10.2478/sggw-2018-0025

Annals of Warsaw University of Life Sciences – SGGW
Land Reclamation No 50 (4), 2018: 313–326
(Ann. Warsaw Univ. of Life Sci. – SGGW, Land Reclam. 50 (4), 2018)

Evaluation of correlation between parameters from CPTU and DMT tests and soil type behavior chart

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Abstract: *Evaluation of correlation between parameters from CPTU and DMT tests and soil type behavior chart.* This paper presents the correlation of soil parameters obtained from the dilatometer of the Marchetti (DMT) and the cone penetration tests (CPT). The data for the development of these correlations come from four experimental sites of the Department of Geotechnical Engineering of the Warsaw University of Life Sciences – SGGW: test embankment in Antoniny, and the Koszyce and Nielisz water dams, Stegna test site, WULS-SGGW Campus. Additionally, the relationship between the soil behavior type classification index (I_c) from the Cone Penetration Test (CPT) and the material index (I_D) from the dilatometer test (DMT) based on the Robertson method, modified in this paper, is presented. Finally, a new soil behavior type classification chart was presented, allowing to determine not only the type and condition of the soil, but also the stress history (*OCR*).

Key words: DMT, CPT, mineral and organic soils, chart diagram

INTRODUCTION

Field and laboratory tests are used to determine the geotechnical parameters of soil. Both methods have their advantages and disadvantages. The advantage of laboratory tests is a well-defined state of stress and strain, as well as the ability to control the conditions of water outflow from the sample. Moreover, the investigations are expensive and time-consuming. Field studies are characterised by the possibility of their implementation in *in situ* conditions. The disadvantage of these methods is the need to rely on empirical correlations in the interpretation of the results obtained, and the difficulty of determining the impact of penetration probe on the soil structure and measurement results. In recent years, geotechnical engineering are more willing and more likely to apply *in situ* tests. The progress in the design of measuring devices and the broader interpretation of the results obtained from these tests are of great importance (Schnaid 2009). One of the methods combining these two features is the Marchetti dilatometer (DMT) (Młynarek et al. 2006, Młynarek 2007, Schnaid 2009, Bihs et al. 2010, Long et al. 2010, Godlewski and Wszędyrówny-Nast 2016).

The analysis and construction of the empirical relationship between the q_t and K_D parameters from the CPTU and DMT tests is not only formal, but finds justification for two reasons:

– in the widely accepted ground testing program, static investigations are the dominant research in *in situ* methods. They recommend such a program for instructions for the design of engineering structures, e.g. the manual for

designing wind turbines cited in the literature (2012), and scientific studies e.g. Robertson (2009). Dilatometer tests are usually complementary in this program;
– the advantages of the CPTU and SCPTU tests include the direct determination of undrained shear strength parameters for soil, shear modulus G_0 and parameters of the process of consolidation and soil stratigraphy description (Lunne et al. 1997, Młynarek 2007).

From the DMT test, deformation modulus are obtained directly, while empirical relationships should be used to determine undrained shear strength. Constructing so--called interrelationship of both studies is considered very valuable. An example is the description of continuous changes in undrained shear strength in the sublayer using the parameter from the CPTU test and supplementing this information in places where only the DMT test was performed. In the case of subsoil from Poland, these dependencies have significant limitations to the dependencies proposed in the world literature (Lechowicz et al. 2011, Młynarek et al. 2016, 2017, 2018). With such limitations one should also count in relation to the functional relationship between the parameters q_t and K_D.

The Marchetti dilatometer was created by Silvano Marchetti. The device was put into use in the early 1980s in the United States and Europe. In addition to Marchetti, John H. Schmertmann (USA) made a significant contribution to the development of the device, which systematized the procedure of determining soil parameters based on DMT (Dilatometer Marchetti Test) results. Experiments carried out over the years with the use of the DMT device allowed to acquire data which allowed for the clarification of the interpretation of dilatometer results (Schmertmann 1986). The dilatometer was quickly appreciated by geotechnicians. It is used to determine soil characteristics in almost 50 countries, e.g. in Europe, Asia, North America. The Marchetti dilatometer test is the basic method of testing geotechnical parameters in *in situ* conditions recommended by Eurocode 7 (Frank et al. 2004). It is certainly an advanced device applicable in the study of both cohesive and non-cohesive soils in field conditions with a rich palette of the acquired parameters.

