Comparison of soil properties obtained from CPT and DMT in-situ tests

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ABSTRACT: The piezocone penetration test (CPT) and flat dilatometer test (DMT) are routinely used in geotechnical practice and are both considered adequate for detailing of soil profile and determination of soil properties. In the paper, results of ground characterization and evaluation of soil properties will be compared based on the combined use of CPT and DMT at different locations, each with different ground composition. Evaluation of both tests in terms of soil type, undrained shear strength, constrained modulus and friction angle are presented and results are compared. The main objective is to show that companion sets of CPT and DMT at a given site could be used to better define the geotechnical ground model and to increase confidence in the derived soil properties.

Keywords: in-situ tests, CPT, DMT, soil properties

1. Introduction

The piezocone penetration test (CPT) and Marchetti flat dilatometer test (DMT) are frequently used in site characterization and determination of soil properties. Often the CPT and DMT tests are combined in order to increase the reliability of stratigraphy delineation and determination of soil properties. Although many consider each of these in-situ tests to be adequate by themselves, the results should generally be confirmed by laboratory geotechnical investigations.

The standard piezocone test CPT is a strength related test, which provides cone tip resistance q_t, sleeve friction f_s and pore water pressure u_2 just above the cone tip along the CPT probe. Contrary to the CPT test, the DMT test is more stiffness than strength related, as it is based on two distinctive pressure readings taken at the start of dilatometer membrane inflation and upon reaching 1.1 mm of movement against the soil in the membrane center. According to Eurocode 7 [1], CPT and DMT should be mainly used for the determination of soil profile. Neither of them measures mechanical properties of soils directly, but they can be derived based on theoretical or empirical correlations with different degree of accuracy.

Herein, some contiguous results of CPT and DMT results in different soil conditions at 7 locations are presented and compared in order to check the validity of established empirical relationships in determining the basic soil properties, such as soil classification based on material index I_D, undrained shear strength c_u, constrained modulus M and friction angle of soils φ'.

Additionally, the validity of CPT-DMT correlations as proposed by Robertson [14] was verified on the collected data.

2. Evaluation of soil properties from CPT and DMT

2.1. CPT

The CPT tests were carried out according to EN ISO 22476-1 [2]. Cone resistance q_c, sleeve friction f_s, and pore pressure u_2 were recorded continuously and then used for the determination of geotechnical properties as follows:

Undrained shear strength c_u for fine grained soils [15]:

$$c_u = \frac{q_t - \sigma_v}{N_{kt}} \tag{1}$$

where q_t is corrected cone resistance, σ_v initial vertical stress and N_{kt} empirical constant typically between 10 and 18 [15].

Friction angle φ' for coarse grained soils [12]:

$$\tan\varphi' = \frac{1}{2.68}\left(\log\left(\frac{q_c}{\sigma_v - u}\right) + 0.29\right) \tag{2}$$

where u is initial pore pressure.

Friction angle φ' for fine grained soils [10]:

$$\varphi' = 29.5° \cdot B_q^{0.121}(0.256 + 0.366\, B_q + \log Q_t) \tag{3}$$

where B_q is pore pressure ratio $(u_2 - u)/(q_t - \sigma_v)$ and Q_t is normalised cone resistance $(q_t - \sigma_v)/(\sigma_v - u)$.

Constrained modulus M [13]:

$$M = \begin{cases} (q_t - \sigma_v) \cdot \min(Q_t, 14) & I_c \geq 2.2 \\ 0.0188(q_t - \sigma_v) \cdot 10^{0.55 I_c + 1.68} & I_c < 2.2 \end{cases} \tag{4}$$

where I_c is soil behaviour type index:

$$\mathrm{I_c} = ((3.47 - \log \mathrm{Q_t})^2 + (\log \mathrm{F_r} + 1.22)^2)^{0.5} \tag{5}$$

and F_r is normalised friction ratio $f_s/(q_t - \sigma_v) \cdot 100\%$.

