Soil Behavior Type using the DMT

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Keywords: Soil Behavior Type, CPT, DMT

ABSTRACT: The most promising penetration tests available in practice today are the cone penetration test (CPT) and the flat plate dilatometer test (DMT). Each test has advantages and limitations. Relationships between the two in-situ tests can be used to expand and improve correlations and applications using shared experience and databases. A modified chart to evaluate soil type using the main DMT parameters (I_D and K_D) is presented along with contours of normalized M_{DMT} and G_o on the modified chart. A new DMT-based chart is presented based on generalized soil behavior type descriptions. A method to evaluate the existence of microstructure (e.g. age and cementation) in soils using a combination of CPT and DMT is also presented.

1 INTRODUCTION

The electric cone penetration test (CPT) was developed in the Netherlands in the 1960's and has a strong theoretical background as well as the advantages of being fast, near continuous, repeatable and economical. These advantages have lead to a steady increase in the use and application of the CPT in many places around the world.

The flat-plat dilatometer test (DMT) was developed in Italy by Professor Marchetti in the 1980's and has become popular in many parts of the world, since it is simple, robust, repeatable and economical. However, the DMT has little theoretical background and is harder to push in to very stiff ground compared to the CPT. The DMT is carried out every 200 mm whereas CPT readings are taken every 20 to 50 mm. The DMT requires a pause in the penetration that makes the test slower than the CPT and hence, typically more expensive. Both tests do not include a soil sample, although it is possible to take small diameter soil samples using the same pushing equipment used to insert either the CPT or DMT.

Each test has advantages and limitations. Robertson (2012) presented linkages between the two in-situ tests to expand and improve correlations and applications by applying existing experience and databases from one test and extrapolating to the other test.

Robertson (2012) suggested an update to the CPT-based soil behavior type chart using behavior type descriptions. The objective of this paper is to present a modified chart to estimate soil type using normalized DMT parameters and to suggest a new chart using soil behavior type descriptions.

2 CPT-BASED SOIL BEHAVIOUR TYPE

One of the major applications of the CPT has been determination of soil stratigraphy and the identification of soil type. This has been accomplished using charts that link cone parameters to soil type. Early charts using cone resistance, q_c and friction ratio ($R_f = 100\ f_s/q_c$) were proposed by Douglas and Olsen (1981), but the charts proposed by Robertson et al. (1986) and Robertson (1990) have become very popular (e.g. Long, 2008).

Robertson et al (1986) and Robertson (1990) stressed that the CPT-based charts were predictive of soil behavior, and suggested the term 'soil behavior type' (SBT), because the cone responds to the in-situ mechanical behavior of the soil (e.g. strength, stiffness and compressibility) and not directly to soil classification criteria using geologic descriptors based on physical characteristics, such as grain-size distribution and soil plasticity (e.g. Unified Soil Classification System, USCS). Grain-size distribution and Atterberg Limits are measured on disturbed soil samples. Fortunately, soil classification criteria based on grain-size distribution and plasticity often relate reasonably well to in-situ soil behavior (at least for young, uncemented soils) and hence, there is often good agreement between USCS-based classification and CPT-based SBT (e.g. Molle, 2005). However, several examples can be given when differences can arise between USCS-based soil types and CPT-based SBT. For example, a soil with 60% sand and 40% fines may be classified as 'silty sand' (sand-silt mixtures) or 'clayey sand' (sand-clay mixtures) using the USCS. If the fines have high clay content with high plasticity, the soil behavior may be more controlled by the clay and the SBT will reflect this behavior and will generally predict a more clay-like behavior, such as 'silt mixtures - clayey silt to silty clay'. If the fines were non-plastic, soil behavior can be controlled more by the sand and the SBT will generally predict a more sand-like soil type, such as 'sand mixtures - silty sand to sandy silt'. Very stiff, heavily overconsolidated fine-grained soils tend to behave more like a coarse-grained soil in that they tend to dilate under shear and can have high undrained shear strength compared to their drained strength and can have a SBT in either clayey silt or silty sand. These few examples illustrate that SBT may not always agree with traditional USCS-based soil types based on samples and that the biggest difference is likely to occur in the mixed soils region (i.e. sand-mixtures & silt-mixtures). Geotechnical engineers are often more interested in the in-situ soil behavior than a classification based only on grain-size distribution and plasticity carried out on disturbed samples, although knowledge of both is helpful.