The main advantage of dilatometer testing is a fast, low-complex and reliable measurement procedure. Following the test it is easy to classify the soil and set the geotechnical parameters such as: soil coefficient of earth pressure at rest (K_o), undrained shear strength (S_u), overconsolidation ratio (OCR), constrained modulus (M), deformation modulus (E), shear modulus (G), and coefficient of consolidation (c_h). Despite the numerous advantages of using a dilatometer for geotechnical investigations, it should be remembered that the target soil parameters are obtained as a result of empirical correlations of the soil reference parameters, which are determined on the basis of standards, publications, tests or recommendations, and the DMT test results empirical relationships on the appropriate graduation of the measuring apparatus (Marchetti 1980, Roque et al. 1988, Yu et al. 1993, Smith and Houlsby 1995, Totani et al. 1998) as follows:

material index: $I_D = (p_1 - p_0) / (p_0 - u_0)$ (1)

horizontal stress index: $K_D = (p_0 - u_0) / \sigma'_{v0}$ (2)

dilatometer modulus:

$$E_D = 34.7 \cdot (p_1 - p_0) \quad (3)$$

after combination of I_D and K_D (Robertson 2015):

$$\frac{E_D}{\sigma'_{v0}} = 34.7\, I_D K_D \quad (4)$$

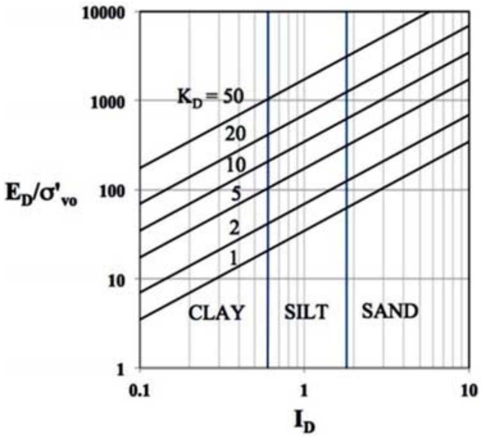


FIGURE 1. Modified DMT-based chart for soil type based on dimensionless I_D and E_D/σ'_{v0} (Robertson 2015)

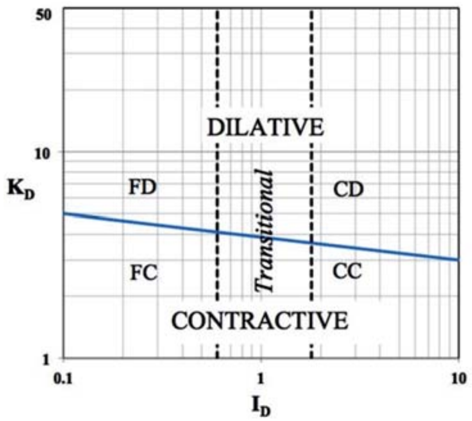


FIGURE 2. Proposed DMT-based soil behavior type classification (SBT) chart for soils with little or no microstructure (Robertson 2015): CD – coarse-grained dilative (mostly drained); CC – coarse-grained contractive (mostly drained); FD – fine-grained Dilative (mostly undrained); FC – fine-grained contractive (mostly undrained)

effective preconsolidation stress (Kulhawy and Mayne 1990):

$$\sigma'_p = 0.5 \cdot (p_0 - u_0) \quad (5)$$

where:

p_0 – *A*-pressure reading, corrected for Z_m, ΔA membrane stiffness at 0.05 mm expansion, and 0.05 mm expansion itself, to estimate the total soil stress acting normal to the membrane immediately before its expansion into the soil (0.00 mm expansion);

p_1 – *B*-pressure reading corrected for Z_m and ΔB membrane stiffness at 1.10 mm expansion to give the total soil stress acting normal to the membrane at 1.10 mm membrane expansion;

p_2 – *C*-pressure reading corrected for Z_m and ΔA membrane stiffness at 0.05 mm expansion and used to estimate pore-water pressure;

ΔA – the external pressure which must be applied to the membrane in free air to keep it in contact with its seating;

ΔB – the internal pressure which, in free air, lifts the membrane center 1.00 mm from its seating;

Z_m – gage pressure deviation from zero when vented to atmospheric pressure (an offset used to correct pressure readings to the true gage pressure);

σ'_{v0} – vertical effective stress at the centre of the membrane before insertion of the DMT blade;

u_0 – pore-water pressure acting at the centre of the membrane before insertion of the DMT blade (often assumed as hydrostatic below the water table surface).

