Behaviour of Portuguese granitic residual soils represented in DMT and CPTu soil behaviour type (SBT) charts

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ABSTRACT: Residual soil in-situ characterization implies specific interpretation methodologies, different from those established for sedimentary soils that are the base for the most common interpretations. The reason for that is related with the presence of a cementation structure inherited from the parent rock that strongly influences mechanical behaviour. The application to residual soils of sedimentary based approaches, leads frequently to unrealistic results, thus being important to check their validities. In this context, Soil Behaviour Type (SBT) charts based in in-situ tests can represent a useful tool in the required differentiation, as well as in the construction of specific approaches to work with residual soils. The present work focus on the efficiencies and misinterpretations of the available charts to detect and foresee the cementation intensity of these soils, based on the significant (S)DMT and (S)CPTu data from Portuguese granitic spots, consolidated in several research programs.

Keywords: Residual soils; SDMT tests; SCPTu tests; Soil Behaviour Type charts

1. Introduction

The interpretation of in-situ tests in residual soils is usually complex since the established methodologies used worldwide are primarily directed to characterize sedimentary transported soils. In most part of the cases, direct applications of the methodologies used in sedimentary transported soils lead to erroneous interpretations, due to the presence of a cohesive intercept that arises from cementation micro-structure [1, 2, 3]. In granular soils, such as the residual soils from granites, cementation creates a second strength parameter that is not consider in the common in-situ test interpretation methodologies dedicated to sedimentary soils, namely the cohesive intercept, and the angle of shearing resistance is over predicted, because it incorporates the cementation influence [4]. This deviation is globally recognized by the scientific community and it is present in the interpretations of all the in-situ tests more commonly used. To solve the problem adequately, friction and cohesion have to be individualized, therefore multi-parameter tests are required. (S)DMT, (S)CPTu and PMT tests can be considered for these purposes, while SPT and dynamic probing (DPs) have to be discarded.

As a consequence of these considerations, it becomes unavoidable both the need to identify whether a cementation micro-structure is or is not present and the consequent development of specific interpretation methodologies that can represent independently the cohesive and friction contributions. In the first case, soil behaviour type charts (SBT) such as those commonly used with CPTu tests, are certainly a very useful tool to sign the presence of cementation structures and identifying some related behaviors. Some attempts have been made to establish specific methodologies dedicated to residual soils, but a global interpretation methodology dedicated to all types of residual soils is far from being achieved. The main attempts have been concentrated in the granitic residual soils due to their presence all around the globe and a certain similarity of their weathering paths. In Portugal, the Porto and Guarda granites have been intensively studied for this purpose and specific correlations based in DMT and CPTu data have been recently purposed [3, 5].

2. DMT and CPTu Calibration frameworks

The residual soils arising from Porto and Guarda granitic formations are very alike and result from the mechanical and chemical weathering. An initial grain dismantling occurs, increasing the level of water penetration inside the rock mass, followed by the hydrolysis of potassium and sodium feldspars that will generate kaolinite clay. Some basic properties of these soils are presented in Table 1, as collected in the Porto Geotechnical Map [6] as well as in published data of Porto and Guarda granites [3, 7]. In that table, data is divided according the common geotechnical horizons that are present in Porto and Guarda massifs, identified acording to the N_{SPT} reference index. It is important to stress that cohesion intervals presented in that table are expected to be lower than the reality, due to the disturbance arising from sampling that partially destroys the cementation structure. On the other hand, in Tables 2 and 3 the DMT and CPTu parameter ranges are also presented, due to its interest in the present context.

Table 1. Reference geotechnical parameters

N_{SPT}	ASTM Classif.	γ (kN/m³)	k (m/s)	c' (kPa)	ϕ' (º)
10-30	SM-SC	17-19	10^{-6}-10^{-7}	5-30	33-37
30-60	SM	18-20	10^{-6}-10^{-7}	10-40	35-38

Table 2. Basic and intermediate DMT parameters

N_{SPT}	P_0 (MPa)	P_1 (MPa)	I_D	K_D	E_D (MPa)
10-30	0.3-1.0	1.0-2.5	1.0-3.0	15-25	25-75
30-60	1.0-2.5	2.0-5.0	1.0-3.5	10-40	60-120

