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Braja M. Das
Editor-in-Chief

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Design parameters of Portuguese granitic residual soils obtained from DMT tests

ABSTRACT: Cemented soils are often seen as non-textbook materials, since they don't fit into the usual behavior of transported soils in the light of classical Soil Mechanics theories. This fact creates several problems on the interpretation of in-situ test results, when the classical approaches are used, limiting the application of common in-situ tests. Departing from a long experience in characterizing Portuguese granitic soils with Marchetti's Dilatometer (DMT) a large calibration box (CemSoil Box) was constructed to work with artificially cemented silty sands, aiming the evaluation of static penetration influence in the loss of cementation strength, and the overall effects on the stiffness response, giving rise to adequate correlations for deriving design parameters. The experience was based in the development of artificially samples tested in triaxial cell and in the CemSoil Box, where blades could be pre-installed and pushed in. Water level, suction and seismic velocities were monitored during the experience. The final results allowed for the establishment of specific correlations to derive strength (cohesion intercept and angles of shearing resistance) and stiffness (deformability and small strain shear modulus) parameters, as well as a specific methodology for controlling suction influence on the respective results..

KEYWORDS: Residual soils, granitic formations, DMT, geotechnical parameters.

1. INTRODUCTION

Residual soils show specific mechanical behavior different from those established for sedimentary transported soils, since the presence of a cemented matrix plays an important role on strength and stiffness behavior, especially at shallow depths (low confining stresses). In fact, cementation structures generate a cohesive-frictional material expressed in a Mohr-Coulomb strength criterion with a cohesion intercept and an angle of shearing resistance that cannot be deduced by the common sedimentary correlations developed for such soils, while stiffness is markedly increased, especially at small strain levels. Moreover, water levels at significant depth are frequent in residual profiles, generating suction phenomena also with significant influence in strength and stiffness properties. The work presented herein integrates a long term research activity that aimed for the establishment

of a model for characterizing residual soils using Marchetti's Dilatometer test (DMT), on its own or combined with other tests, performed by the author since 1995 within his professional activity in Laboratório de Geotecnia e Materiais de Construção (LGMC of CICCOPN) and MOTA-ENGIL, in very fruitful partnership with FEUP. In the last two decades this partnership developed several studies on residual soils from Porto Granite Formation in order to improve the knowledge and measurement of its mechanical behavior, using the last generation technologies of testing equipments. The main conclusions arising from these studies were summarized by Cruz (2010) gathering the information presented by Viana da Fonseca (1996), Rodrigues (2003), Cruz et al (2004a, 2004b) and Cruz & Viana da Fonseca (2006):

- a) Both DMT and CPT_u tests give important information about soil type, easily integrated within borehole information, showing higher capacity for detecting thin layers when compared with borehole information;
- b) The definition of soil type is achieved through a quantitative value (I_b and I_c for DMT and CPT_u , respectively), that constitutes an important mean to numerical data treatment and to interpret mechanical behavior of difficult soils such as intermediate (mixed) soils or residual soils;

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Table 1. Indexation of tested samples.

Strength (kPa)	Destructured non-cemented	Mixture 1	Mixture 2	Mixture 3	Mixture 4
Uniaxial (q_u)	20.8	72.6	124.9	273.0	312.3
Diametral (q_t)	1.5	7.2	15.3	33.2	39.4
Reference NSPT	--	10-30	30-60	>60 (ISRM W5)	

- c) Unit weight can also be derived by both tests, with fair accuracy identical to laboratorial results;
- d) Global data has shown very consistent patterns, reproducibility and convergence to the trends observed in other *in-situ* test results;
- e) The combination of intermediate *DMT* parameters can simultaneously represent the influence of soil type, stiffness, density and pore-pressure, which is decisive in correlation quality;
- f) K_p can be used to derive the at rest stress of state, being obtained from a lift-off horizontal pressure; its calculation is made with good approximation by combining *CPTu* and *DMT* data;
- g) K_p profile is close to the pattern of *OCR*, hereby designated virtual overconsolidation ratio, νOCR , giving valuable information in residual soil cementation strength contribution;
- h) From the strength point of view, *DMT* alone (through νOCR) or combined with *CPTu* (M/q_t) can provide numerical information related to the strength arising from cementation structures (with a sign in cohesion intercept) and to adequately correct the angle of shearing resistances when these are derived from sedimentary correlations;
- i) It is possible to deduce high quality stiffness parameter data from *DMT*, such as constrained, deformability and maximum shear modulus; these evaluations are supported by Theory of Elasticity and numerical values are obtained by a high resolution measurement system.

