following the path crossed with DMT tests in these soils (Cruz 2010).

In this context, Porto and Guarda regions are perfect for this purpose due to the intensive research promoted and developed by FEUP (in Porto) and IPG (in Guarda), creating a fundamental knowledge of the behaviour of these granitic soils. Furthermore, the existence of Porto Geotechnical Map (COBA 2003), here designated as PGM, provides reliable and important geotechnical information on Porto Granitic Formation, which is very useful in defining trends and supporting characterization needs. This information was analyzed by Cruz (2010) and prepared under the perspective of mechanical evolution through the weathering (Cruz et al. 2015), which is particularly useful in the present context. Furthermore, the calibration work of Cruz (2010) with DMT tests in residual soils, based in Porto and Guarda residual soils, created a very important in-situ reference base for comparing CPTu results. In that work, after a calibration experiment performed in the high quality experimental site of Polytechnic Institut of Guarda (IPG) (Rodrigues 2003, Cruz, 2010), adaptations, corrections and new correlations were settled to derive geotechnical parameters of these soils by DMT tests. The experimental work was performed in a calibration box where DMT tests were performed in artificially cemented soils (remoulded from Guarda granitic soils), followed by triaxial testing in both artificially and naturally cemented soils, leading to a specific set of correlations with the main geotechnical parameters of residual soils. To close the cycle, DMT tests were performed in the natural massif from where the experimental samples were retrieved, which confirmed the adequacy of established correlations.

As a consequence, information obtained by MOTA-ENGIL and IPG in granitic residual environments of the North and Center of Portugal, where pairs of CPTu and DMT tests were available, was gathered to generate the present study. At the end, 8 locations were selected, where 20 pairs of tests were performed, including the well characterized experimental site of IPG that served the calibration work of Cruz (2010), mentioned above. Data arising from these tests were firstly compared and analyzed together with PGM data, at a macro-level, allowing to recognize CPTu patterns of behaviour in residual soils and evaluating the adequacy of current correlations to obtain geotechnical parameters for design. On the other hand, due to its previous calibrations DMT tests were used to compare and control, being used as a reference for representing the mechanical properties of each experimental site.

2 CHARACTERIZATION OF PORTO AND GUARDA GRANITES

In Porto, the fundamental geological unit (Porto Granitic Formation) was installed at around 10 km depth at the end of Hercinic orogeny and can be described (COBA, 2003) as a leucocratic alkaline rock, comprising quartz, biotite and muscovite with the latter prevailing, white alkali-feldspar often in mega-crystals, white sodic plagioclase, and minor amounts of dark minerals. The alkali feldspar usually presents the higher grain size and is mostly orthoclase, sometimes microcline. As for plagioclases, oligoclase-albite and albite are commonly present. Guarda granitic formation is constituted by a leucomesocratic granite with quartz, sodic and potassic feldspars commonly in mega crystals, biotite and muscovite, as well as kaolin, sericite and clorite as secondary minerals (Rodrigues 2003).

The residual soils arising from both formations are the result of mechanical and chemical weathering, respectively by means of grain dismantling and hydrolysis of K-feldspar and Na-feldspar, which lead to the formation of kaolinite clay. Biotite (and amphibole, if present) are affected by oxidation to form iron oxides and quartz and muscovite remain stable due to their high weathering resistance. The consequent soil is described as sand evolved by a kaolin matrix with frequent less-weathered rock boulders (Cruz 2010). From mechanical point of view, these granitic masses are very complex and mostly characterized by its gradation from upper levels to lower (W2) sound rock, improving its behaviour with depth. Typically, after a thin layer of top soil (usually < 3.0 m thick) the residual profile starts with a thick layer of medium compact residual soil, referenced by NSPT ranging between 10 and 30 blows (G2), which is sometimes followed by a compact transition layer corresponding to NSPT between 30 and 60 (G3). According to PGM data (COBA, 2003), the medium compact layer can reach 15 to 20m of thickness and it is common to find boulders within this soil mass. The transition layer is generally thinner than 5m. In few areas (just 3 main spots in Porto) or in small pockets dispersed in the weathered mass, more intensively kaolinized soils can be found, corresponding to NSPT lower than 10 (G1). These residual units evolve in depth to decomposed (W5) to highly weathered (W4) rock massif represented by NSPT values typically higher than 60 and further to medium (W3) to slightly weathered (W2) granite. Although this may suggests a homogeneous evolution with depth, these formations show erratic profiles, either horizontally or with depth as a consequence of variations in climate conditions, composition of the parent rock and intensity of joint systems with its influence in water penetration level. CPTu and DMT tests are only feasible in residual soils, since in the transition materials (W4 and W5) are typically characterized by NSPT higher than 60, which means that is very difficult to push-in any of the equipments into the ground.