Robertson in 2012 developed (Fig. 1) the dependence of the I_D from E_D/σ'_{v0} with the variable value K_D by using Equation 4. Robertson suggested that for fine-grained soils with little or no

TABLE 1. Index properties of organic soils at the Antoniny, Koszyce, Nielisz and mineral soil from Stegny and WULS-SGGW Campus test sites (Wolski et al. 1989, Lechowicz and Rabarijoely 1996)

Site	Type of soil	Organic content I_{om} (%)	$CaCO_3$ content (%)	Water content w_n (%)	Liquid limit w_L (%)	Unit density of soil ρ ($t \cdot m^{-3}$)	Specific density of soil ρ_s ($t \cdot m^{-3}$)
Antoniny	amorphous peat	65–75	10–15	310–340	305–450	1.05–1.10	1.45–1.50
	calcareous gyttja	5–20	65–90	105–140	80–110	1.25–1.40	2.2–2.30
Koszyce	amorphous peat	70–85	5–15	400–550	450	1.05–1.1	1.45–1.50
	calcareous gyttja (G_y)	10–20	65–80	120–160	80–110	1.20–1.35	2.1–2.25
	calcareous gyttja (G_y)	15–20	65–75	180–220	100–110	1.25–1.30	2.2
Nielisz	organic mud (M_{or})	20–30	–	120–150	130–150	1.25–1.30	2.25–2.3
	organic mud (M_{or})	10–20	–	105–120	110–130	1.30–1.45	2.30–2.40
Stegny	Pliocene clays	< 1	< 5	19.20–28.50	67.6–88.0	2.1–2.2	2.68–2.73
WULS-SGGW Campus	boulder clay	–	–	5.20–20.10	21.9–26.6	2.0–2.2	2.68–2.73

microstructure, the boundary between contractive and dilative behavior at large strains occurs when $OCR \approx 4$. Based on Marchetti (1980) and equation $OCR = (0.5\ K_D)^{1.56}$, an $OCR = 4$ corresponds to a $K_D \approx 5$. For coarse-grained soils with little or no microstructure, the boundary between contractive and dilative behavior at large strains occurs at a state parameter $\psi \approx -0.5$. Based on Robertson (2012) and Equation 6, this corresponds to a $K_D \approx 3$. A contour between $3 < K_D < 5$ is shown on Figure 2 to represent the approximate boundary between dilative and contractive behavior at large strains for soils with little or no microstructure.

$$\psi = 0.56 - 0.33 \cdot \log(25 \cdot K_D) \qquad (6)$$

DESCRIPTION OF THE TEST SITE

This paper presents the test results of organic subsoil obtaining from Antoniny and Koszyce located in the valley of the Noteć river in Wielkopolska province and Nielisz sites located in the valley of the river Wieprz in Lublin province, the WULS-SGGW Campus with and the Stegny site located in Warsaw, where the Department of Geotechnical Engineering WULS-SGGW where a laboratory and field testing programme has been carried out under and outside of the main dam embankment. Table 1 show the index properties of organic soils at the Antoniny, Koszyce, Nielisz and mineral soil at Stegny and WULS-

-SGGW Campus test sites (Wolski et al. 1988, 1989, Lechowicz and Rabarijoely 1996).

METHODOLOGY FOR DETERMINING CORRELATION BETWEEN PARAMETERS OF DMT AND CPT TESTS

Correlation q_t–K_D

Determining the correlation between the parameters obtained from the DMT and CPT tests consists of comparing the obtained values for the same data in the form of a graph. The correlations obtained and examined between them should be used by geotechnicians in the design for obtaining various parameters of the soil while performing only one type of *in situ* testing equipment.

As mentioned in the beginning of this paper, there is a number of reports and research works focused on determining the correlation of the results from DMT and CPT tests. However, already Marchetti (1980) had discovered a strong dependence of the horizontal stress index (K_D) on the overconsolidation ratio (*OCR*), which he defined as:

$$OCR = (0.5 \cdot K_D)^{1.56} \tag{7}$$

A few years later, Kulhawy and Mayne (1990), Mayne and Liao (2004), Mayne (2016) noticed that the *OCR* in CPT tests significantly influences the normalized values of the q_t and suggested to use the following formula in the analysis of fine-grained soils:

$$OCR = \frac{0.3 \cdot (q_t - \sigma_{v0})}{\sigma'_{v0}} \tag{8}$$

The overconsolidation ratio (*OCR*) is an independent variable that occurs in the function describing the static presentation process (Młynarek 2007, Mayne and Agarby 2018). The geological regime (genesis) and the engineering regime (Powell 2005) have an influence on the numerical values of this coefficient. The cone resistance depends on the effects of the preconsolidation, the measure of which is the *OCR*. In turn, Robertson (2009) suggested that the *OCR* is dependent on the q_t is dependent on the *OCR* value and may be reflected in the following formula:

$$OCR = \frac{0.24 \cdot (q_t - \sigma_{v0})}{\sigma'_{v0}} \tag{9}$$

Equations 7 and 8 show that the value of K_D from the DMT tests can be determined on the basis of the normalized value of cone resistance $(q_t - \sigma_{v0}) / \sigma'_{v0}$ using the equation (Robertson 2009):

$$K_D = 0.8 \cdot \left(\frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \right)^{0.8} \tag{10}$$