2. EXPERIMENTAL CONDITIONS

As a consequence of this work, it became fundamental to develop experimental work in controlled environment to calibrate the field experimental data, overcoming sample disturbance and variability present when natural soils are tested in laboratory. To do so a special apparatus (CemSoil box) was created to work with large artificially cemented samples, aiming the evaluation of static penetration influence in the loss of cementation strength, and the overall effects over

the stiffness response, to produce adequate correlations for deriving design parameters.

Cem Soil Box was conceived as a confinement border to hold tight block samples of large dimensions and thus, it cannot be considered a calibration chamber. Nevertheless, international calibration chamber experience was taken into account whenever it was adequate, including available studies related to both *CPTu* (Lunne et al., 1997) and *DMT* tests (Huang, 1989; Whittle and Aubeny, 1992; Yu et al., 1992; Finno, 1993; Smith and Houlsby, 1995). CemSoil box can be described as a 1.5m height steel box with a square cross section of 1.0m, with 3mm thick steel walls, reinforced by metal bars placed at 1/3 and 2/3 of its height. Each panel was fixed to the adjacent with a profile of 5 screws (10mm) with 150mm of influence radius. Due to the wall-wall fixation system, in two of the faces this reinforcement system was in contact with the wall by a central 7mm thick H beam (100 × 50mm) placed vertically. This system aimed to reduce horizontal displacements during compaction processes. The inner surfaces (vertical walls and bottom surface) of the cell were covered with a plastic film, in contact with the steel wall, followed by 15mm Styrofoam plates in order to create a gradual transition from the soil to the external frontier.

The experience was based in the development of artificially cemented samples tested both in triaxial cell and in CemSoil Box, where *DMT* blades could be pre-installed and/or pushed-in, aiming to simulate different cementation levels and calibrate specific correlations for deriving strength and stiffness properties. Based on soil-cement mixtures, obtained following the standards or reported procedures for artificial cementation, it was possible to create comparable controlled conditions, namely in curing times, compaction procedures, final unit weights and void ratios, avoiding the undesirable scattering and deviations resulting from sampling and sample variability influences. The whole experience relied upon residual soils from Guarda Granite Formation, which shows patterns of behavior identical to those observed in Porto Granite Formation, where the previous research had been performed. Four different compositions of soil-cement mixtures and one uncemented were prepared to be tested in CemSoil Box, followed by an exhaustive laboratorial program, including uniaxial, tensile and triaxial testing at low to medium confining stresses. Overall, 40 unconfined, diametral

Figure 1. Plant and Cross section of Cemsoil instrumentation.

and triaxial (CID) compressive tests were executed. Uniaxial and tensile strengths were selected to be used as cementation reference indexes. In Table 1, uniaxial and diametral compressive strengths test results are presented. For reference these results are indexed to usual N_{SP} ranges found in Porto and Guarda natural residual soils (Cruz, 2010) corresponding to identical ranges of uniaxial and diametral strengths.

