(S)DMT Tests in structured soils. Lessons learned from Portuguese granitic massifs characterization.

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ABSTRACT

Characterization of structured soils by in-situ tests cannot be interpreted with success by applying the methodologies dedicated to sedimentary soils, due to the presence of cemented structures that deeply influences its mechanical behaviour, deviating from Classical Soil Mechanics concepts. From the shear strength point of view, structured soils are represented by two parameters that must be derived simultaneously (cohesion intercept and angle of shearing resistance), which is only possible to achieve in tests that measure more than one parameter, such as DMT, CPTu or PMT tests. In its turn, deformability of structured soils is characterized by 2 yield points, one related with beginning of weak bonds yield (first yield) and another one related with the complete breakage of the bond structure (bond yield or gross yield), which are not present in de-structured soils. As consequence, moduli decay curves are more pronounced than those typically displayed in sedimentary soils.
The research based in Portuguese granitic environs tested by (S)DMT has shown its usefulness in the characterization of these structured materials. The whole research frame included the characterization of several sites by means of CPTu and DMT tests, laboratorial testing, a calibration apparatus where DMTs were performed in artificially cemented soils closely controlled by triaxial and other laboratorial tests and several sets of SDMT, PMT, CPTu and triaxial tests performed in a high-quality experimental site (IPG). The accumulated experience arising from these experimental frames will be summarized and discussed in the present paper.

Keywords: (S)DMT; granites; residual soils; in-situ characterization.

1. Introduction

Soils affected by cemented structures are common in nature both in sedimentary deposits, developed during the diagenesis processes or by chemical precipitation, and in rock massifs affected by the weathering processes. In the latter, residual soils correspond to a mass where macro-fabric does not have any influence on mechanical behaviour, while in highly weathered to decomposed rock massifs (W_4 and W_5), usually designated by Intermediate Geo Materials (IGM), rock matrix strength become close to the residual soils, although the relic structures are still present and may have influence in global behaviour. Saprolites is the designation given to these 3 levels of weathering and its main distinctive characteristic is the presence of a cemented structure.

The presence of cemented structures in soils deeply affects their strength and stiffness, deviating from the common behaviours observed in transported sedimentary soils. Therefore, specific models must be developed to interpret field and laboratorial data.

2. Residual soil and IGM's behaviour

Saprolites are materials that result from the weathering of an original unweathered rock massif. Evolution of mechanical behaviour with weathering is rather complex to follow and depend on many variables, such as the geologic nature, presence of minerals of strong influence, anisotropy structures, among others. The subject represents a particular domain of geotechnical engineering that has been widely studied and published. Within this paper, the subject will only be briefly presented. Cruz (2010) can be very useful if a deeper understanding is wanted.

Departing from the unweathered and fractured rock massif, the continued weathering affecting the rock matrix generates mechanical degradation moving towards a generalized soil mass with no signs of the original macro-fabric. The first three weathering degrees of ISRM classification (W_1 to W_3) are represented by principles and models of rock mechanics, where macro-fabric and rock matrix plays the fundamental role in the strength and stiffness responses. In more advanced weathering degrees, chemical weathering is extended to the whole massif, with the rock matrix becoming more and more friable and weathered. This evolution is mainly governed by the increasing porosity of rock matrix, the weakening of grains and the reduction of bonding between grains. Weathering degrees W_4 and W_5 represent transition behaviour where micro or macro fabrics can rule the behaviour, while in residual soils the macro-fabric is no longer present. During the whole process, the interparticle cementation decreases with the increasing weathering but it is never completely lost.

From this point on, leaching and chemical precipitation have great influence in the soil structure, adding or subtracting minerals that may be deposited or leached, changing the original trends and characteristics observed in the saprolites. The discussion presented herein refers to the Porto and Guarda saprolites.

The characteristics of the materials or massifs and the respective evolution through weathering is highly variable according to their initial geology. The investigation of mechanical evolution with weathering has been greatly centred in the comprehension of the phenomena in granites, which was of great benefit for the presented research. Some references on the subject are Fookes et al. (1971), Baynes and Dearman (1978), Wesley (1990), Viana da Fonseca (1996), Blight (1997), among others. Detailed discussion and main references can be found in Cruz (2010).

Fig. 1 (Wesley, 1988) illustrates comprehensively the mechanical evolution from fresh rock (W_1) towards saprolite and lateritic soils.

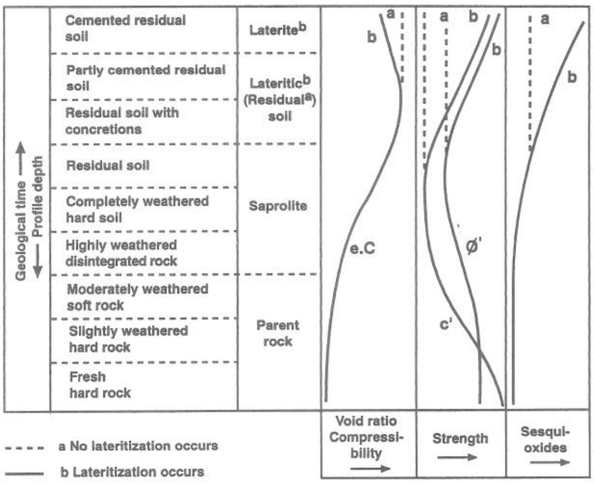


Figure 1. Mechanical evolution through weathering (after Wesley, 1988).