2.2. DMT

The DMT tests were carried out according to ISO/TS 22476-11 [3] using the Marchetti flat dilatometer [6]. A dilatometer blade was pushed into the soil with a penetration rate of 2 cm/s. Measurements were made in 20 cm intervals. Once at the testing depth, a circular steel membrane was expanded horizontally into the soil. Two pressures were measured: pressure A, which is required just to begin moving the membrane against the soil, has to be achieved within 20 s from the start of the test, and pressure B, which is required to expand the center of the membrane by 1.1 mm into the soil, within 20 s from the measurement of pressure A. Upon correction of the recorded pressures A and B due to the membrane stiffness, material index I_D, horizontal stress index K_D, and dilatometer modulus E_D were calculated in order to determine geotechnical properties as follows:

Undrained shear strength c_u for fine grained soils [6]:

$$c_u = 0.22\sigma_v' \cdot (0.5K_D)^{1.25} \tag{6}$$

Safe estimate of friction angle φ' for sands [7]:

$$\varphi' = 28° + 14.6° \log K_D - 2.1°(\log K_D)^2 \tag{7}$$

Constrained modulus M [6]:

$$M = R_M \cdot E_D \tag{8}$$

where R_M is defined as:

$$R_M = \begin{cases} 0.14 + 2.36 \log K_D & \text{if } I_D \leq 0.6 \\ R_{M,0} + \left(2.5 - R_{M,0}\right) \log K_D & \text{if } 0.6 < I_D < 3 \\ 0.5 + 2 \log K_D & \text{if } I_D \geq 3 \\ 0.32 + 2.18 \log K_D & \text{if } K_D > 10 \\ \geq\ 0.85 & \end{cases} \tag{9}$$

where $R_{M,0} = 0.14 + 0.15(I_D - 0.6)$.

2.3. CPT-DMT correlations

Although the CPT and DMT tests have been used extensively for over 40 years, relatively little has been published regarding comprehensive correlations between the two in-situ tests. Preliminary correlations between the main parameters of CPT and DMT have been investigated by Mayne [11] and Robertson [14], who proposed a preliminary set of correlations that link normalized CPT parameters (I_c and Q_t) with primary DMT parameters (I_D, K_D and E_D), as given by Eqs. 10, 11 and 12.

$$I_{D\_CPT} = 10^{1.67 - 0.67 I_c} \tag{10}$$

$$K_{D\_CPT} = \begin{cases} 0.3\ (Q_t)^{0.95} + 1.05 & I_c > 2.6 \\ \frac{0.144\mathrm{Q_t}}{I_{D\_CPT}} & else \end{cases} \tag{11}$$

$$E_{D\_CPT} = 34.7 I_{D\_CPT} \cdot K_{D\_CPT} \cdot \sigma_v' \tag{12}$$

Such correlations are not only useful to recognize analogies and diversities between both tests, but can also be used to improve correlations and applications by comparison and extrapolation from one test to the other [9]. Throughout the paper, Eq. 10 was used to compare the CPT soil behavior type classification with the DMT soil classification in order to observe if both test methods give the same soil classification.

3. Experimental results

In the following sections, the results of DMT and CPT investigations are presented and compared. They were performed at five locations in Slovenia, one in Albania and one in Austria. At each location, pairs of CPT and DMT investigations were performed at close spacing in order to avoid the spatial variability of ground conditions. The list of locations with the number of CPT-DMT pairs and total number of CPT and DMT results considered in the analysis is shown in Table 1.

Table 1. List of investigations

Location	Country	Number of DMT-CPT pairs	Number of results compared
Brežice	Slovenia	3	47
Jesih štradon	Slovenia	2	121
Port of Koper	Slovenia	3	353
Porto Romano	Albania	1	90
Rižana valley	Slovenia	14	440
Srmin	Slovenia	2	89
St. Kanzian	Austria	1	71
	Total:	**26**	**1211**

Part of the detailed results obtained in Port of Koper, Porto Romano, Rižana valley and St. Kanzian were recently presented in a previous study [5], where only results for one representative pair of CPT and DMT results at each location was considered in the final analysis. Herein, only the comparative CPT and DMT results for Brežice, Jesih štradon and Srmin will be given in detail with a brief description of ground conditions at specific locations. All collected data are considered in the final comparisons in discussion section.