CemSoil block samples ($1.0 \times 1.0 \times 1.5\text{m}^3$) were produced and compacted in homogeneous layers of 70–80mm, aiming to produce similar void ratios in CemSoil and triaxial testing, and thus creating comparable situations. The compaction in CemSoil box was handmade, using a round wood hammer with 40cm diameter. Considering the main goals of the experiment, two *DMT* blades were positioned during the compaction processes, one being placed 20cm above CemSoil base level and the other 25cm below the surface upper level of the cemented soil. Numerical modeling of the *DMT* using the strain path methodology (Whittle & Aubeny, 1992) pointed out some useful indications about the soil volumes that may be influenced by the dilatometer insertion. From this study, it was concluded that effects in the surrounding soil would be negligible at ratios between influenced zone and respective blade thickness higher than 10. Furthermore,

taking the aforementioned studies, it seemed fair to place the pushed-in blade at a distance of 250mm from the lateral and the back panels, since it represents a diameter ratio higher than 10 (at least 17) and leaves a significant soil thickness between expansion membrane and the cell wall placed in its front, guaranteeing the good quality of measurements during expansion.

Meanwhile, two open tube PVC piezometers were installed, one located nearby the water entry and another in the opposite corner, in order to control water level and respective stabilization during the main experiment. In addition, six tensiometers (one profile of six or two profiles of three) and three pairs of geophones to evaluate P and S seismic wave velocities (one profile) were also installed, respectively for suction and seismic wave velocity measurements.

In Figure 1 plant and cross-section of CemSoil box and distribution of measuring equipments is presented. Regular measurements of suction pressures and seismic wave velocities were made for different curing times, before and after saturation phase, which was settled two days before each test. Finally, at each pre-selected testing day, *DMT* measurements of the first and second installed blades were taken, followed

by the second blade testing proceeding pushing-in towards the first blade testing depth (Cruz, 2010).

3. OBTAINED RESULTS

The results obtained in the experimental program led to some important findings and conclusions as presented below (Cruz, 2010).

In the first place, the comparison of pushed-in and pre-installed blades showed that respective penetration generates different disturbance paths in non-cemented and cemented soils. In fact, in non-cemented soils the basic *DMT* parameters (P_0 and P_1) are higher in the case of pushed-in tests, revealing the expected effect of densification around the measurement system, while in cemented soil mixtures the same insertion procedure reduces their values by local destructuration of bonding. Pushed-in *DMT* test results (pre-installed is not feasible in usual practice) obtained in the present experiment revealed that *DMT* intermediate parameters (I_p , E_p , K_p) are the key for the success of its application in residual soils. In fact, it was observed that *DMT* basic (P_0 and P_1) and intermediate parameters are sensitive to the variations of strength and stiffness behaviors due to both cementation and suction, giving credibility to the calibration work. Moreover, the obtained ranges in the selected mixtures for the experiment were coherent with those obtained *in-situ* on the natural ground of Guarda Granitic Formation, from where those mixtures were composed.

From the identification and physical points of view, the evaluation of soil type was very accurate when compared with Triangular Classification based in grain size analysis and the unit weights obtained by I_p and E_p (Marchetti & Crapps, 1981) represented well those of remolding.

Concerning to strength analysis, the key parameter is a virtual overconsolidation ratio ($vOCR$) calculated by the same expressions proposed by Marchetti & Crapps (1981) for sedimentary soils, which is dependent on K_p and I_p , as previously observed by Cruz et al. (2004b) and Cruz & Viana da Fonseca (2006). During the main experiment it was observed that K_p was influenced by both suction and cementation magnitudes. Being so, based in $vOCR$, it was possible to establish calibrated correlations for deriving a global cohesive intercept ($c'g$) generated by the combination of cementation and suction. In fact, once suction effects on strength and stiffness seem to be adequately represented by *DMT* testing, the methodology developed for a global cohesion intercept evaluation integrates the suction component, whenever it is present. In addition, a special procedure to separate cementation and suction contributions could also be proposed, using the result obtained below water table (where suction is

not present) as reference, which is then subtract to the global results obtained above the water level. The calculated differences are due to suction effects represented by the second term of Fredlund et al. (1978) strength criteria (with suction, $u_a - u_w$, multiplied by the tangent of angle of shearing due to suction, ϕ_b). If ϕ_b is not available a value of 15° was found to be reasonable, since it has been proven that a variation of $\pm 5^\circ$ on the referred parameter doesn't introduce significative deviation, as reported by Cruz (2010). The experiment also showed that angles of shearing resistance could be derived by the sedimentary approach proposed by Marchetti (1997) followed by the application of a correction factor based in the magnitude of $c'g$ (or $vOCR$).