An unweathered granitic matrix has a large cohesion and high angles of shearing resistance due to the strength of the intergranular bonds and the interlocking texture. In early weathering stages, both cohesive intercept and angle of shearing resistance are only slightly reduced by the degree of weathering since mineralogical changes and internal weakening of the grains are minimal. The main product of granites weathering arises from the hydrolysis of feldspars into kaolinitic clay, while quartz remains unweathered. The obtained kaolinitic clay is characterized by low plasticity and low activity, thus with minimal mineralogical influence. Weathering of biotite also occurs by oxidation of the iron components.

With advancing weathering mechanical parameters decrease, showing a tendency for the cohesive intercept (in terms of Mohr-Coulomb failure envelope) to be reduced by relaxation of grain boundaries and micro-fracturing, while angles of shear resistance are slightly higher than the same soil in a remoulded state. Globally, the loss of strength with weathering can be fairly represented by a reducing cohesion intercept (c') due to weakening of contact forces. The cohesive intercept is present even when soils show strong contraction during shear and can be a result of many other contributions apart from bonding, such as electrostatic forces, adhesion of clay particles, contact cementation developed with time and pressure (ageing) and suction due to development of negative pore pressures in unsaturated conditions. In the most part of situations chemical bonding and suction give the fundamental contribution for strength (Viana da Fonseca and Coutinho 2008). The loss of strength is naturally followed by an increasing deformability that results from the increasing porosity and the decreasing cementation magnitude.

Globally, at any stage, saprolites are characterized by variable grain strength as function of mineralogy, the presence of a bonding structure that influences strength and stiffness and a void ratio highly influenced by the weathering level. The continuous evolution of the grain size distribution and the variable density along weathering leave no space for the stress history concept. These characteristics contrasts with those observed in sedimentary soils where the grain strength is uniform (weaker particles are eliminated during transport phases), the void ratio depends directly on the stress history, which plays an important role in strength and stiffness behaviour, and cemented structures only occurs in geologic aged deposits (Brenner et al. 1997).

In its turn, the stress-strain behaviour is characterized by the presence of 2 precocious yield points that are not present in de-structured soils. One at the beginning of weak bonds yield (first yield) and another one when the bond structure globally fails (bond yield or gross yield). Furthermore, the presence of bonding generates moduli decay typically more pronounced than those displayed in soils without cementation influence.

3. Characterization of saprolites

Geotechnical characterization of saprolites face some challenges, since the current interpretation models dedicated to transported soils cannot represent adequately the residual masses. In fact, the existing in-situ interpretation methodologies do not allow to derive simultaneously two strength parameters and cannot predict adequately the modulus degradation curves.

On its turn, laboratorial tests suitable for cohesive-frictional characterization are not efficient to cover the usual heterogeneity of weathered masses, because the number of tests possible to integrate in current campaigns is generally insufficient to do so. Furthermore, laboratorial tests depend on the quality of samples, but sampling deeply affects the cementation structure. Therefore, laboratory tests are useful to calibrate field parameters but cannot work efficiently without support in-situ information.

As consequence, saprolites characterization demands for in-situ continuous profiling spaced according to the perceived local heterogeneity of the residual mass, which requires appropriate in-situ test methodologies to obtain realistic geotechnical parameters. Multi-parameter tests such as DMT, CPTu or PMT are best suited to try the simultaneous evaluation of strength parameters, while the simultaneous acquisition of mechanical and seismic responses can be very useful in the correct definition of stiffness properties and moduli decay laws. SPT and

DPSH are dynamic tests, which introduces considerable damage in the cementation integrity. Besides, they cannot derive the two strength parameters based in only one test parameter and are inappropriate for stiffness characterization. SDMT is a very useful tool to write the history of these geo-materials, due to its stress-strain test condition, the continuous profiling, the lower level of disturbance generated during the penetration phase (e.g. comparing with PMT and CPTu tests), and the possibility of simultaneous seismic acquisitions. The experimental work presented herein, illustrates its efficiency in the characterization of these soils.

4. Experimental work with SDMT

The presence of granitic masses is common in Portugal, motivating the development of new in-situ testing methodologies dedicated to this type of massifs. The important construction held in the country for the last 20 years, gave impulse to several research works aiming the characterization and the comprehension of the granitic residual soil geotechnical behaviour. The research on residual soil characterization using DMT tests within this period is further summarized.