As already referred Porto Geotechnical Map (PGM) offers a huge quantity and variety of data that was used to compare field data. This data was prepared and organized in a sense of mechanical evolution with weathering and may be consulted for more detailed analysis in Cruz (2010) and Cruz et al. (2015). In this paper, we will only refer to the intervals of parameters that can be deduced by CPTu tests and only within the geotechnical unit where the tests were performed (G2, 10<NSPT<30).

3 PRESENTATION AND DISCUSSION OF RESULTS

In terms of soil identification, PGM data reveals an expected increase of fine content and plasticity with weathering, as a result of the chemical weathering of feldspars into kaolinitic clay. According to ASTM Unified Classification, UC (D2487 1998) soils are mainly represented by silty sands (SM), while soils with high kaolin content are represented by clayey sands (SC) and silts of low plasticity (ML). Physical ranges reveal an also expected increase of void ratio (e) and porosity (n) and decreasing unit weights (γ), while permeability is not greatly influenced by the weathering degree. On its turn, strength is characterized by the presence of an effective cohesion that is due to the cemented structure, as well as a shear resistance angle arising from the granular condition of these soils. Stiffness is compatible with the ranges of strength results. In the following tables a summary of the basic, intermediate and classification CPTu parameter ranges (Table 1) is presented and the resulting geotechnical CPTu deduced parameters are compared with DMT and PGM (Tables 2 and 3).

Table 1.Basic, intermediate and classification CPTu parameters

q_t (MPa)	f_s (kPa)	u_2 (kPa)	Q_T	F_R (%)	B_q	I_c
2.5-10	100-300	-75-50	25-150	<10	-0.05-0.05	1.5-3

Table 2. Comparison CPTu, DMT and PGM results (general)

Test	γ(kN/m^3)	k (m/s)	N_{SPT}	v_s (m/s)
CPTu	17-20	10^{-6}-10^{-8}	10-30	150-250
DMT	17-20	--	--	--
PGM	17-20	10^{-6}-10^{-7}	--	--

Table 3.Comparison CPTu, DMT and PGM results (strength and stiffness)

Test	c' (kPa)	ϕ (º)	Ψ	M (MPa)
CPTu	--	34-42	-0.2 – 0.0	40-150
DMT	4 -20*	31-37*	--	40-150
PGM	< 15	33-37	--	< 25

* Obtained by applying residual correlations (Cruz, 2010)

The CPTu field data was treated and interpreted using GEOLOGICISMIKI software. As it can be observed, the corrected point resistance varies from 2.5 to 10 MPa, slightly increasing with depth, which corresponds to the expected evolution with vertical effective strength, unit skin friction ranges within 50 and 300 kPa also increasing with depth and pore water pressure decreases with depth attaining significant negative values explained for the dilatant behaviour exhibit by these soils (Fig. 1). In the plots, the residual mass lies below 3m depth, being the upper part constituted by sedimentary cover. As a consequence of this, Q_T ranges within 25 and 150, F_R is always smaller than 10% and B_q is around zero.