3.1. Brežice

The first location is near Brežice (Slovenia), situated on the banks of river Sava. The presented site investigations were conducted for the construction of dykes along the reservoir for the hydropower plant Brežice. The ground consists of silty sand to sandy silt on the top and is up to 6 m thick. This layer was of primary interest mainly due to its susceptibility to liquefaction. Beneath silty sand, the gravel layer is found, which is underlain by soft marl rock.

Fig. 1 shows the comparison of the CPT and DMT results in terms of material index I_D, undrained shear strength c_u, constrained modulus M and friction angle φ' for CPT and DMT tests. Material index I_D, as obtained from DMT and converted from CPT I_c [14], gives relatively good estimate of the basic soil type and allows for the determination of typical soil layers.

Due to the nature of soils at the location, the results for the undrained shear strength c_u are not relevant. Nevertheless, CPT test was able to detect some thin layers of clayey silts as opposed to DMT.

In terms of constrained (oedometer) modulus M, DMT predicts lower values than CPT and presumably more in-line with the laboratory results. The predicted constrained moduli derived from CPT are generally larger than those obtained from DMT values, although a similar trend with depth can be observed. Because of the different orientation of soil testing and different spacing between two consecutive readings (20 cm compared to 2 cm for DMT and CPT, respectively), the DMT and CPT test methods capture rapid changes in soil stratigraphy differently.

The CPT and DMT predictions of peak friction angle for silts and silty sands agree well and are in-line with common values for silty sands.