Table 3. Basic and normalized CPTu parameters

N_{SPT}	q_t (MPa)	f_s (kPa)	Q_{Tn}	F_R (%)	B_q
10-30	5-15	100-250	250-500	1.5-2.2	0.0-0.5
30-60	15-25	250-500	300-500	1.5-3.0	-0.5-0.0

where:
N_{SPT} is the blowcount of standard penetration test (SPT);
γ is the unit weight;
k is the coeficient of permeability;
c‘ is the effective cohesive intercept;
ϕ' is the effective angle of shearing resistance;
P_0 and P_1 are the dilatometer corrected pressures;
I_D is the dilatometer material index;
E_D is the dilatometer modulus;
K_D is the dilatometer horizontal stress index;
q_t is the CPT corrected cone resistance;
f_s is the CPT side friction;
Q_{Tn} is the CPT normalized cone resistance;
F_R is the CPT normalized friction ratio;
B_q is the CPTu pore pressure index.

Based in important facilities and equipments available in Instituto Politécnico da Guarda (IPG) a long framework was established aiming the development of specific correlations that could represent these soils in routine analysis.

2.1. IPG 1, calibration of DMT tests

After a deep characterization of the granitic massif located within the IPG campus [2], an experimental framework based in artificially cemented soils was settled, to avoid sampling disturbance and micro-fabric heterogeneities that would generate dificulties in comparing situations, namely the magnitude of cohesion. This framework is designated by IPG 1 in the course of this document.

The research frame consisted in the construction of artificially cemented mixtures in a large calibration chamber where it was possible to perform DMT tests, controlled by triaxial test results performed in artificial mixtures remoulded exactly in the same conditions of void ratios and curing periods. With this procedure, sampling and fabric variations were avoided and so, DMT and triaxial tests reflect the same strength behaviour. The result of this research was a set of correlations established to obtain the cohesive intercept and the angle of shearing resistance [3] represented by the following equations:

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

$$\emptyset_{corr} = \emptyset_{sed} - 3.45\ln(vOCR) + 5.44 \quad (2)$$

where:
c'_g is the global cohesion (cementation + suction), kPa;
$vOCR$ is the virtual overconsolidation derived from [8];
ϕ_{corr} is the corrected angle of shear resistance, degrees;
ϕ_{sed} is angle of shear resistance derived from sedimentary approach [9], degrees.

The obtained correlations were then applied in the local massif from where the artificial cemented samples were reconstituted, checking the adequacy of the correlations applicability in the local natural ground, followed by a correlations testing phase in Porto granitic formation where DMT, CPTu and triaxial tests are available [10] and well referenced within the Porto Geotechncial Map, a very important document that gathers characterization results of these soils in campaigns performed within the city limits. The result is a validated substantial database applied in different granitic formations and different weathering degrees, which became a very useful tool to other research works on the in situ characterization of these materials.

2.2. IPG 2, calibration of SCPTu tests

The successful work with the DMT calibration opened the door to implement identical frameworks dedicated to piezocone (CPTu) and pressuremeter (PMT) tests. Therefore, a new testing program was carried out, consisting of six sets of SDMT, SCPTu and PMT tests, as well as boreholes and sampling for triaxial tests, placed along a straight line in the same natural massif of Guarda residual soils used in the DMT calibration. This framework is designated by IPG 2 in the course of this document.

The SDMT tests allowed measuring regularly shear wave velocities with depth, scarcely available in the previous investigation phases. The obtained results show that the two previously referred geotechnical units (Tables 1 to 3) can be respectively represented by intervals of 170 to 300 m/s and 250 to 400 m/s.

Taking advantage of the well-known interchangeability, DMT tests were then used to calibrate CPTu data, avoiding the long and complex work based in the calibration chamber and obtaining a much higher volume of data, adequate for statistical analysis. In order to have good convergence of results, DMT and CPTu tests were carried out within 1m. The acquired CPTu and DMT data allowed to define a set of correlations to derive independently cohesive intercept and angles of shearing resistance, represented by the following equations:

$$c'_g = 12.8\ln(Q_{Tn}) + 1.6\ln(F_R) - 32.2 \quad (3)$$

$$\emptyset_{corr} = \emptyset_{sed} - 5.27\ln(Q_{T1}) - 0{,}99\ln(F_{R)} + 19.71 \quad (4)$$

where:
c'_g is the global cohesion (cementation + suction), kPa;
Q_{Tn} and F_R are normalized CPTu parameters
ϕ_{corr} is the corrected angle of shear resistance, degrees;
ϕ_{sed} is angle of shear resistance derived from sedimentary approaches, degrees.