From classification point of view, DMT accordance with local soils has been previously revealed by Cruz and Viana da Fonseca (2006), later confirmed by PGM data (Cruz 2010). If I_c classification (Robertson 2010) is used CPTu results are very consistent with these findings, as shown in Figure 2. In the same figure unit weights obtained by DMT (Marchetti & Crapps 1980) and CPTu (Robertson 2010) are also represented, since this is a parameter with direct influence in the determination of vertical in-situ stresses and consequently in deriving strength and stiffness parameters. The plot represents the comparison between DMT, CPTu and, which reveal a high level of accuracy of both tests. The same consistency is found with the permeability (Robertson 2010) that is coincident with the in situ permeability ranges represented in PGM (Table 2). As a consequence of these findings, it can be concluded that CPTu derived results for identification and physical characterization are representative of the main residual units of Porto and Guarda granites.

On the other hand, once residual and sedimentary soils do not follow the same pattern of behaviour, it turns to be relevant detecting the presence of cementation, in order to select the adequate methodologies for obtaining the best geotechnical approaches. For this purpose, interpreted charts to detect cementation have been proposed for SPT and (S)CPTu (Schnaid et al. 2004) and (S)DMT (Cruz 2010) tests. These charts were previously applied with success to CPTu (Schnaid et al. 2004; Viana da Fonseca et al. 2007) and DMT results (Cruz 2010) obtained in the experimental sites in granitic formations nearby the Portuguese cities of Porto and Guarda. Being so, the actual data was plotted in the CPT diagram presented in Figure 3, which revealed not strongly structured soils, lying near the lower bound line for cemented materials and converging to the previous findings. Previous CPTu data from Porto granites is also plotted. It should be stressed that between the two straight lines the level of cementation is variable, increasing as one goes up in the plot. In the context of strength behaviour, the range of N_{SPT} deduced from CPTu (Robertson 2010) match perfectly with the results obtained in the field, indicating that the established correlation between the two tests is also valid in residual soils, at least in this specific environment.

The shear resistance angles deduced from CPTu data (Robertson 2010) point out to 35º to 42º, which are convergent with DMT results obtained by applying the correlation for granular sedimentary soils (Marchetti 1997) but quite divergent from the results of PGM within 33º to 37º, as revealed by Table 2 and Figure 4. In the right hand side plot of the same figure, are also represented the shear resistance profiles, obtained by applying the correction proposed for DMT tests (Cruz 2010, Cruz et al. 2014). The gap is related to the cemented structure of these soils that creates an overall resistance assumed to be purely frictional when sedimentary approaches are followed (Cruz 2010).