4.1. Phase 1

Field characterization of several granitic sites located in Porto and Guarda, by means of DMT and CPTu tests performed side-by-side, followed by intact sampling and laboratory testing. A first approach for deducing strength parameters was established by comparing DMT results with triaxial data obtained in intact samples retrieved using thin wall Shelby samplers (Cruz and Viana da Fonseca 2006a). The triaxial reference used in the calibration was naturally affected by sampling with important influence in cohesion determination. The IPG experimental site was constituted in 2003 (Rodrigues 2003).

4.2. Phase 2

The IPG experimental site incorporated a field granitic residual mass with available area for testing, a calibration chamber adequate for DMT and CPTu testing in controlled conditions (CEMSOIL) and a laboratorial structure that includes high quality triaxial equipment. This structure allowed to develop a calibration frame based in artificially cemented samples remoulded in the same conditions for DMT and triaxial testing, removing the effects of sampling from the comparison (Cruz 2010). The artificial mixtures were remoulded from previously de-structured granitic soil mixed with Portland cement. During the experiment, water level and suction were controlled, and seismic measurements (V_s and V_p) were taken. DMT and triaxial tests on local natural samples were also performed, allowing to compare behaviours between artificially and naturally cemented soils (Cruz 2010). Based on this experiment, a set of new correlations to obtain cohesion magnitude and angles of shearing resistance from DMT was established (Cruz 2010; Cruz et al. 2014; Cruz et al. 2018).

4.3. Phase 3

After phase 2, a new testing program was carried out in the IPG site, consisting in six sets of SDMT, SCPTu and PMT tests, as well as 2 boreholes and quality sampling for triaxial tests. The previous DMT calibration allowed to use it as a bridge to calibrate CPTu, taking advantage of the considerable number of CPTu-DMT pairs of tests (Cruz et al. 2018). Both together are now being used to calibrate PMT in the IPG site.

Furthermore, the regular results of shear wave velocities obtained during this framework allowed a better understanding of the stress-strain and the moduli decay behaviours of these soils. A logistic decay model was proposed, fitting well in the studied residual soils (Rodrigues et al. 2020).

The presented work was always compared and supported by the Porto Geotechnical map (COBA 2003), which is rich in field and laboratory data related with whole range of weathering degrees of Porto Granites. The available data allowed to analyse the mechanical evolution from W_1 to residual soils, giving an important contribution for the global understanding of the Porto granites behaviour (Cruz 2010, Cruz et al. 2015). Guarda and Porto granites are very similar and can be easily integrated within the same global behaviour.

The obtained results and lessons learned along the way will be further summarized and briefly discussed.

5. Obtained results

5.1. Field Conditions

The residual soils from Porto and Guarda granitic formations are very alike and result from mechanical and chemical weathering of the original massif. Typically, these materials are constituted by non-plastic silty sands to sandy silts, rarely clayey sands, classified as SM or SC according to the Unified classification (ASTM D 2487, 1998), while under Wesley Classification dedicated to residual soils and IGM materials (Wesley 1988) they fall within the Group A (soils without strong mineralogical influence), in the sub-groups A(a) and A(b), respectively associated to materials with or without macro-fabric influence. The sandy fraction is mainly represented by the unweathered quartz while the fine content is mostly the result of the weathering of feldspars. Fine content (#200) is mostly lower than 30%, while clay content hardly overcomes 10%. They are excellent as earthfill materials.

From the geotechnical point of view, these residual masses fall within two main units represented by N_{SPT} uncorrected values of 10 to 30 and 30 to 60, while decomposed (W_5) to highly weathered massif (W_4) are commonly represented by N_{SPT} higher than 60. Void ratios range mostly between 0.4 to 0.8 generating angles of shearing resistance varying from 32 to 40º. Permeability coefficient (k) fall within 10^{-6} to10^{-7} m/s, meaning drained conditions in the most practical loading situations. Some basic properties of these soils are presented in Table 1, while Table 2 presents the observed ranges of in-situ tests in these soils.

The experience in Portugal demonstrates that with a good (current) penetration capacity DMT tests can be performed in the residual soils, and even in W_5 massif when adequate anchor system is used. Since DMT is a two-phase test (penetration and measurement are separated), it is also possible to pursuit the dynamic penetration to overcome stronger spots, with or without data acquisition (Cruz & Viana da Fonseca 2006b).

Table 1. Saprolites geotechnical ranges

N_{SPT}	ASTM	γ(kN/m³)	K (m/s)	c'(kPa)	ϕ (°)
10-30	SM-SC	17-19	10^{-6}-10^{-7}	5-30	32-37
30-60	SM	18-20	10^{-6}-10^{-7}	10-50	35-38
> 60	SM	20-22	10^{-6}-10^{-7}	30-70	35-40