Using the same procedure followed with DMT validation, the correlations were then tested in the Porto Granites, using 8 local experimental sites where pairs of DMT and CPTu tests were available [5]. Once again, the Porto Geotechnical Map [6] data was used.

As a consequence of these two calibration frameworks, a significant amount data about the residual soil behaviour is now available, namely in what concerns to the cohesion magnitude and angles of shearing resistance and their variation in depth, involving in situ (DMT, CPTu, PMT) and laboratorial (triaxial and oedometer test) results. In the following sections, this will be discussed in terms of the global behaviour that can be perceived when using identification and soil behaviour charts based in (S)DMT and (S)CPTu tests.

3. Detecting cementation structures

The observed differences between behaviours of residual and sedimentary soils generate the need for different methodologies of interpretation and procedures to check if the cementation structure is present or not. Several diagrams for this purpose have been proposed, based in seismic shear velocities versus SPT [11], CPTu [11, 12] and DMT [3, 13]tests. In the present case, SCPTu [12] and SDMT [13] proposals were selected to evaluate the presence of the cementation structure.

Robertson proposal using SCPTu data is based in the plot of normalized cone resistance, Q_{Tn}, and the small strain rigidity index, I_G, defined as the ratio between the shear modulus (G_0) and the net cone resistance (q_n). The modified small strain rigidity index, K^*_G, of that chart can be calculated by:

$$K^*_G = \frac{G_0}{q_n}(Q_{Tn})^{0{,}75} \tag{5}$$

where
K^*_G is the modified small strain rigidity index;
G_0 is the small strain shear modulus, MPa;
q_n is the CPTu net cone resistance, MPa;
Q_{Tn} is the normalized cone resistance.

In the case of DMT data, the ratio between small strain shear modulus, G_0, and the DMT constrained modulus, M_{DMT}, plotted against the horizontal stress index, K_D, was used before with good results in Porto and Guarda residual soils [13], thus used again in the actual framework. The new data allowed to re-define the sedimentary/residual bound, since the actual data widen the K_D range and leading to a more sustainable analysis (Fig. 2). The equation defining the border line is expressed by:

$$\frac{G_0}{M_{DMT}} = 10 K_D^{-1} \tag{6}$$

where M_{DMT} is the constrained modulus derived from DMT, MPa.

The results obtained in the six SCPTu tests performed in the IPG 2 experimental site are presented in Fig. 1, while Fig. 2 includes results obtained in IPG 1, IPG 2 and Porto granites. In this latter, comparable situations obtained in sedimentary soils are also presented.
The positive answer given by both methodologies detecting the cementation structure that is known to be there is quite clear, revealing that this approaches could be used to select the adequate interpretation methodology in routine analysis.

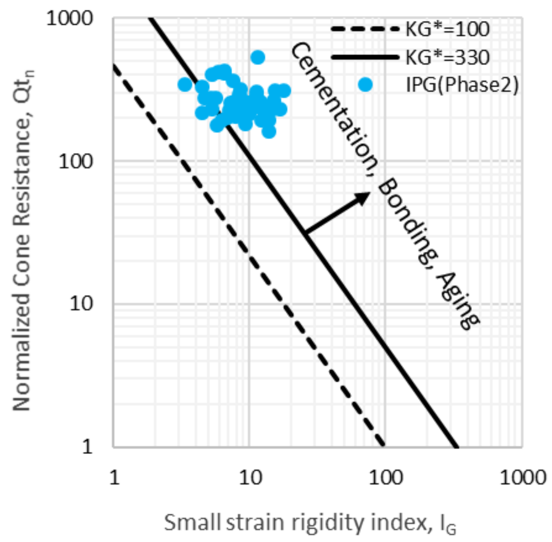


Figure 1. CPTu data of IPG 2 represented in $Q_{tn} - I_G$ space [12].