By converting Equation 10, the q_t can be determined based on the following equation:

$$q_t\,(CPT) = 1.322 \cdot \sigma'_{v0} \cdot K_D^{1.25} + \sigma_{v0} \tag{11}$$

The horizontal stress index (K_D) and the material index (I_D) obtained from dilatometer tests and from CPT soundings of normalized values of cone resistance $(q_t - \sigma_{v0}) / \sigma'_{v0}$ and friction ratio $F_r = [f_s / (q_t - \sigma_{v0})]$ 100% to recognize the type of soil behavior type classification were proposed by Robertson (2009).

Based on the results of the CPT and DMT tests from the discussed objects (test embankment: Antoniny site, embankment dams: Koszyce, Nielisz, and Stegny site and WULS-SGGW Campus in Warsaw), the correctness of these correlations has been analysed in this paper and the following results have been obtained. The studies of soil parameters obtained from Equations 12 and 13, from the direct measurement by the probe and from the correlations proposed in this work have been compiled in the form of graphs (Fig. 3) and Table 2.

$$q_t(\mathrm{CPT}) = A_0 \cdot \sigma'_{v0} \cdot K_D^{A_1} + \sigma_{v0} \tag{12}$$

$$K_D(\mathrm{DMT}) = \frac{A_2 \cdot (q_t - \sigma_{v0})^{A_3}}{\sigma'^{A_4}_{v0}} \tag{13}$$

Comparing the measured values of q_t and K_D with the calculated relation-

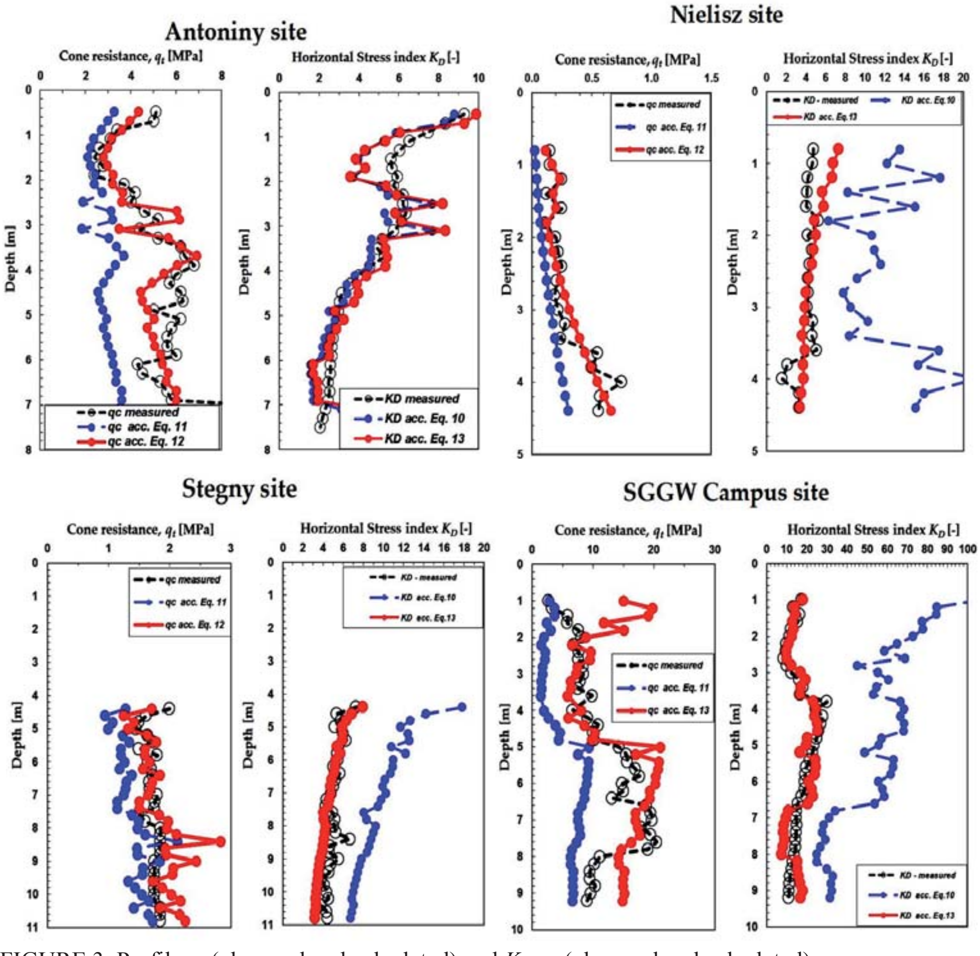


FIGURE 3. Profile q_t (observed and calculated) and K_{DMT} (observed and calculated)