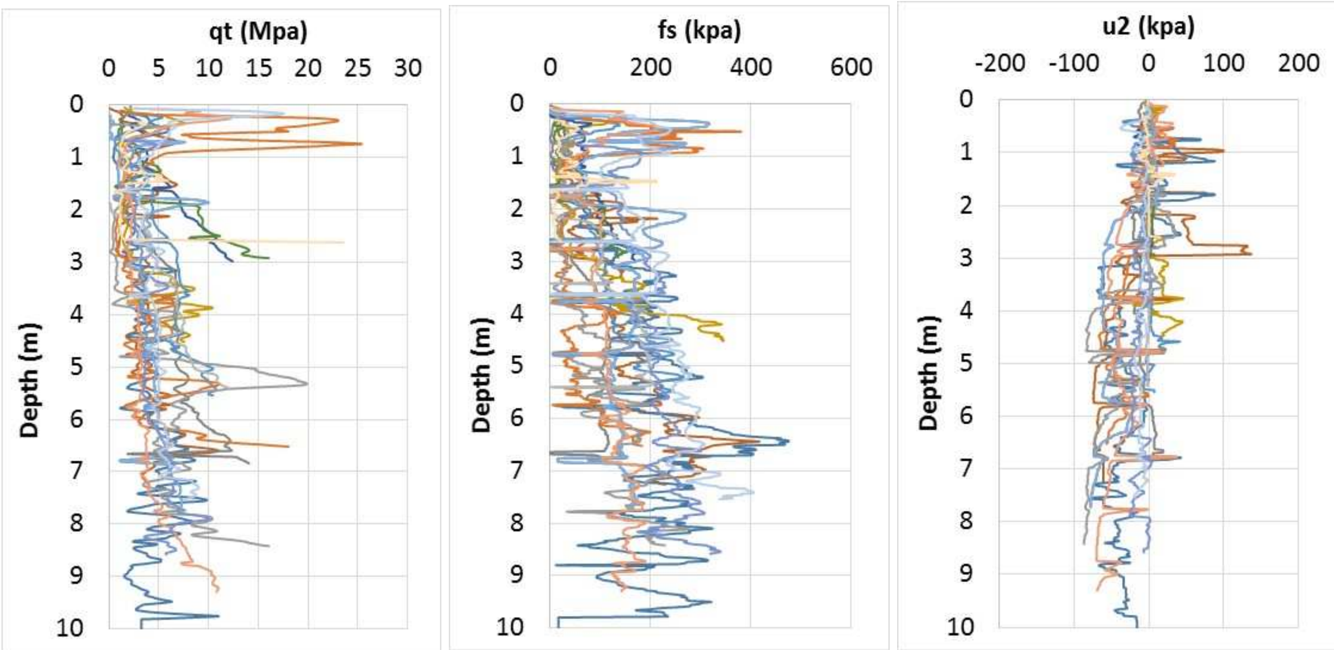

Figure 1. Evolution of CPTu basic parameters in the whole set of experiments

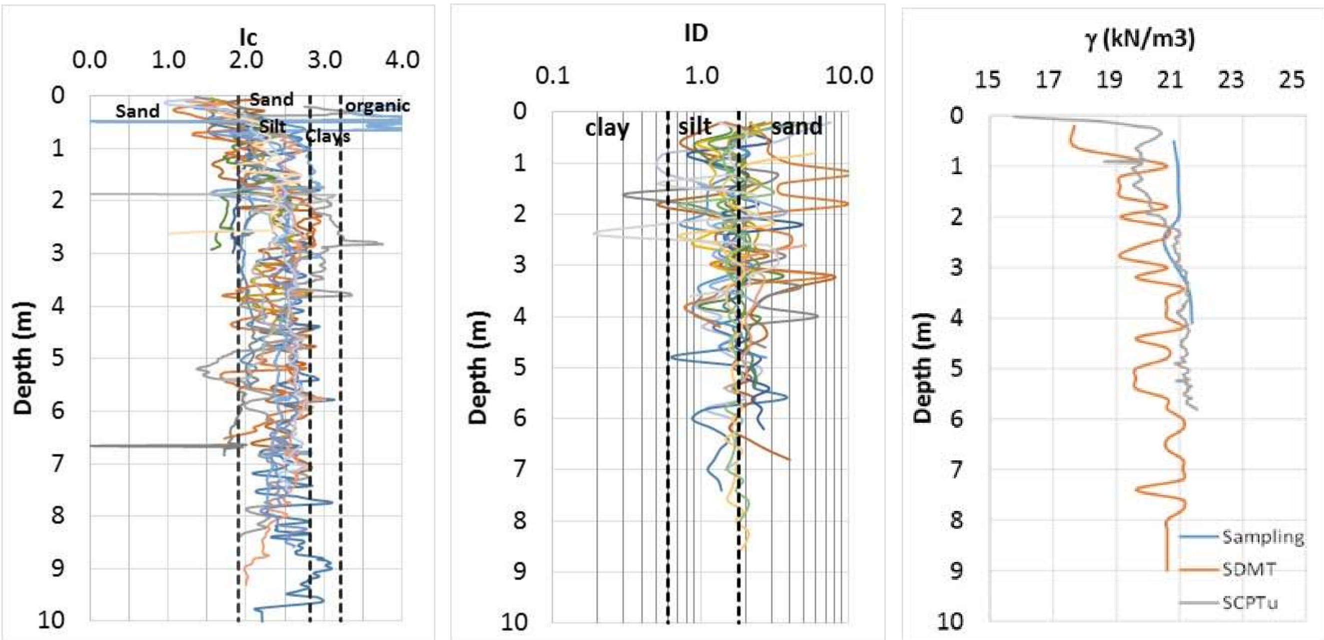

Figure 2. Identification and unit weights

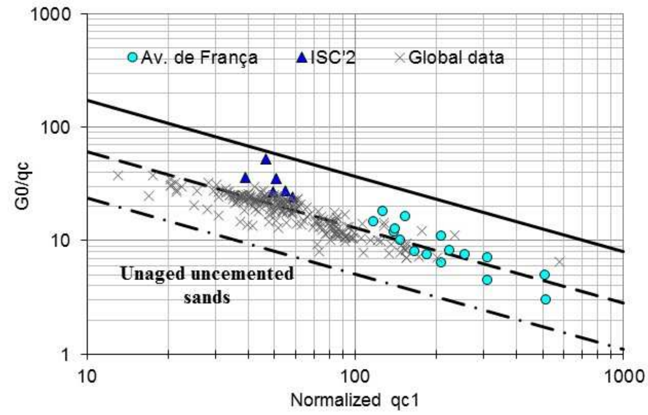

Figure 3. Cementation plot (Viana da Fonseca et al., 2007)

In terms of stiffness, the comparison is made through the constrained modulus (*M*), but similar behaviour can be observed when using G_0. Primarily, it is important to recognize that DMT is better suited for deducing deformability parameters, since they are based in stress and displacement measurements, while CPTu is mainly a strength test. Nonetheless, at least in the present study differences between *M* obtained by CPTu (Robertson 2009) and DMT (Marchetti 1980) are not significant, as shown in Figure 5. The plot on the right hand side represents an illustrative example of the convergence level between DMT and CPTu, found in this study.

On its turn, shear wave velocities deduced from CPTu data (Robertson 2010) fall within 150 and

250m/s, which fits the common register found in these soils (Fig. 6). In the central plot of same Figure, deduced velocities from CPTu results are directly compared with the velocities obtained from seismic devices incorporated in DMT and CPTu, revealing a good convergence between deduced and
real values, although the earlier are slightly higher. Another important issue in the detection of cementation can be established by using the ratio M/q_t, as proved by Cruz & Viana da Fonseca (2006) and Cruz (2010). Marchetti (1997), synthesizing the work of different authors, suggested that in sedimentary soils values of between 5 and 10 correspond to normally consolidated soils, whereas values of M/q_c between 12 and 24 would represent overconsolidated soils. In the plot on the right hand side of Figure 6, the great majority of residual values are within 10 and 15 falling in the overconsolidated interval. In this case, this ratio is somehow related with the cementation magnitude, in the same manner identified by Cruz (2010) in DMT case. A specific research framework was settled and has been carried out by MOTA-ENGIL and IPG, in the IPG experimental site (Rodrigues 2003, Cruz 2010) aiming to establish correlations to derive effective cohesion and angles for shearing resistance of these soils.