Table 2. Saprolites in-situ test ranges

	W5	G8	G4
Wesley Classif.	A(a)	A(b)	A(b)
N_{SPT}	> 60	30-60	10-30
q_d (MPa)	>20	10-20	5-10
q_c (MPa)	---	15-25	5-15
f_s (MPa)	---	0.2-0-5	0.1-0.3
p_y (MPa)	1-6	1.0-3.0	0.5-1.5
p_l (MPa)	2.5-10	1.5-4	1-3
E_{PMT} (MPa)	50-150	15-40	10-25
I_D		1.0-3.5	1.0-3.0
K_D		10-40	5-25
E_D (MPa)		60-120	25-75
v_p (m/s)	1250-2000	800-1500	400-800

5.2. DMT basic and intermediate parameters

DMT is based in the measurement of two inflating pressures (P_0 and P_1) needed to displace a circular membrane within 0.05 mm and 1.10 mm and a third pressure (P_2) obtained at 0.05 mm in a deflating phase. Departing from these field measurements, four intermediate parameters are calculated, namely material index, I_D, the horizontal stress index, K_D, the dilatometric modulus, E_D and the pore pressure index, U_D. The definition of these basic and intermediate parameters is in accordance with Marchetti (1980) and Lutenegger and Kabir (1988). Despite the final geotechnical parameters obtained from the test, these intermediate parameters should be analysed once they can give valuable information about the behaviour of the studied soils.

I_D is a very stable parameter that correctly identifies these soils as silty sands to sandy silts, independently of the level of cementation (Fig. 2). In the present case, I_D is also a kind of a "weathermeter" since the evolution of fines is closely related with weathering evolution.

Horizontal stress index, K_D, is a key parameter in these soils because it is sensitive to cementation and suction (Marchetti 1980, Cruz 2010). In the studied soils, K_D profiles are typically constant with depth with magnitudes always higher than 2 (within 5 and 40) varying according to the cementation level (Fig. 2).

Dilatometer modulus, E_D, is the DMT stress-strain parameter, which represents the ratio $E / (1 - \nu^2)$ and is the base for deducing the moduli. Theory of Elasticity is used to derive E_D by considering that membrane expansion into soil can be represented by the loading of a flexible circular area of an elastic half-space.

The combination of I_D with E_D gives an adequate evaluation of the unit weight (Marchetti and Crapps 1981) that typically converge to laboratorial evaluations, no matter the level of cementation. This is fundamental for the correct K_D determination, once it depends on the in-situ vertical effective stress. Fig. 3 illustrates a global comparison of Porto and Guarda DMT results and the respective laboratory determinations.

U_D only works below the water level and is useful to understand the drainage behaviour. In the case of the studied granitic residual soils, the parameter is mostly zero, confirming the expected drained response.

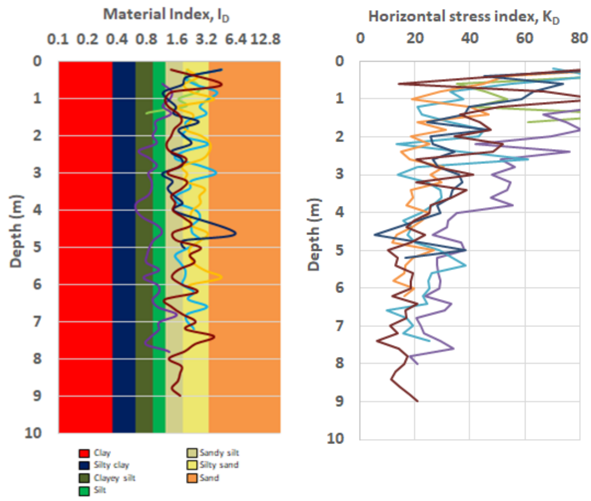


Figure 2. I_D and K_D representative profiles of residual soils.

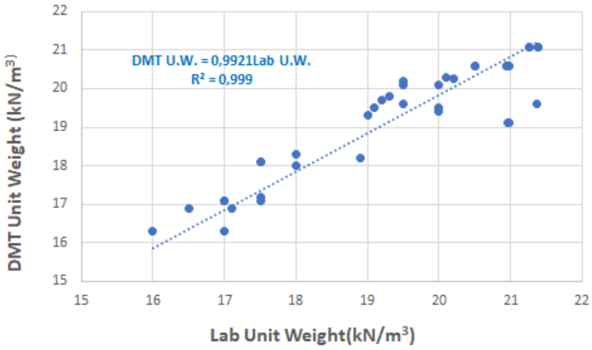


Figure 3. Comparison of DMT and laboratory unit weights.

5.3. Soil behaviour type (SBT) diagrams

Soil behaviour type charts (SBT) give also valuable insights of the mechanical responses and should be considered in current analysis. There are 3 basic charts based in the combination of E_D, K_D and U_D *versus* I_D that give information on expectable soil behaviour.

The E_D-I_D, used in the estimation of unit weight, represents simultaneously the soil nature and its in-situ density. Fig. 4 represents the Portuguese saprolites, showing the same type of soil but with higher densities in the case of Guarda granites, corresponding to lower weathering degree.

The U_D-I_D chart is useful to follow the drainage behaviour and can be fundamental in the interpretation of residual soils with high fine contents (silty and clayey). In the case of Portuguese saprolites, the parameter fits in the behaviour of sedimentary soils with similar grain size as represented in Fig. 5.