TABLE 2. Values of empirical coefficients A_i for Equations (Eqs. 12, 13)

Soil type	Coefficient values				
	A_0 (-)	A_1 (-)	A_2 (-)	A_3 (-)	A_4 (-)
Sand	15	1.4	0.20	0.20	1.0
Boulder clay (depth 0–3 m)	4.0	1.4	0.09	1.0	1.0
Boulder clay (depth > 3 m)	3.0	1.25	0.12	1.12	1.0
Pliocene clay	1.8	1.25	0.45	0.45	1.0
Mud, organic mud	2.5	1.4	0.11	0.11	1.0
Peat	88	1.4	0.008	1.0	1.0
Gyttja	80	1.4	0.007	1.0	1.0

ships (Eqs. 12, 13, Figs. 3, 4) indicate that the newly proposed correlations give similar results to the measured data at 95% confidence level. The pairs of observations q_t and K_D are assigned to the same value of the effective vertical component of the geostatic stress $\sigma' v_0$ for both parameters. The maximum error obtained between q_t measured and q_t calculated by Equation 12 is 35% and the average error is 14%, whereas in the case of a dilatometer (K_D measured and K_D calculated) based on Equation 13 it is 34 and 10.9% respectively for the analysed dataset included in this paper. Very good correlation has been recorded for organic and Pliocene clay soil. These new formulas are recommended for the design of geotechnical facilities. The use of the calculated values of q_t to the said undrained shear strength or primary constrained modulus may lead to a fundamentally separate assessment of the strength and stiffness of the subsoil (according to PN-EN 75014688-2). This issue was discussed in the literature and concerned the problem of compliance of shear strength

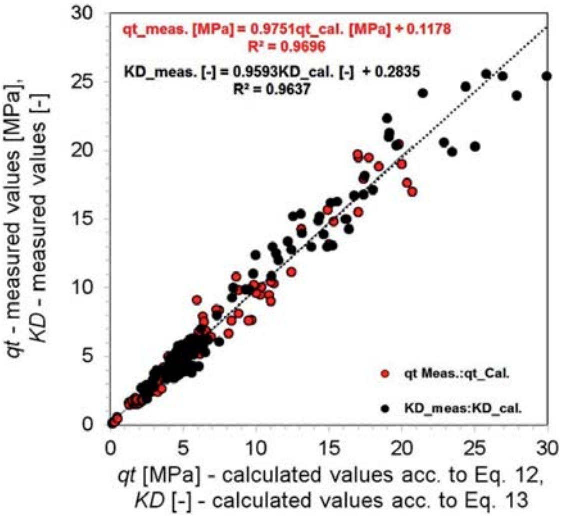


FIGURE 4. Comparison between calculated and measured q_t and K_{DMT} values

values and the primary compressibility modulus determined on the basis of the cone resistance from the CPTU test and DMT parameters (Lechowicz et al. 2011, Młynarek et al. 2013, 2016, 2018), these showed that this relationship is influenced by such factors as the effect of pre-consolidation (*OCR* value) the type and condition of the ground. In the case of organic soils, the number of variables that affect the cone resistance and parameters from the DMT tests is much larger (Młynarek et al. 2008).

Correlation I_c–I_D

The next parameters that have been used in the analysis between CPT and DMT in this paper are the I_c and I_D parameters. The analysis consists of a comparison (Eq. 14) of the calculated Robertson value (I_c) with the material index from DMT (I_D) for the following plots (Fig. 5). In addition, a different correlation between the index I_c from the CPT and the index I_D from the dilatometer, previously researched by Robertson (2009) and expressed by the formula have been analysed herein (Fig. 5):

$$I_c = 2.5 - 1.5 \cdot \log(I_D) \tag{14}$$

As can be observed, although the diagrams of these parameters do not overlap, they have a very similar trend. Therefore, when performing field tests with the CPT probe, the K_D parameter can be obtained, or performing only the DMT test allows to obtain q_t using the proposed formulas without worrying about the correctness of the result.