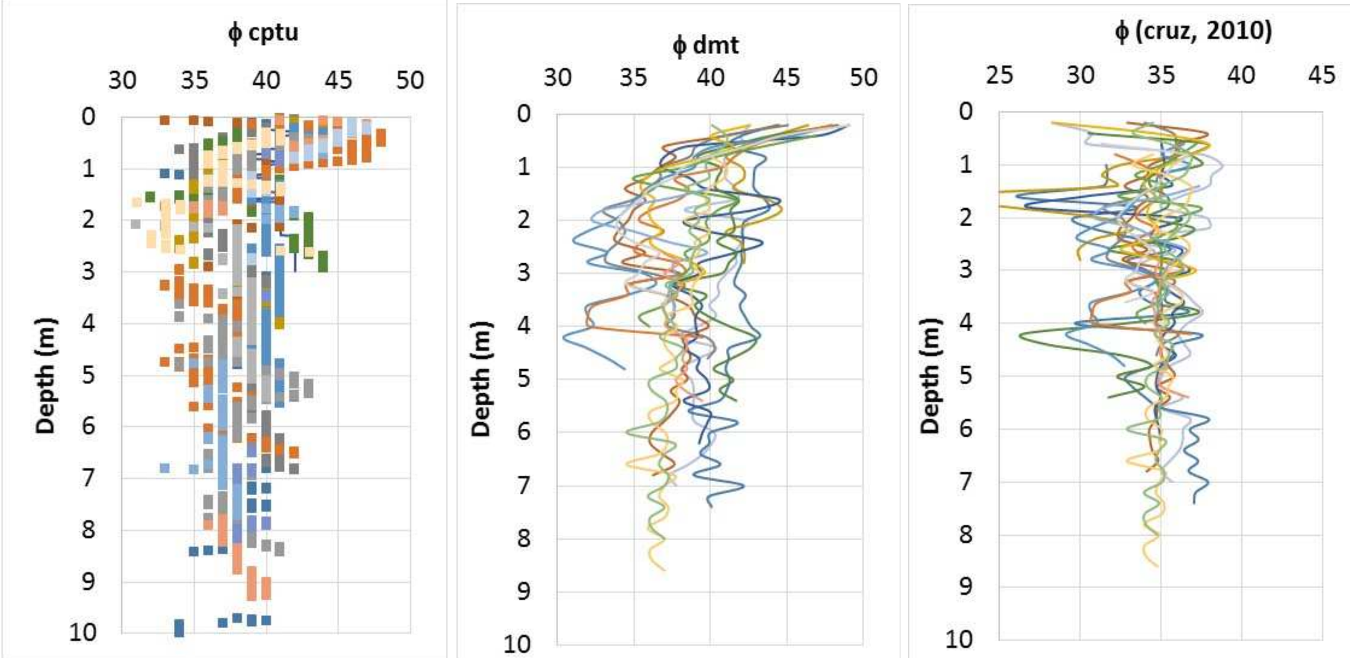

Figure 4. Strength parameters obtained from DMT and CPTu results

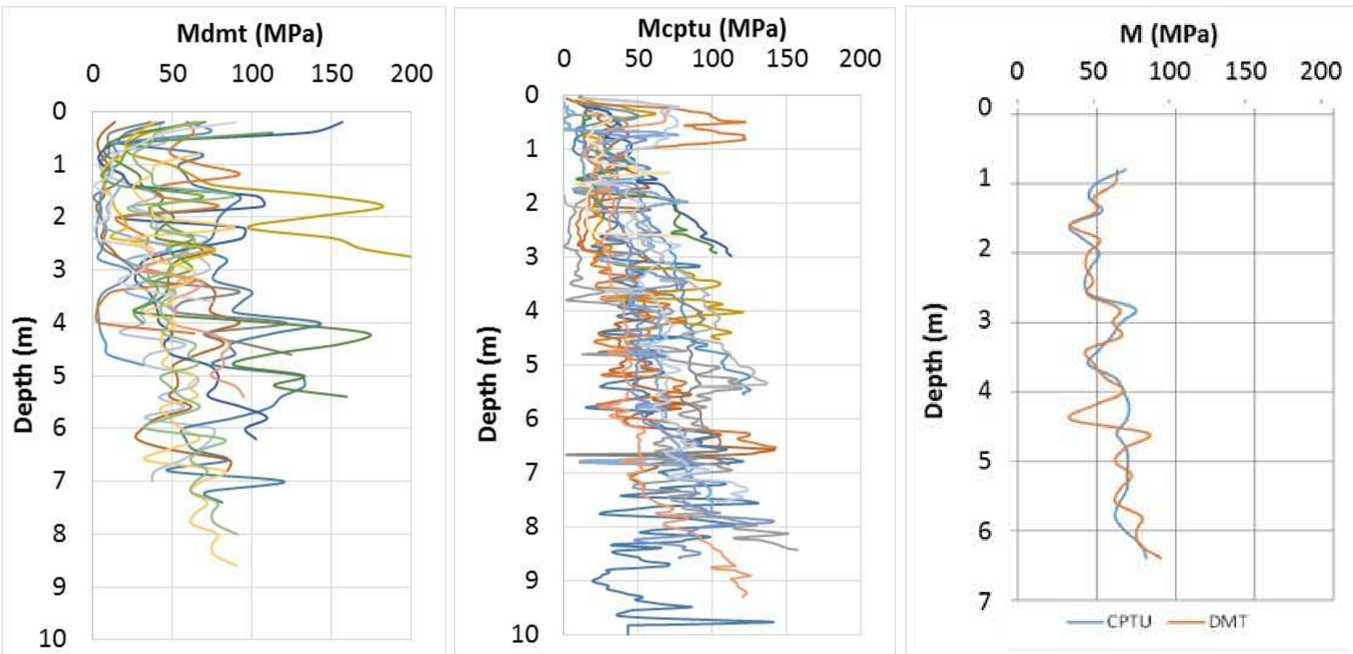

Figure 5 – Constrained modulus obtained from CPTu and DMT results

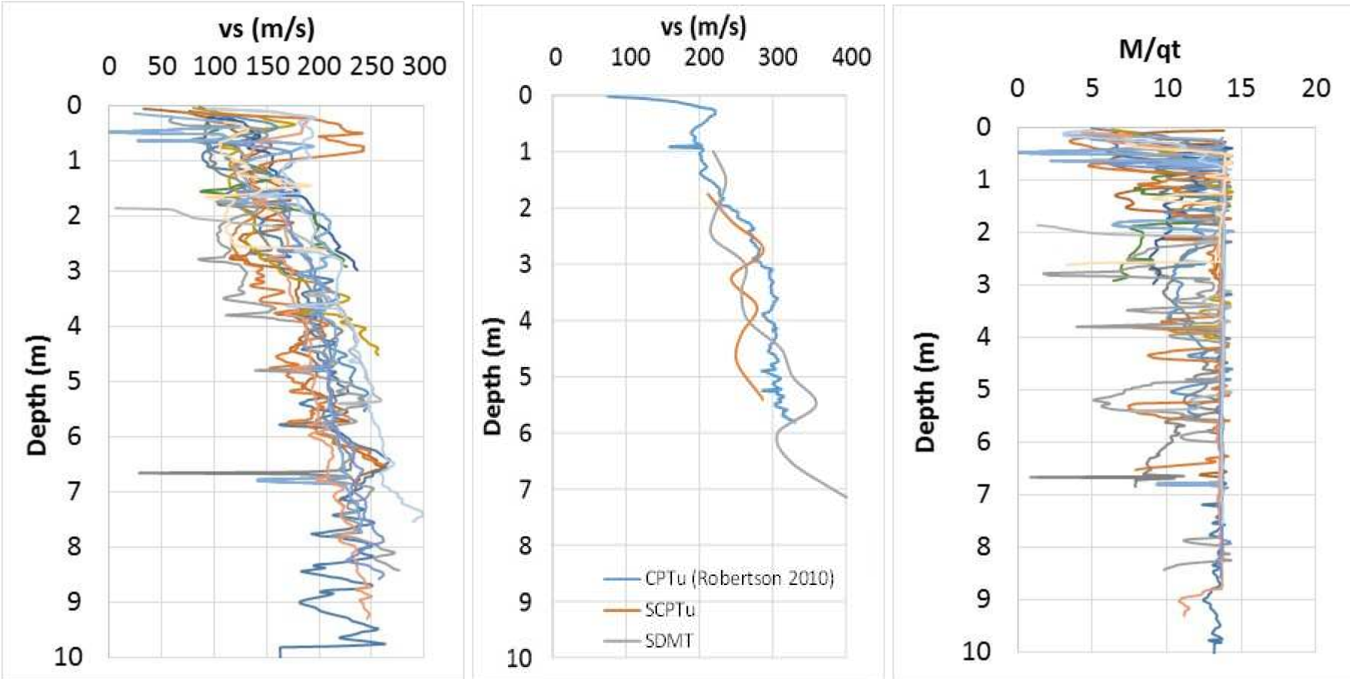

Figure 6 – Shear wave velocity and M/qt profiles

4 CONCLUSIONS

A significant volume of analyzed and treated CPTu data was compared with Porto Geotechnical Map geotechnical ranges and with DMT results obtained by following the proposals of Cruz (2010), in tests performed in pair with CPTu. The results prove that CPTu tests correctly predict most part of the main geotechnical parameter ranges, with the exception of the deduction of cohesive strength (a correlation has to be settled) and the angle of shear strength that is over predicted when sedimentary approaches are followed. The ratio M/qt seems to be an interesting parameter to solve this problem, thus a specific research program is under development in IPG experimental site.

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