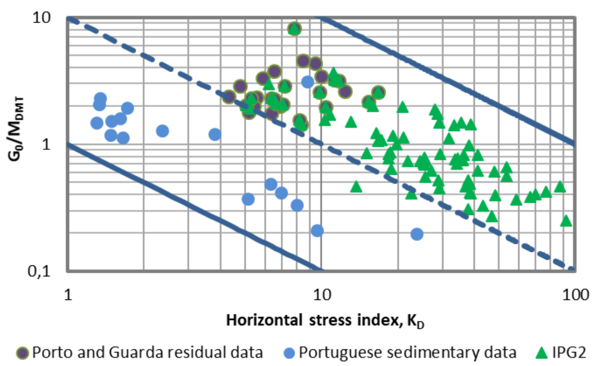


Figure 2. Porto and Guarda residual data represented in G_0/M_{DMT} vs K_D diagram [13].

4. Representation of residual soils in Soil Behaviour Type (SBT) charts

4.1. SCPTu Charts

Soil behaviour type (SBT) charts, such those commonly used in CPTu tests, are widely recognized as a very efficient tool to anticipate the behaviour of soils in practical contexts of engineering design and construction. Several diagrams have been proposed since the earlier times of mechanical cones. Actually, with electrical piezocones, the mostly used normalized diagrams are those proposed by [14, 15], and the more recent diagram introduced by [12] that identifies not only the type of soil, but also whether its behavior in shear is dilative or contractive. Robertson's diagrams [12, 14] are based in the normalized cone resistance (Q_{Tn}), the normalized friction ratio (F_R) and the pore pressure index (B_q) normalized parameters while Schneider's diagram is written in terms of normalized cone resistance (Q_{T1}) and the excess of pore pressure (u_2) normalized by the effective vertical stress. Fig. 3 and Fig.4 [14], Fig. 5 [12] and Fig. 6 [15] show the whole dataset of Porto and Guarda granitic residual soils plotted in correspondent diagrams. Global cohesion contours derived from Eq. 3 are also represented in Fig. 3 and Fig. 5.

Starting from Robertson chart [14], the data globally falls within zones 4, 5 and 6 (clayey silts to clean sands), but also reaches the zone 3 (clay to silty clay) in the case of Porto granites. The same data plotted in Robertson's chart [12] is identified as sand-like or clay-like with dilatant behaviour. The clay-like identification in both charts is a deviation from the behaviour of these soils, which are mostly non-plastic silty sands to sandy silts (SM, according to ASTM Unified Classification [16]), rarely clayey sands (SC) with plasticity index, IP, lower than 10% and the in-situ permeability typically falling within 10^{-6} to 10^{-7} m/s [3, 13].

These deviations could be related to a lower efficiency level when applied to soils with micro-strucuture, as referred by [12], but it is also possible that the lower depth interval of readings (every 1cm that contrasts with the 20cm interval of DMT tests) may be able to catch the materials in the close vicinity of the ancient joints, whose weathering degree is higher, therefore more clayey [5]. The identified dilative behaviour in shear is in accordance with the results of triaxial testing (with internal strain measurement) obtained for the same levels of local confining stresses [3].

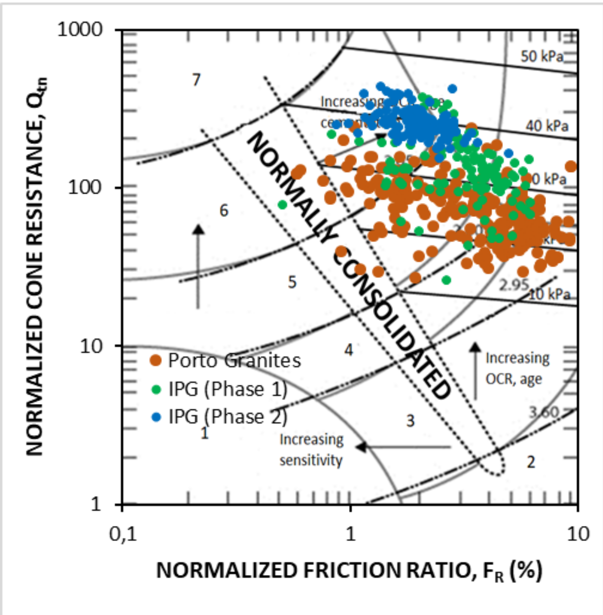


Figure 3. Representation of residual data on $Q_{Tn} - F_R$ chart [14].