In the case of K_D-I_D it is possible to generate 2 different charts (Fig. 6 and Fig. 7). One representing the cohesive magnitude according with the specific weathering level, somehow represented by I_D (Cruz et al.

2021). The I_D values higher than 3.3 (dashed line in the plot), represent clean sands where the expected low fine contents should generate more unstable cementation structure. The isolines were calculated using *Matlab R2016b*. The second one, proposed by Robertson (2015), allow to anticipate the behaviour in shear and identifies the expected drainage condition.

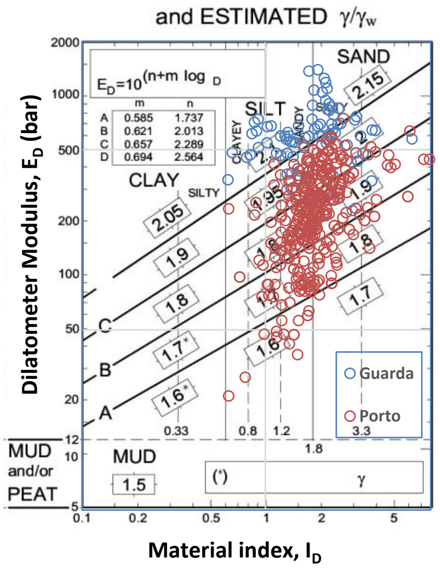


Figure 4. E_D-I_D soil behaviour type.

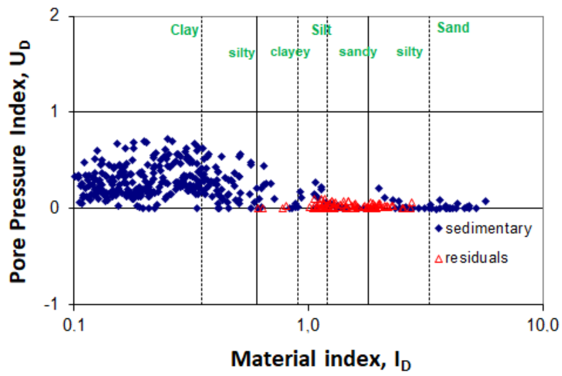


Figure 5. U_D-I_D soil behaviour type.

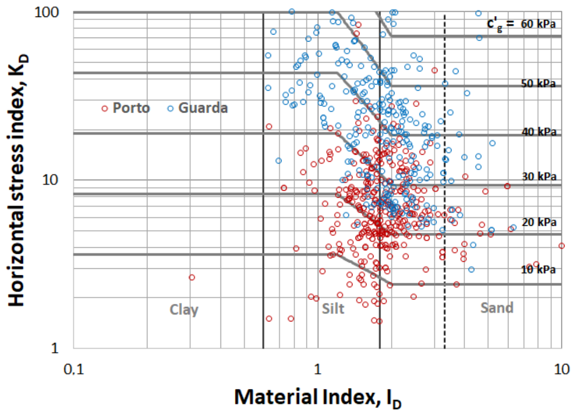
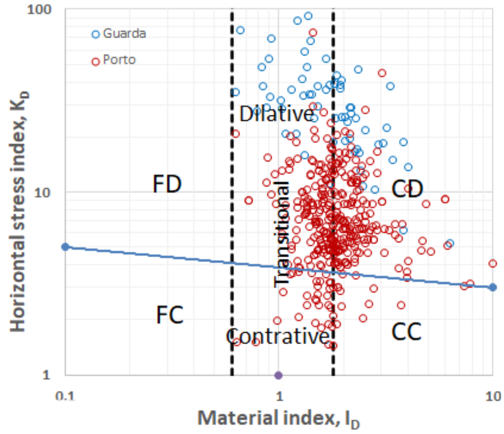


Figure 6. K_D-I_D soil behaviour type with cohesion.

When G_0 from seismic waves is available, another SBT chart can be produced, corresponding to the ratio G_0/M_{DMT} vs K_D initially proposed by Marchetti et al. (2008). This chart seems to be efficient in the detection of cementation structures, as highlighted in Fig. 8 (Cruz et al. 2021). The results plotted below the dashed line represent sedimentary deposits with similar grain size.



CD – Coarse grained dilative (mostly drained)
CC – Coarse grained contractive (mostly drained)
FD – Fine grained dilative (mostly undrained)
FC – Fine grained dilative (mostly undrained)

Figure 7. K_D-I_D soil behaviour type.