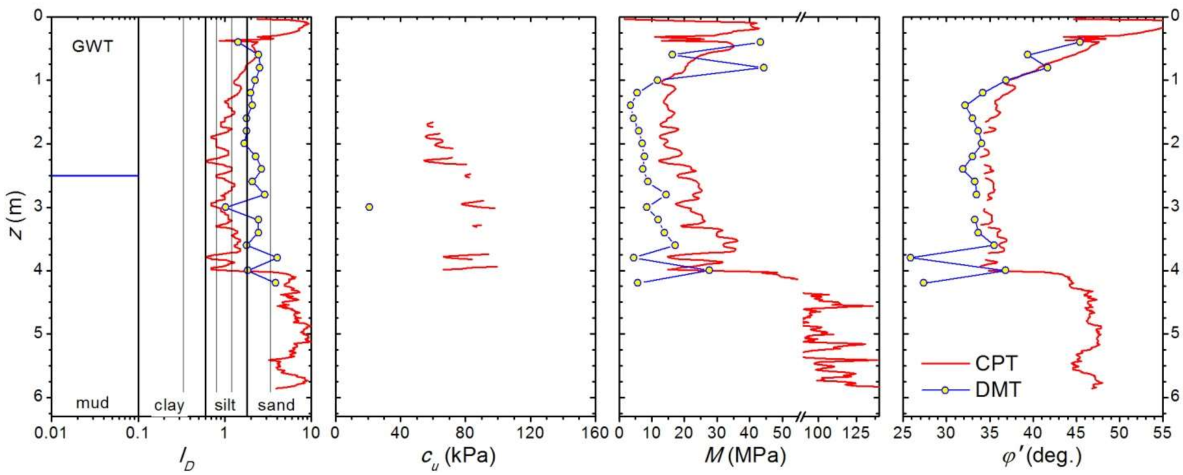

Figure 1. Comparison of CPT and DMT results at Brežice

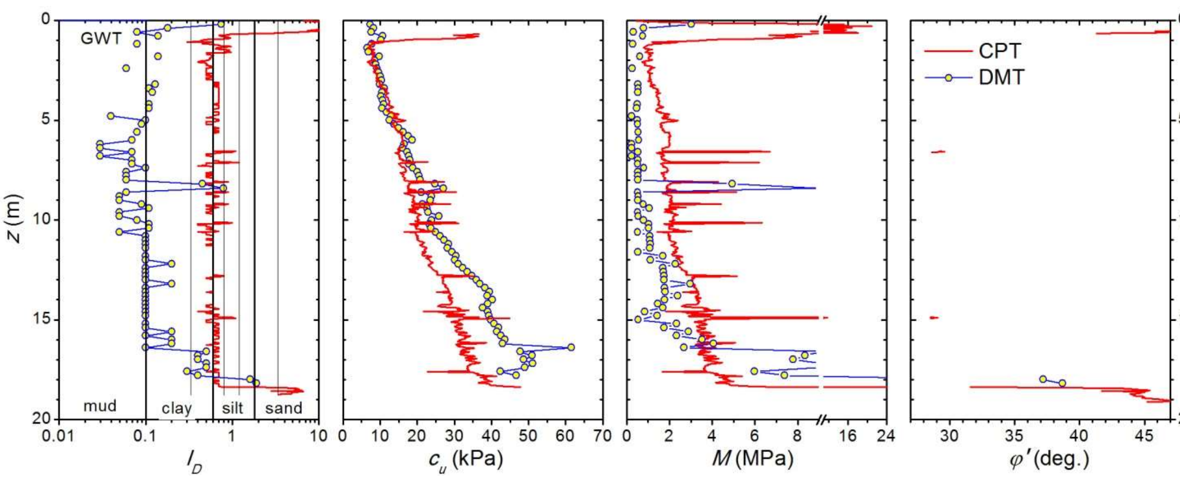

Figure 2. Comparison of CPT and DMT results at Jesih štradon

3.2. Jesih štradon

The second location Jesih štradon is located on the southern outskirts of Ljubljana (Slovenia). The ground consists of deep alluvial sediments, mainly very soft clayey silts and clays of high plasticity underlain by a thin layer of clayey gravel at the depth of 18 m. In Fig. 2, only the results of one CPT and DMT pair are presented.

The soil type was captured differently by both tests. DMT material index I_D is very low indicating mud rather than silty clay and clay due to the very soft consistency of the soils. The material index I_D obtained from the CPT provides better estimate than DMT for soil type, which is in accordance with the actual soil classification obtained from the boreholes. In this particular case, we can observe that the classification based on DMT results relies on the soil stiffness, whereas the classification based on

CPT is rather based on soil's strength. The comparison of the undrained shear strength c_u shows good agreement with similar trend.

At greater depths DMT predicts up to 20% larger values of undrained shear strength c_u than CPT. Taking into account the past geotechnical experience in this area, c_u obtained from DMT gave more relevant values. The agreement between predicted constrained modulus M is surprisingly poor. CPT overpredicts constrained moduli M due to the very soft state of the soil with high void ratio with a value of about 2.0. The predicted friction angles for clayey gravel at the bottom of both probes show anticipated values for gravelly soils, where DMT, not being designed for gravelly soils, was not applied.

3.3. Srmin

The third location is in Srmin near Koper, Slovenia, where ground investigations by means of CPT and DMT tests were performed for the construction of up to 12 m high motorway embankment.

Ground consists of stiff clayey to silty layer on top followed by soft clay layer. Between soft clay and flysch bedrock, about 2 m thick sandy gravel layer is placed.

The artesian ground water is found in gravel and soft clay layer while upper stiff silty clay layer is not fully saturated. The artesian groundwater head almost coincides with ground surface.

The comparison of CPT and DMT results performed in the area is shown in Fig. 3. The soil type along the probes was well captured. Undrained shear strength c_u, predicted by both tests agree favorably in the upper clayey silt layer, but less so in the transition area. Here, the presence of silty layers increases undrained shear strength c_u as predicted by CPT. The trend of predicted constrained moduli M according to both tests agree well with obvious deviations in values in the upper more stiff layer and once the probes are within the weathered rock zone. Friction angles φ' for the lower layer predicted by both tests agree well, with DMT unable to reach the final CPT depth.