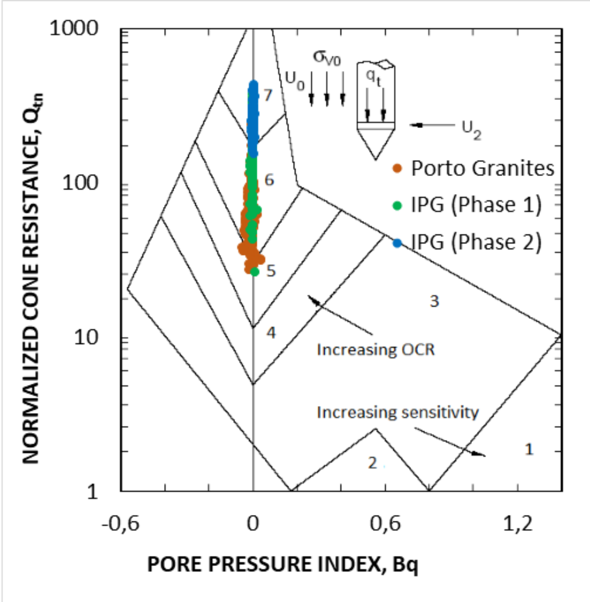
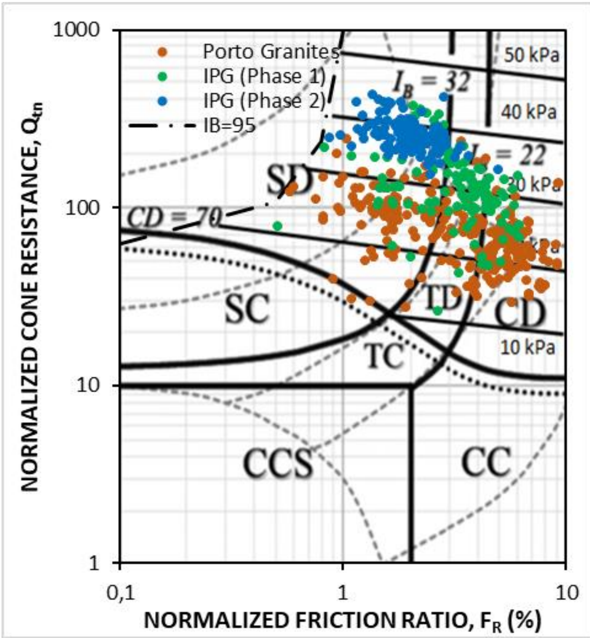


Figure 4. Representation of data on $Q_{Tn} - B_q$ chart [14].



CCS – Clay-like Contractive, Sensitive; CC – Clay-like Contractive; CD – Clay-like Dilative; TC – Transitional Contractive; TD – Transitional Dilative; SC – Sand-like Contractive; SD – Sand-like Dilative

Figure 5. Representation of residual data on $Q_{tn} - F_R$ chart [12].

On its turn, both Robertson's classifications allow to represent cohesion contours (Fig. 3 and Fig. 5), once the chart and correlation are based in the same variables. The data distribution in these graphs locates the soils in the overconsolidated side, which roughly corresponds to dilative side of Robertson's chart [12]. The increase in cohesion (cementation and/or suction) magnitude moves them towards the groups 8 and 9 [14], roughly following the curves shape of the modified soil behaviour index (I_B) represented in the 2016 Robertson chart [5].

Finally, the identification using the chart of Fig. 6 [15] points out to essentially drained soils, converging to the known behaviour of these soils.