On the basis of the results obtained for the discussed sites, a graph illustrat-

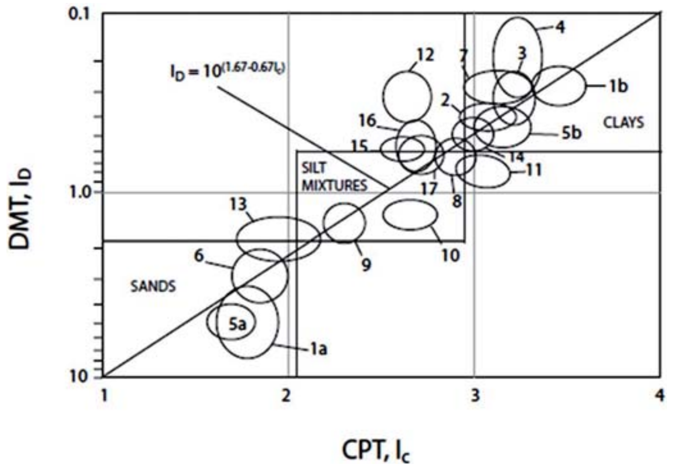


FIGURE 5. Summary of published average values of I_D versus I_c from adjacent CPT and DMT profiles (Robertson 2009): (1a) deltaic sand; (1b) soft silty clay; (2) soft clay; (3) soft varved sensitive clay; (4) soft glacial clay; (5a) medium dense sand; (5b) soft clayey silt; (6) loose silty sand-tailing; (7) loose silt and fine sand-fill; (8) stiff fissured clay; (9) stiff silty sand to sandy; silt – residual soil; (10) stiff silty sand, sandy; silt – residual soil; (11) stiff silty sand to clayey silt-residual soil; (12) stiff cemented silt; (13) silty sand; (14) silty clay; (15) very stiff clay; (16) (17) very stiff clay; (18) very stiff clay; soft sensitive clay; (19) sand to silty sand

ing this dependence was created (Fig. 5), additionally allowing for the determination of its value for the following soil types: $I_c < 2.05$ for sand; $2.05 < I_c < 2.9$ for clay; and $I_c > 2.9$ for silt.

In Figure 5 developed by Robertson (2009), there is no defined area for organic soils such as mud, organic mud, peat and gyttja. Therefore, in this paper a decision was made to modify this soil

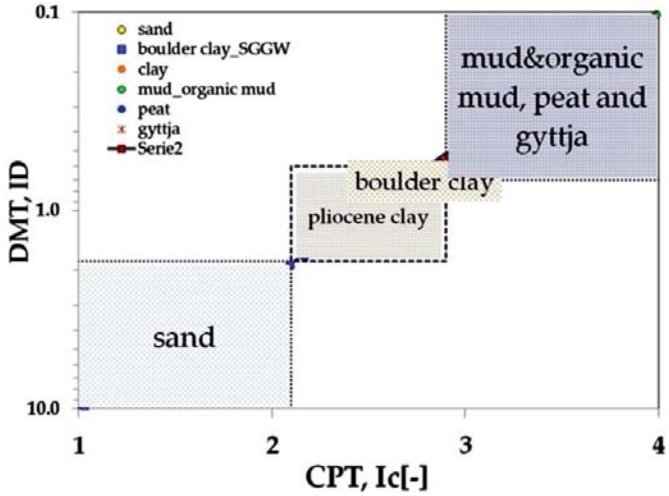


FIGURE 6. Relationship between I_c from CPT tests and I_D from a dilatometer based on the modified formula

TABLE 3. Published records from adjacent DMT-CPT probes from Poland (*OCR* value for each site by order: Koszyce: in the range of 1.5–4; Antoniny: at 3–5 for peat, and 1.5–2.5 for gyttja; Mielimąka: in the range of 1.5–4; Nielisz: decreasing from 3 to 2 with depth; WULS-SGGW Campus: boulder clays with the *OCR* = 3–7)

No	Site	Organic and mineral soil type	Depth (m)	I_D (-)	K_D (-)	E_D/σ'_v (-)	q_t (MPa)	F_r (-)	I_c (-)
1	Koszyce	gyttja	3.1–4.5	0.14–0.47	4.8–7.2	23–115	0.12–0.18	8.8–9.6	1.2–2.0
2	Koszyce	peat	1–1.9	0.14–0.61	18–85	91–170	0.33–4.5	1.5–7.7	1.2–2.2
3	Antoniny	peat	0.9–2.3	0.2–0.7	6.2–7.5	47–180	3.4–4.2	4.4–12	1.5–2.3
4	Antoniny	gyttja	6.7–7.5	0.25–0.55	2–2.5	21–39	5.6–50	1.3–5.6	1.6–2.1
5	Mielimąka	peat	4.8–6.6	0.18–0.49	1.5–1.8	11–25	0.35–0.6	8–11	1.4–2.0
6	Mielimąka	gyttja	7.4–9.4	0.16–0.34	1.7–1.8	9.7–19	0.37–0.7	7–8	1.3–1.7
7	Nielisz	mud	1.4–10	0.1–0.94	1.7–4.1	14.5–57	0.12–1.3	7–10	1–2.5
8	WULS--SGGW Campus	sandy clay	3–6.8	0.1–0.6	2–3	15–40	2.5–5	2–3.5	3.6–4.1
9	WULS--SGGW Campus	sand	6.9–9.5	1.8–10	8–30	300–1000	10–25	5–18	2–3.8