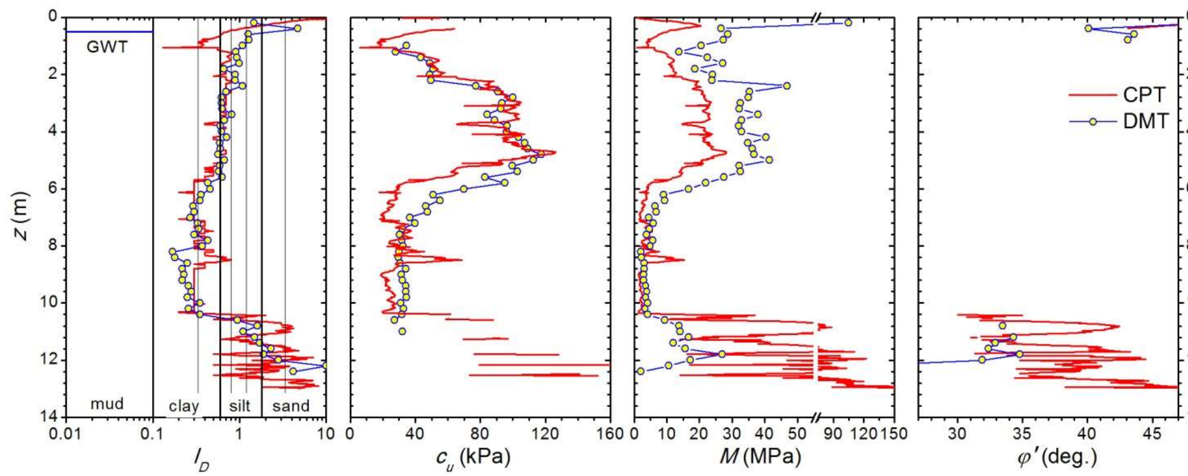

Figure 3. Comparison of CPT and DMT results at Srmin

4. Discussion

The results of the CPT and DMT tests from all 7 sites are used here to test the proposed correlations presented in section 2 (Eqs. 10, 11 and 12).

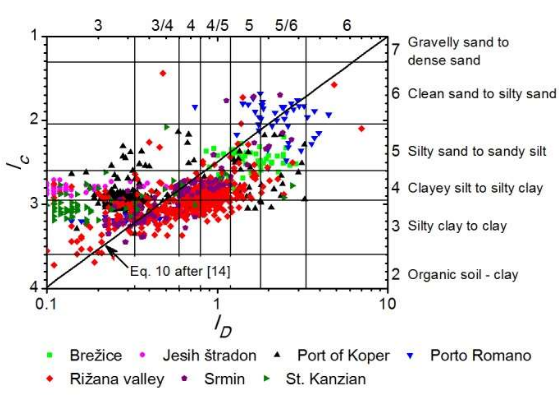

Figure 4. Soil classification according to I_D (DMT) and I_c (CPT)

Fig. 4 shows the comparison between material indexes I_D and I_C as obtained from the DMT and CPT tests, respectively. Since soil stratification is important for any geotechnical design, reliable soil classification from in-situ tests is of vital interest. Fig. 4 also shows soil behavior types 2 to 7, developed for the interpretation of the CPT results. They can be compared with three soil classes determined from DMT: clays, silts and sands with $I_D < 0.6$, $0.6 < I_D < 1.8$ and $I_D > 1.8$, respectively. It is evident that within seven presented cases, mostly clayey and silty soils were present. Only in Porto Romano, a sandy layer was identified by both tests. Relatively large scatter of results comes mainly from the transition zones between soil layers that may be differently classified by each test and in very soft clay. It is interesting to observe the groups of points in Fig. 4 at around $I_C = 3$. The smallest I_D was obtained for very soft clays from Jesih štradon and silts from St. Kanzian. For St. Kanzian this may be explained by partial drainage during the DMT test, which is typical for the so called "niche silts", where partial drainage occurs during the test [9]. The group of black points from Port of Koper is classified as clay by DMT and clayey silt to silty clay by CPT. Clayey layer from

Porto Romano has points evenly distributed around Robertson's line, while the points for stiff clayey layer from Rižana valley are positioned to the right of Robertson's line. Therefore, we have five different clayey to silty soils with very similar I_C values but significantly different I_D. In these particular cases both tests give satisfactory soil classes but fail to classify the soils according to fractions of clay and silt. Especially the DMT classification relies mostly on soil stiffness that strongly depends, in case of fine-grained soils, on consistency and less on soil particle size.