On the other hand, *DMT* stiffness evaluation in residual soils proved to be as accurate as in sedimentary case, either in the case of constrained modulus, M , (or Young modulus derived from simple Elasticity Theory relations — $E = 0.8M$ — when Poisson coefficient is taken equal to 0.3) or in the case of small strain shear modulus (G_0). Concerning to Constrained Modulus, the general correlations (Marchetti, 1980) applied to sedimentary soils also fits in these soils which is a direct consequence of the sensitivity shown by intermediate parameters (included in the basic correlation) to both suction and cementation. It is important to mention that indexation of the dilatometer modulus to typical strain was also achieved in this calibration experiment, which showed that E_p results correspond to triaxial secant young modulus determined within 10^{-3} to 10^{-4} of axial strain (Cruz, 2010). As for small strain shear modulus, correlations proposed by Cruz & Viana da Fonseca (2006), $G_0/E_p = f(I_p)$, were confirmed by the experiment, which was not a surprise since they had been calibrated by seismic wave velocities, and so not affected by sampling or penetration disturbances. In Table 2 correlations calibrated by this experiment are presented.

To check the adequacy of these calibrated correlations a specific *DMT* survey was performed *in-situ* in Guarda granitic natural soils (in the same location from where soils for the calibration experiment were taken). The data derived through the mentioned correlations were then compared with reference Cross-hole (*CH*) and triaxial test results. The respective comparisons are presented in Figure 2, which clearly reveals the adequacy of correlations. In fact, global cohesion intercept, angles of shearing resistance and small-strain shear modulus converge to reference data. In the case of global cohesion it is important to observe the decrease of magnitude from surface towards water level, which remains stable after that depth, illustrating the efficiency of *DMT* in detecting suction influence.

Table 2. Correlations for deriving geotechnical parameters in Porto and Guarda Granite Formations.

Parameter	Equation	Reference	Remarks
Stratigraphy	Material Index, I_p	Marchetti [10]	Accurate when pushed in. The division in silty sand/sandy silt reflects real grain size distribution
Global cohesion intercept, c'_s	$c'_s = 7.716 \ln(OCR) + 3.53$	Cruz [1]	Includes suction effects, above phreatic level. M/q_t should provide similar accuracy
Effective angle of shearing resistance, ϕ'_{corr}	$\phi'_{corr} = \phi'_{DMT} - 2.48 \ln(c'_s) - 3.12 \phi'_{DMT}$ obtained by Marchetti (1997) correlation	Cruz [1]	Correction of effects of suction, which are present together with effective components, above phreatic level
Service stiffness, E, M	$E = 0.8 M$ M calculated by Marchetti (1980) correlation	Marchetti [10]	Corresponds to strain levels ranging from 10-3 to 10-4 in reference to conventional axial strain
Dynamic stiffness, G_0	$G_0 / E_0 = 9.771 I_p^{-1.053}$	Cruz & Viana da Fonseca [6] Cruz [1]	Correlation calibrated by seismic CH data and confirmed by the present research results

Figure 2. Comparisons of derived DMT data with reference tests.

4. CONCLUSIONS

A calibration experiment based in large block samples ($1.0 \times 1.0 \times 1.5 \text{ m}^3$) and triaxial testing was performed aiming to derive geotechnical parameters from DMT tests. Specific calibrated correlations were established for the evaluation of cohesion intercept, angle of shearing resistance, service stiffness and small strain shear modulus. A special procedure

to differentiate suction from cementation contributions was also settled. *In-situ* results obtained in natural residual granitic massif were used to check the adequacy of final correlations, revealing significant convergence. As a consequence, it was found that these correlations are representative in Porto and Guarda granitic formations and can constitute a reference base for developing specific correlations related

to other residual soils of different nature or other difficult geomaterials.

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