Robertson (1990) proposed using normalized (and dimensionless) cone parameters, Q_{t1}, F_r, B_q, to estimate soil behavior type, as well as soil behavior type index, I_c;

$$Q_{t1} = (q_t - \sigma_{vo})/\sigma'_{vo} \quad (1)$$

$$F_r = [(f_s/(q_t - \sigma_{vo})] \, 100\% \quad (2)$$

$$B_q = \Delta u / (q_t - \sigma_{vo}) \quad (3)$$

$$I_c = [(3.47 - \log Q_{t1})^2 + (\log F_r + 1.22)^2]^{0.5} \quad (4)$$

Where:

σ_{vo} = in-situ total vertical stress

σ'_{vo} = in-situ effective vertical stress

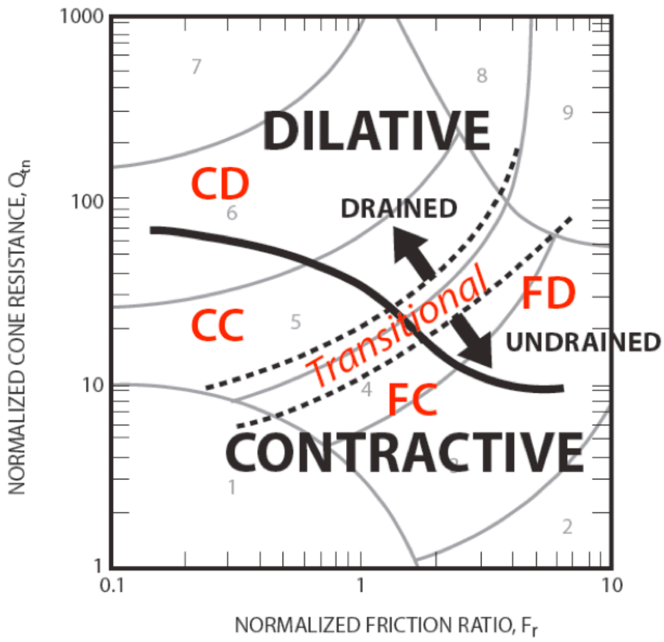
u_0 = in-situ equilibrium water pressure

Δu = excess penetration pore pressure = $(u_2 - u_0)$

In the original paper by Robertson (1990) the normalized cone resistance was defined using the term Q_{t1}. The term Q_{t1} is used here to show that the cone resistance is the corrected cone resistance, q_t and the stress exponent for stress normalization is 1.0.

In general, the normalized charts provide more reliable identification of SBT than the non-normalized charts, although when the in-situ vertical effective stress is between 50 kPa to 150 kPa there is often little difference between normalized and non-normalized SBT. The above normalization was based on theoretical work by Wroth (1984). Robertson (1990) suggested two charts based on either $Q_{t1} - F_r$ or Q_{t1} - B_q but recommended that the $Q_{t1} - F_r$ chart was generally more reliable, especially for onshore data.

The geotechnical profession has a long history of using simplified classification systems with geologic descriptors, and it will likely be some time before the profession fully accepts and adopts the more logical framework based on mechanical response measurements directly from the in-situ tests. However, Robertson (2012) suggested an updated version of the CPT SBT chart using descriptions based more on soil behavior, in an effort to move away from descriptions based on physical characteristics. The updated SBT chart also uses a modified normalized cone resistance, Q_{tn} that uses a variable stress exponent, based on soil type. A slightly modified version is shown in Fig. 1. Fig. 1 recognizes that uncemented coarse-grained soils with a state parameter (ψ) less than -0.05 and uncemented fine-grained soils with an OCR > 4 are generally dilative at large strains. Included in Fig. 1 is a region (dashed lines) that defines the approximate boundaries between drained and undrained response during a CPT.



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

Fig. 1. CPT-based soil behavior type (SBT) chart for soils with little or no microstructure (modified from Robertson, 2012)

Fig. 1 represents a simplified chart that identifies the four broad groups of soil behavior, where dilative and contractive response is defined at large strains. The chart applies mainly to soils that have little or no microstructure. The term microstructure is used to describe soils that have '*unusual*' characteristics (Leroueil and Hight, 2003) compared to '*ideal*' soils that have little or no microstructure. There are several causes for the development of microstructure in soils, such as: aging, cementation, stress and strain history, etc.

3 DMT PARAMETERS

The flat dilatometer is a stainless steel blade with a flat, circular steel membrane mounted flush on one side. The test involves two readings *A* and *B* that are corrected for membrane stiffness, gage zero offset and feeler pin elevation in order to determine the pressures p_0 and p_1. Readings are taken every 200 mm during a pause in the penetration and the corrected pressures p_0 and p_1 are subsequently used for interpretation. The original correlations were obtained by calibrating DMT results with high quality soil parameters from several test sites in Europe (Marchetti, 1980). Many of these correlations form the basis of current interpretation, having been generally confirmed by subsequent research.