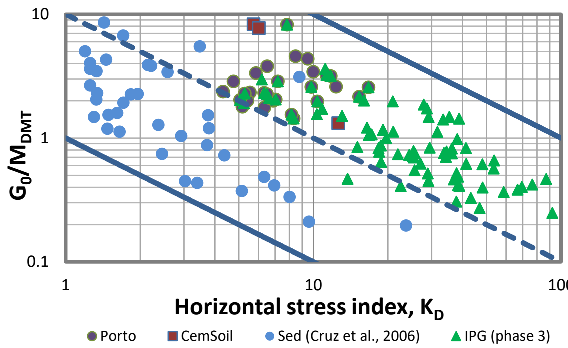


Figure 8. Cementation detection in G_0/M_{DMT} - K_D chart

The results of Portuguese saprolites represented in those charts give a comprehensive picture of how they work. They are mostly medium dense to dense sandy silts to silty sands, exhibiting drained behaviour and dilatancy at low confining stresses. The cemented structure is identified in all SDMT results, resulting in a cohesive intercept mostly within 10 and 50 kPa. Results higher than 50 kPa represented in the figures correspond to isolated less weathered spots within the residual mass.

5.4. Strength parameters

From the strength point of view, once DMT is a multi-parameter test, it was possible to attempt separate correlations to obtain the shear strength parameters. As stated previously, residual soils develop a stress-strain behaviour very similar to the behaviour observed in overconsolidated clayey sedimentary soils, where the pre-consolidation pressure is replaced by the cohesive intercept arising from cementation strength. In this case, the OCR generated in the case of clays becomes a virtual OCR (vOCR) that reflect the ratio between cementation strength and in-situ effective stresses. Accordingly, the OCR correlation proposed by Marchetti and Crapps (1981) for granular soils was selected to derive vOCR.

Note that the parameter is obtained from K_D and I_D, reflecting simultaneously cementation and weathering.

Considering this strength model, attempts were made to correlate K_D, vOCR and even M/qt (from combined CPTu and DMT tests) with the triaxial cohesive intercept obtained in natural samples retrieved by means of Shelby sampling (Cruz and Viana da Fonseca 2006a). K_D correlation revealed to be the less effective, probably because one parameter is not enough to integrate a varying degree of cementation within a varying fine content. The other two attempts for correlation displayed good and similar sustainable possibilities.

During the research frame it became obvious that sampling generates a degradation of cementation structure, thus the used reference could not adequately represent the one in the field. The experimental work using a calibration chamber and triaxial testing allowed to avoid sampling and get stronger based correlations. Comparisons between triaxial strength results obtained in natural and artificial samples (prepared with equivalent densities and similar compressive strengths), revealed similar strength envelopes apparently not affected by the different sample origins. Fig. 9 shows the correlation between vOCR and a global cohesion intercept (c'_g) representing cementation strength and suction. The correlation based in natural samples is plotted in the same figure, revealing the gap that sampling may introduce.

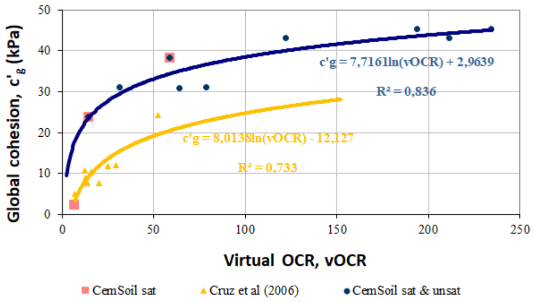


Figure 9. Correlation to obtain cohesive intercept.

The evaluation of angles of shearing resistance of the residual soils using sedimentary correlations (Marchetti 1997) produces results that are consistently higher than the in-situ values represented by triaxial testing, following the same trends observed in other in-situ tests applied in the same conditions. The reason for this is related with the contribution of the cemented structure to the overall strength, which is incorporated in the result of angles of shearing resistance. Therefore, once the magnitude of cohesion is known, it can be used to correct the angle deduced from sedimentary models. The correlations arising from the research, after re-analysis of data in 2022, are represented by the following equations:

$$c'_g = 7.716\ln(vOCR) + 2.94 \quad (1)$$

$$\emptyset_{corr} = \emptyset_{sed} - 3.45\ln(vOCR) + 8.20 \quad (2)$$

where c'_g is the global cohesion generated by the cementation and suction; vOCR is the virtual overconsolidation derived from Marchetti and Crapps (1981); ϕ_{corr} is the corrected angle of shear resistance; ϕ_{sed} is angle of shear resistance derived from sedimentary correlation (Marchetti 1997).

5.5. Stiffness parameters

DMT is a very efficient test in modulus determinations because of its stress-strain based evaluation, which is sustained by Theory of Elasticity (Marchetti 1980). The dilatometric modulus, E_D, deduced considering a semi-spherical expansion is then adjusted as function of the type of soil (I_D) and the level of cementation structure (K_D), increasing the accuracy of constrained modulus (M_{DMT}). From this parameter and considering adequate Poisson coefficient it is possible to obtain both deformability modulus (E') and working strain distortion modulus (G_{DMT}). Considering the local experience, a Poisson coefficient equal to 0.3 was taken for these determinations. However, the main question is what moduli are we obtaining in each specific situation, given the moduli dependency on stress and strain levels?