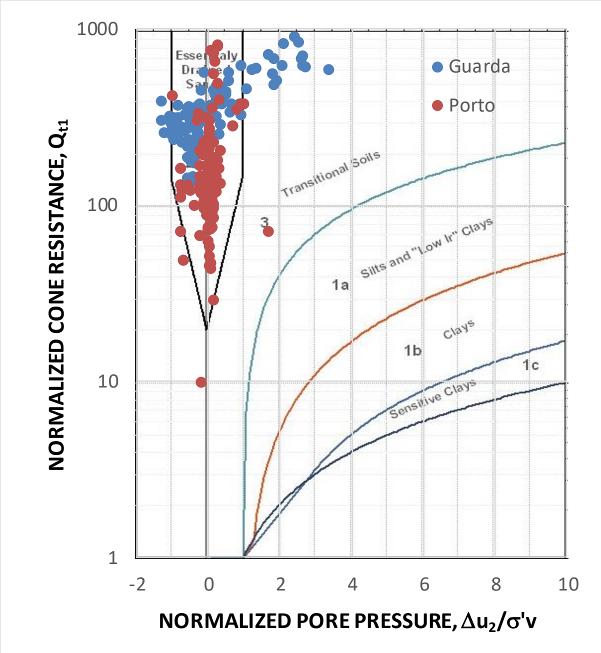
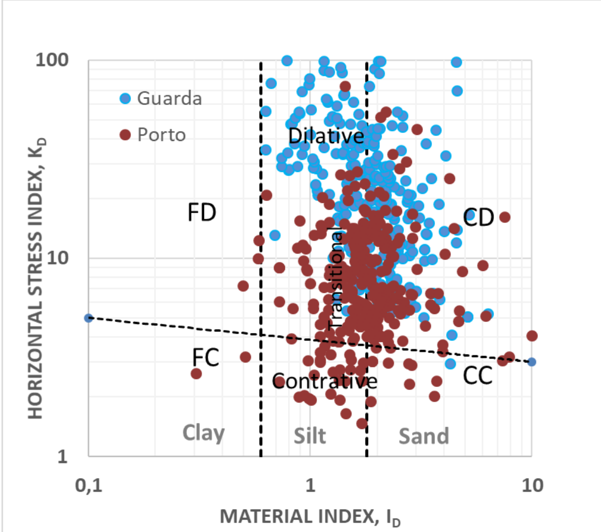


Figure 6. Representation of residual data on $Q_{tn} - \Delta u_2/\sigma'_v$ chart [15].



CD – Coarse-grained Dilative (mostly drained)
CC – Coarse-grained Contractive (mostly drained)
FD – Fine-grained Dilative (mostly undrained)
FC – Fine-grained Contractive (mostly undrained)

Figure 8. Residual data in K_D vs I_D chart [17].

4.2. SDMT charts

Concerning to DMT tests it is not common to represented data in Soil Behaviour Type charts, but only identification profiles of Material index (I_D) with depth. However, considering the usefulness of the CPTu SBTn charts to anticipate fundamental behaviours, [17] proposed a set of diagrams for soils with little or no micro-structure that could be derived from DMT results. The fundamental diagrams are mostly based in the horizontal stress index, K_D, plotted against the material index, I_D, which incorporates normalized stiffness contours (E_D, M_{DMT} and/or G_0 normalized by vertical effective stress, as presented in Fig. 7), or zones identifying the behaviour in shear (Fig. 8). The limit line dividing dilative from contractive behaviours in Figure 8 was developed departing from the CPTu soil behavior type diagram previously presented in Figure 5 [12].

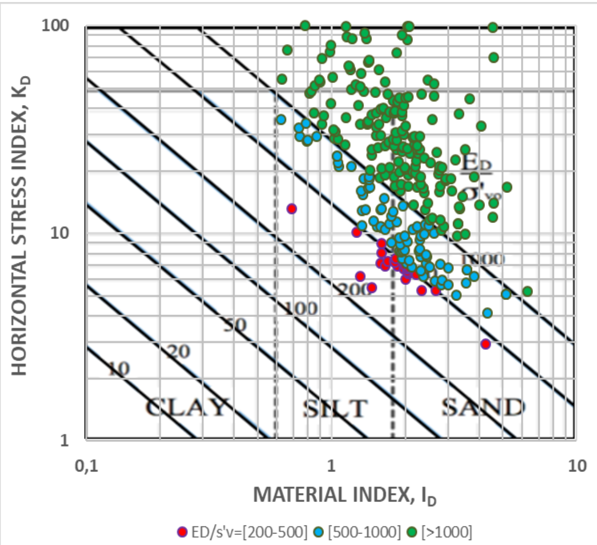


Figure 7. Residual data in K_D vs I_D chart with E_D/σ'_v contours [17].

In these two referred diagrams, the type of soils are represented by I_D as silty to sandy soils, matching the true grain size distribution and the correspondent drained behaviour well recognized in these soils.