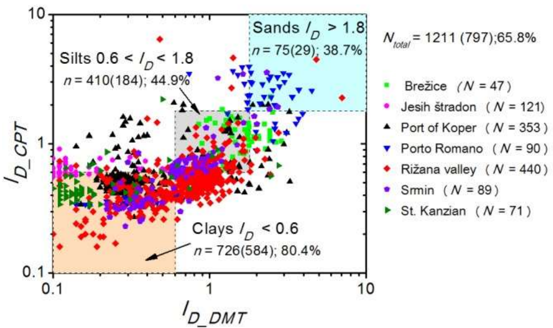

Figure 5. Comparison of CPT and DMT values for I_D

Robertson's empirical relation between I_D and I_C (Eq. 10) is presented in Figs. 6 and 7, where comparisons between material indexes I_{D_CPT} (calculated by Eq. 10) and I_D obtained directly with DMT are shown. For clays ($I_D < 0.6$), the matching is relatively good, with the correlated value showing the same soil type in 80% of cases. For silts ($0.6 < I_D < 1.8$), the correlated values I_{D_CPT} predominately underpredict the DMT values and give the same soil type only in 45% of cases. Sands ($I_D > 1.8$) are classified as the same soil type in 39% of cases. Poor classification of silts in the presented cases comes mainly from the data for Rižana valley where the clayey layer is described as firm lean clay. The CPT results lay in the part of classification diagram, where some discrepancy of classification by soil behavior types and by calculated I_C values has to be expected.

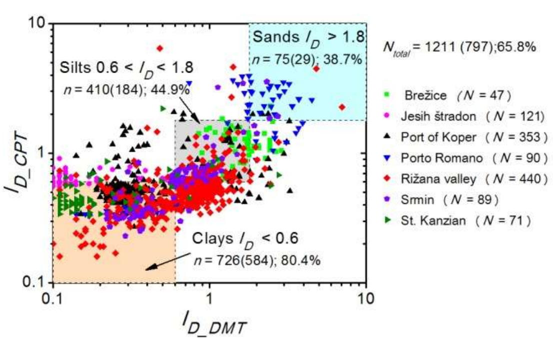

Figure 6. Comparison of CPT and DMT values for I_D

Fig. 7 shows the density distribution of matched I_{D_DMT} and I_{D_CPT} values, with areas where calculated values of $I_{D_{CPT}}$ (Eq. 10) best match the I_{D_DMT} painted in yellow. Fig. 7 also shows that the conversion formula given in Eq. 10, which relates the CPT value of I_c to DMT value of I_D is not accurate enough to be adopted as a general rule, but the magnitude of error can be judged by the presented results.

For the comparison of horizontal stress indexes K_D and E_D values log-log plots are used in Figs. 8 to 11 in order to emphasize the relative error of the correlated CPT values as compared to DMT values obtained at same depths. The lines indicating $\pm 50\%$ relative error are clearly marked.

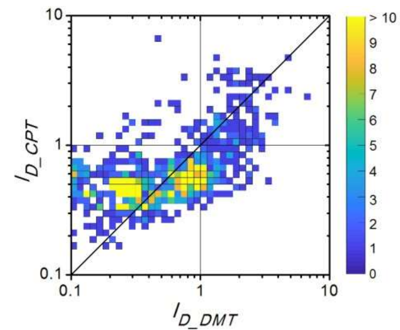

Figure 7. Density plot of CPT and DMT values for I_D

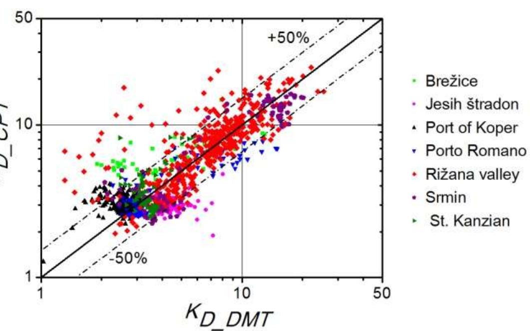

Figure 8. Comparison of CPT and DMT values for K_D

The comparison of horizontal stress indexes K_D shows relatively good concentration around the identity line, with an error that is predominantly less than 50%, but can also be much higher (Fig. 8). The density plot of horizontal stress indexes K_D (Fig. 9) shows a fairly frequent match of K_D values around the equality line with a possible large spread of individual values.