behavior type classification by adding additional organic soils. The following two formulas should be used to determine organic soils (Eqs. 15 and 16, Fig. 6, Table 5). Index I_c is located within the above mentioned ranges for the relevant soil types. Based on the proposed soil behavior type classification, these organic soils are in the following ranges: $I_c > 2.5$ for mud and organic mud; $2.7 < I_c < 3.8$ for peat; and $2.95 < I_c < 4$ for gyttja (Fig. 6, Table 3). Based on this graph, the following relationship was proposed:

$$I_c = 2.5 - 0.651 \cdot \log(I_D) \tag{15}$$

Its conversion allows to obtain the following formula:

$$I_D = 10^{(3.84 - 1.55 \cdot I_c)} \tag{16}$$

DILATOMETER (DMT) BASED MINERAL AND ORGANIC SOILS BEHAVIOR TYPE

This report attempts to create a new soil behavior type classification. In the first stage, measurement data have been collected from the objects discussed in the previous chapters, as well as data from the investigations for the construction of the Warsaw subway. Using the Robertson propositions in this paper, a combination between the σ'_p (Eq. 5) and a dilatometer indexes I_D, K_D and E_D (Eq. 4) was made, we can obtain the relation follows (Eq. 17), are shown in the graph (Fig. 7). A contour between $17.4 < E_D/\sigma'_{v0} < 1{,}041$ is shown on Figure 8 to represent the approximate boundary between dilative and contractive behavior at large strains for soils with little or no microstructure.

$$\frac{E_D}{\sigma'_{v0}} = 69.4 \cdot I_D \cdot OCR \tag{17}$$

CONCLUSIONS

The objective of this paper was to review the published correlations between well-known CPT and DMT *in situ* tests. The results of both tests correlate with the same geotechnical parameters. Based on the tests results (90 profiles) obtained for the analysed test sites, the correlations between CPT and DMT tests have been suggested using two approaches. In the first approach, the formulas proposed by Robertson (2009) were applied. The second approach concerns the comparison between the measured values of q_t and K_D with the calculated values based on the proposed relationships (Eqs. 12, 13, Figs. 3, 4), which indicates that the new proposed correlations give results similar to the measured data.

Modification of the normogram by adding an area for organic soils such as mud, organic mud, peat and gyttja allowed for locating these soils accurately using the I_c and I_D parameters. Therefore, addition of further organic soils to the normogram is proposed in this paper.

A modified chart to estimate soil type using the main DMT normalized parameter (I_D, E_D) is presented. Existing correlations for the *OCR* as contours on the modified DMT chart to provide insight into the correlations. A new soil behavior type classification (SBT) chart is also presented using generalized