The typical stress-strain curves of structured soils are characterized by 2 yield points (not present in non-structured soils), one related with beginning of yield weak bonds (first yield) and another one related with complete breakage of the bond structure (bond yield or gross yield). The representation of SDMT test results in modulus decay curves obtained from triaxial data highlights some interesting patterns (Fig. 10 and Fig. 11).

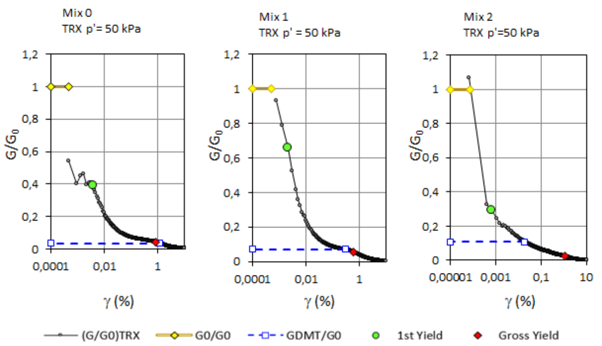


Figure 10. Modulus decay in artificial soils.

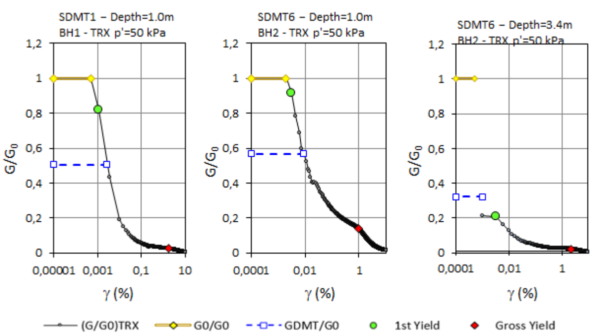


Figure 11. Modulus decay in natural soils.

Firstly, it is observed that G_{DMT} results are within the same locus of the 1st yield, suggesting that installation of the equipment does not affect deeply the cementation structure in the measurement area (Rodrigues et al. 2016). The maximum stiffness obtained at small strain in triaxial tests is in the same order of magnitude as the one obtained by shear wave velocities, revealing the good quality achieved in the sampling processes. Furthermore, the increase in cementation is followed by an increase of the working strain modulus (G_{DMT}) and a decrease of the strain level (γ_{DMT}). This proves that the lower is the level of cementation the lower will be the field of the load transfer inside the ground during the membrane expansion, which have important consequences in design (Rodrigues et al. 2016, Cruz et al. 2023).

In turn, γ_{DMT} in the natural residual soils falls within 0.002 % and 0.009 %, one order of magnitude lower than the obtained in similar grained sedimentary soils with similar grain size $\gamma_{DMT} \approx 0.01\text{-}0.30\%$, illustrating the differences on the stiffness of both soils. In artificial samples, the "working strain modulus" (G_{DMT}) is lower than the observed in natural samples, corresponding to higher γ_{DMT} and falling in the same locus of sedimentary sandy soils found by Amoroso et al. (2014). Fig. 12 represents the locus of G/G_0 vs γ_{DMT} obtained in the triaxial tests performed in IPG samples, plotted together with the sedimentary results (Amoroso et al., 2014).

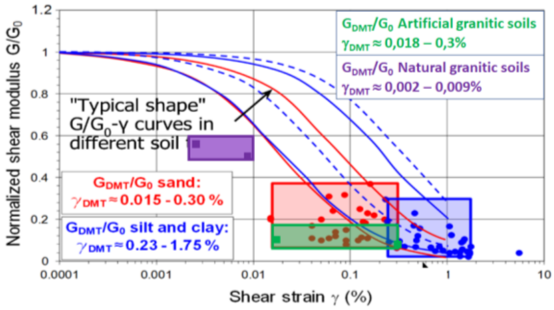


Figure 12. Representation of residual soil G_{DMT}/G_0 together with sedimentary soils (adapted from Amoroso et al., 2014).

These observed differences suggest an important influence of the fabric in the overall stress-strain response and the difficulty of artificial samples to represent natural soils. The subject is recognized by the specialists and the theme is rather complex and not consensual. Detailed discussion on the subject can be found in Cruz (2010).

According to these findings, it becomes clear that the selection of the appropriate modulus to be used in specific context is much improved if the modulus decay curve is settled. In SDMT tests, two different deformability moduli corresponding to different strain levels are obtained. One corresponding to very small strains (obtained from shear wave velocities) and another one corresponding to working strains (obtained by the mechanical response of the test), opening the possibility to attempt the moduli decay determination.

Most of the current methods for representing the non-linear stress-strain behaviour of soil from small to medium strain levels are based on a hyperbolic stress-strain relationship. Amoroso et al. (2014) proposed a specific hyperbolic model to be used in the case SDMT data, as represented by the equation below:

$$\frac{G}{G_0} = \frac{1}{1+\left(\frac{G_0}{G_{DMT}}-1\right)\frac{\gamma}{\gamma_{DMT}}} \qquad (3)$$

where G_0 and G_{DMT} are the maximum and DMT shear modulus, G is the shear modulus, γ is the shear strain and γ_{DMT} is the DMT shear strain.