On its turn, in Fig. 9 classes of similar cohesive magnitudes, obtained through Eq. 1, are represented in the same I_D-K_D diagram [18], clearly showing its adequacy to incorporate cohesive contours for I_D values lower than 3.3, while above this value the representation shows deviation from the observed trend. This might be explained by the I_D values higher than 3.3 (represented by the dashed line in the right hand side of the plot), since they represent clean sands, where the expected very low fine contents should generate much more unstable cementation structure. Therefore, the representation of clean sands in this diagram should be looked with care.

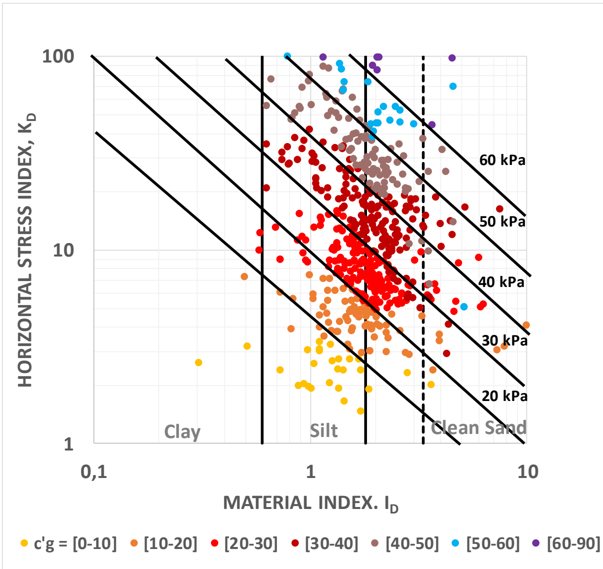


Figure 9. Representation of cohesion contours in K_D vs I_D chart.

Robertson [17] also proposed the same I_D versus K_D chart (Fig. 10) to incorporate contours of an equivalent

Q_{T1} CPTu normalized parameter, in order to increase possibilities for interchangeability of both tests. These contours that were established for sedimentary data, show poor convergence in the case of the studied granitic residual soils.

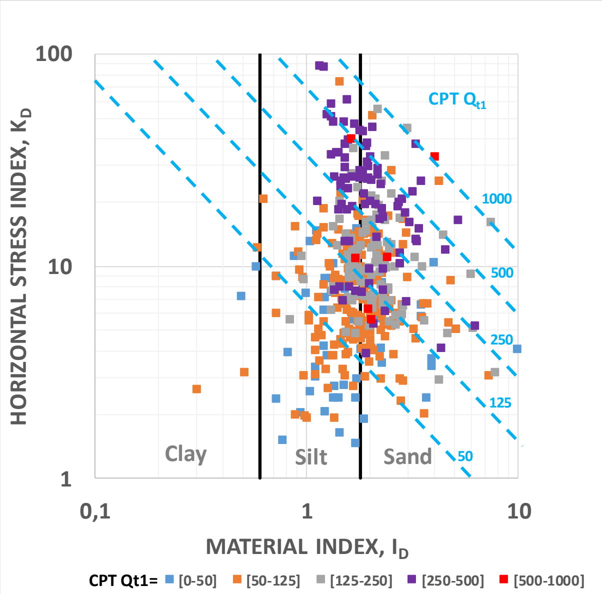


Figure 10. Representation of residual data in K_D vs I_D chart with Q_{T1} contours [17].

5. Conclusions

The work presented herein gathered a significant amount of data related to DMT and SCPTu tests performed in residual soils. The data was obtained in two calibration frameworks dedicated to the interpretation of residual soils with those in-situ tests. Both tests showed efficiency to detect the presence of the cementation structures present in these granitic massifs. Their regular application for discerning sedimentary from residual soils can constitute an important analysis tool to select adequate methodologies of interpretation in routine analysis.

On the other hand, the mechanical behaviour of these soils was also successfully anticipated by the Soil Behaviour Type (SBT) charts commonly used in sedimentary soils with SCPTu data, as well as the recently proposed for SDMT. Moreover, contours of cohesive magnitude could be defined and added to those charts, increasing the usefulness of these tools to foresee the strength behaviour of residual soils. The sustainability of the obtained responses seems very promising showing potential enough to be tested in other environments and other residual soils different from granites.

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