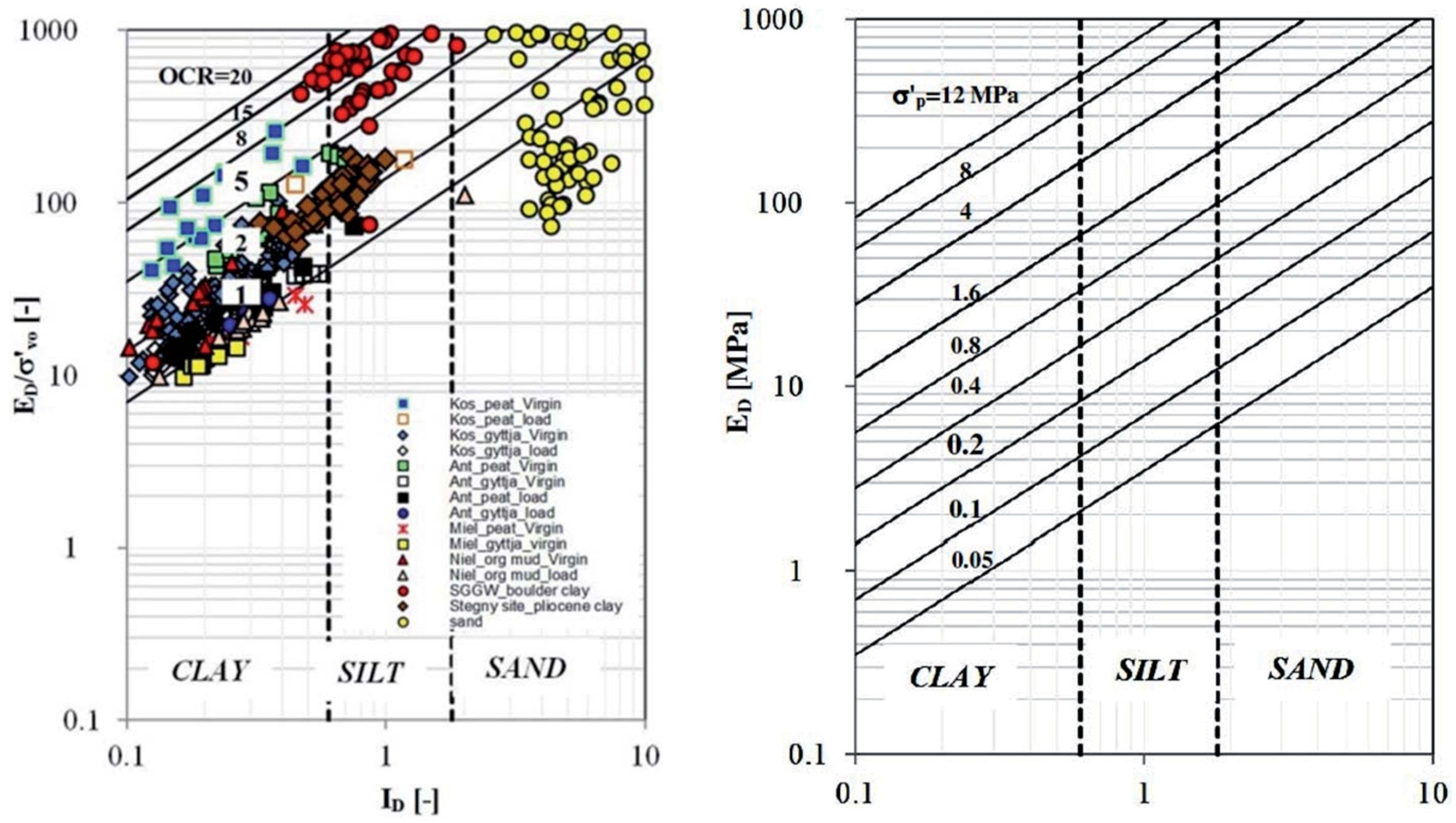
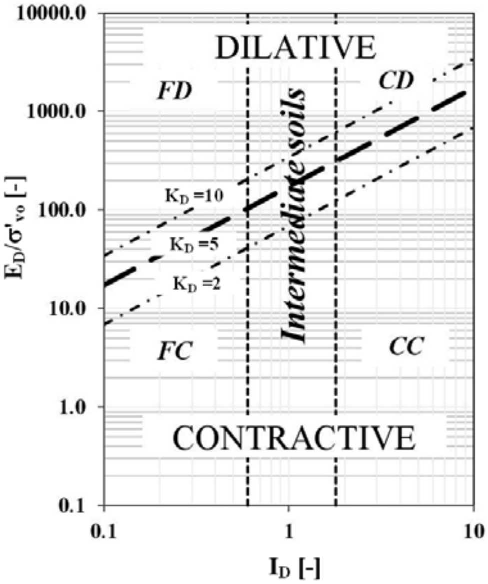


FIGURE 7. Range of *OCR* and σ'_p variability plotted on modified DMT based chart for soil type based on I_D and E_D/σ'_{v0}; on I_D and E_D



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. Proposed DMT-based soil behavior type classification (SBT) chart for soils with little or no microstructure

soil behavior descriptions (e.g. coarse--grained dilative, fine grained contractive, etc.).

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Streszczenie: *Ocena korelacji między parametrami z sondowań CPTU i DMT a wykresem zachowania się gruntów*. Artykuł przedstawia korelację parametrów gruntowych otrzymywanych w badaniach dylatometrycznych Marchettiego (DMT) oraz sondowań statycznych (CPT). Dane do opracowania tych zależności pochodzą z sześciu obiektów doświadczalnych Katedry Geoinżynierii SGGW: nasyp doświadczalny w Antoninach oraz zapór wodnych w Koszycach i Nieliszu, poletko doświadczalne Stegny oraz kampus SGGW. Dodatkowo przedstawiono zależność pomiędzy wskaźnikiem (I_c) z badań sondowań statycznych (CPT) a wskaźnikiem materiałowym (I_D) z dylatometru Marchettiego (DMT) na podstawie wzoru Robertsona z 2009 r., zmodyfikowanego na rzecz tej publikacji. Na zakończeniu w artykule również zaproponowano nowy nomogram klasyfikacyjny gruntów, pozwalający na określenie nie tylko rodzaju i stanu gruntu, ale także historii jego naprężenia (*OCR*).

Słowa kluczowe: DMT, CPT, grunty mineralne i organiczne, nomogram klasyfikacyjny

MS received 10.11.2018

MS accepted 15.12.2018

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