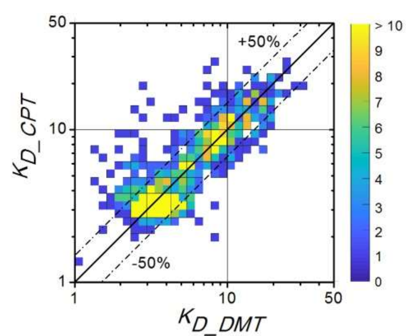

Figure 9. Density plot of CPT and DMT values for K_D

The comparison of E_{D_CPT} and E_D as obtained from DMT tests shows rather large scatter of values around the identity line (Fig. 10). One of the reasons is that E_{D_CPT} is not directly compared with the CPT measurements, but is rather calculated from I_{D_CPT} and K_{D_CPT}. The correlated values E_{D_CPT} mostly exceed the DMT values and, if used to calculate the constrained moduli M using Eq. 9, which is proportional to E_D, they would be generally overestimated for E_D values less than 5 MPa. This can also be observed from the density plot of E_D values (Fig. 11), where most frequent match between E_D DMT values and E_{D_CPT} can be observed well above the +50% error line for E_D values lower than 5 MPa and within -50% error line above $E_D = 5$ MPa.

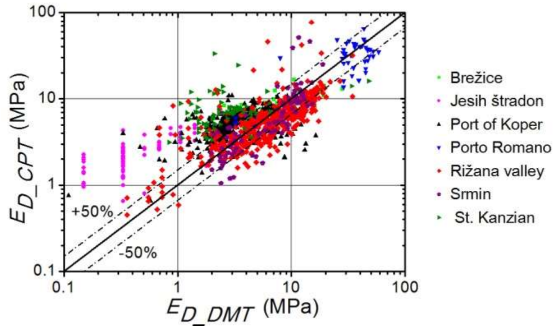

Figure 10. Comparison of CPT and DMT values for $\boldsymbol{E_D}$

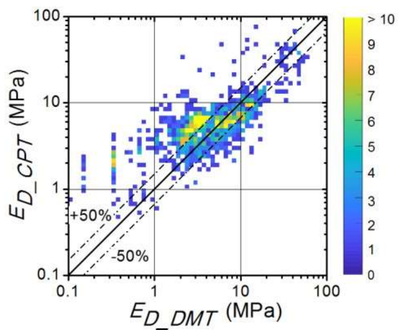

Figure 11. Density plot of CPT and DMT values for $\boldsymbol{E_D}$

The comparison confirms the findings of Marchetti [8] that the proposed CPT - DMT correlations are of approximate nature, with errors generally too high for engineering applications.

It should also be noted, that the presented density distribution diagrams are only valid for used data set and are affected by number of measurements for each material group.

5. Conclusions

The correlations for the evaluation of CPT and DMT tests are still improving based on comparative case histories and laboratory tests. The presented results show that the combined use of piezocone penetration test (CPT) and flat dilatometer test (DMT) can be a useful addition to defining ground profile and material properties. Thus, they can significantly improve the reliability of a geotechnical model. This applies especially to cases when CPT and DMT yield similar results that match other investigations and laboratory data. For the cases presented, the CPT and DMT results agree reasonably well, except for very soft clays, soils with mixture of clay/silt with thin layers of sand (typical for sedimentation of dredged material) and some relatively permeable fine grained soils ("niche silts"), where partial drainage during the DMT test can significantly affect the results [9]. The proposed CPT to DMT correlations were found unsatisfactory for engineering use, and it is better to use or compare the results as obtained by both methods independently. From all seven cases presented in the recently published paper [5] and herein, it can be observed that major differences in ground characterization from both in-situ tests are obtained in very soft clays and in transition zones from fine to coarse grained soil. Therefore, even when combined, the CPT and DMT results should be used with care, based on good knowledge about local ground conditions and by taking into account the results of geotechnical investigations by means of drilling and laboratory testing.

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