This model was the first attempt to derive the modulus decay curve, but it revealed poor convergence, deviating considerably at medium and high strain and underestimating the stiffness of the natural soil. Therefore, other mathematic formulations based on SDMT data were studied, leading to development of the logistic curve expressed below (Rodrigues et al. 2020):

$$G = \frac{a}{(1+e^{-b(log(\gamma)-c)})} \qquad (4)$$

where a = $\lim_{\gamma\to 0} G(\gamma)$ is the logistic horizontal asymptote, b (<0) is the gradient of the curve and c is the natural logarithm transformed x-value of the curve´s midpoint.

Note that taking a=G_0, b=-1, and $c = -log\left(\frac{G_0-G_{DMT}}{G_{DMT}\times\gamma_{DMT}}\right)$ the Eq. 3 is obtained.

Departing from the logistic curve, an attempt was made to correlate the triplet (a, b, c) that define the equation with the DMT test parameters. Concerning to "a", since b<0, and $\lim_{\gamma\to 0}\frac{G}{G_0} = 1$ is straight forward that the parameter should equal G_0. In turn, to obtain "b" and "c" various DMT parameters were considered to provide the most relevant fit. For each dataset resulting from the described experiences, the logistical model was adjusted regarding its parameters, a (=G_0), b and c, using weighted least squares, since the datasets were not uniformly distributed along all the gamma values. Thereafter, each (a, b, c) triplet that provided the best fit to the respective data set was combined with all the SDMT parameters and several combinations/functions of those parameters were tested, using *Matlab R2016b*. The best fits showed that the parameter b is better correlated with vOCR and the parameter c correlated with a combination of G_0 (MPa) and K_D, as represented in Eq. 5 and Eq. 6:

$$b = 0.0004406vOCR - 0.5591 \qquad (5)$$

$$c = -4.041 - 0.02774G_0 + 0.03388K_D \qquad (6)$$

The application of the model produced a reasonable overlap with the decay curves obtained from triaxial testing in natural and artificial samples (Rodrigues et al. 2020). This means that despite the differences observed in the strain level and modulus degradation of the two types of samples the model can represent well both (Fig. 13 and Fig. 14).

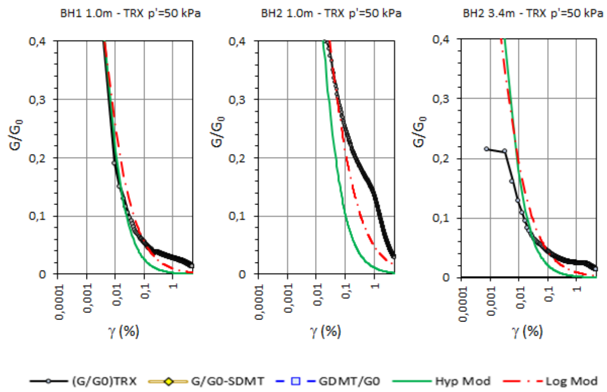


Figure 13. Natural soil modulus decay deduced from hyperbolic and logistic models at medium to high strains.

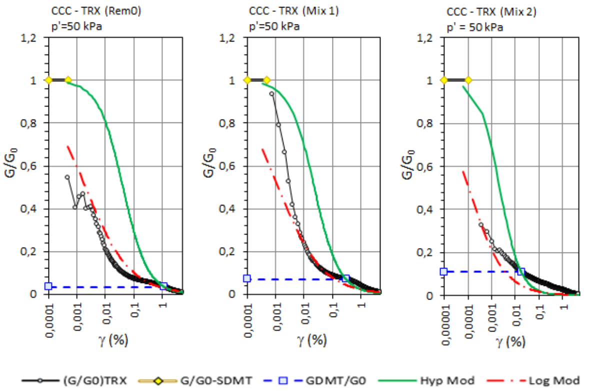


Figure 14. Artificial soil modulus decay deduced from hyperbolic and logistic models.

6. Conclusions

The performed research work highlights the usefulness of DMT tests in cemented structured soils characterization. Based in several research frames based in Porto and Guarda granitic residual soils tested by DMT it was possible to settle methodologies to work with the specificity of these soils. Global information to anticipate the mechanical behaviour of the studied residual soils can be obtained by the SBT charts based in DMT intermediate parameters. The presence of a cementation structure can be detected by G_0/M_{DMT} vs K_D chart.

From the strength point of view the conducted studies generated two correlations to simultaneously derive the cohesion intercept and the angle of shearing resistance. As for stiffness, the experimental data allowed to develop a logistic model for obtaining moduli decay curves that work better than hyperbolic model in the studied soils.

The found correlations represent well the Portuguese saprolites from where they were drawn. In other environments, validation of correlations is recommended, and adjustments may be required. Nevertheless, the path followed in the Portuguese experience can be replicated in other environments, hopefully with success.

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