The interpretation evolved by first identifying three "intermediate" DMT parameters (Marchetti 1980):

Material index, $I_D = (p_1 - p_0) / (p_0 - u_0)$ (5)

Horizontal stress index, $K_D = (p_0 - u_0)/\sigma'_{vo}$ (6)

Dilatometer modulus, $E_D = 34.7\ (p_1 - p_0)$ (7)

The Dilatometer modulus E_D can also be expressed as a combination of I_D and K_D in the form:

$$E_D/\sigma'_{vo} = 34.7\ I_D\ K_D \qquad (8)$$

The key DMT design parameters are I_D and K_D and both are normalized and dimensionless. I_D is the difference between the corrected lift-off pressure (p_0) and the corrected deflection pressure (p_1) normalized by the effective lift-off pressure ($p_0 - u_0$). K_D is the effective lift-off pressure normalized by the in-situ vertical effective stress. Alternate methods have been suggested to normalize K_D, but the original normalization suggested by Marchetti (1980) using the in-situ vertical effective stress is still the most common. It is likely that a more complex normalization for K_D would be more appropriate, especially in sands, but most of the available published records of K_D use the original normalization suggested by Marchetti (1980).

4 LINKS BETWEEN CPT AND DMT

Robertson (2009b) suggested a preliminary set of average correlations that link the main DMT parameters (I_D, K_D) to normalized CPT parameters (Q_{t1}, F_r). The proposed correlations are approximate and influenced by variations in in-situ stress state, soil density, stress and strain history, age, cementation and soil sensitivity. The correlations are unlikely to be unique for all soils but the suggested relationships form a framework for possible future refinements. The resulting correlations are shown in Fig. 2, in the form of contours of I_D, K_D on the CPT normalized SBT chart.

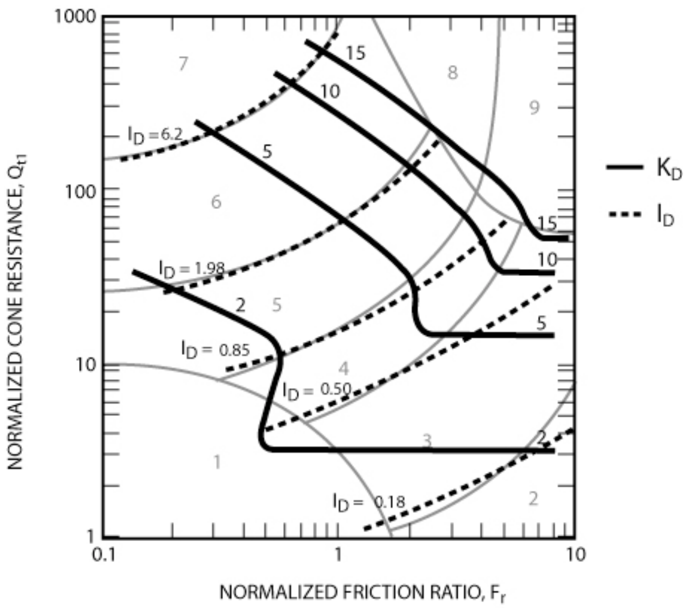


Fig. 2. Approximate correlation between DMT K_D and I_D and CPT normalized parameters for soils with little or no microstructure (After Robertson, 2010)

The proposed average CPT-DMT relationships are:

$$I_D = 10^{(1.67 - 0.67Ic)} \qquad (9)$$

$$K_D = 0.144\ Q_{t1} / [10^{(1.67 - 0.67Ic)}] \qquad (10)$$

$$K_D = \beta\ (Q_{t1})^{0.95} + 1.05 \qquad (11)$$

I_c is the CPT-based SBT Index, as defined by Robertson and Wride (1998). Equation 10 applies to coarse-grained soils when $I_c < 2.60$ and equation 11 applies to fine-grained soils when $I_c > 2.60$ and $0.30 < \beta < 0.7$, and varies with soil sensitivity with an average value for $\beta = 0.3$. An average relationship of:

$$E_D/\sigma'_{vo} = 34.7\ I_D\ K_D = 5Q_{t1} \qquad (12)$$

was used as an intermediate step to obtain the relationships between the normalized DMT parameters I_D, K_D and the normalized CPT parameter Q_{t1}.

Based on data presented by Tsai et al (2009) for young uncemented sandy soils ($I_D > 1.2$) and $K_D < 6$, Robertson (2012) suggested a simplified relationship between the CPT normalized clean sand equivalent cone resistance, $Q_{tn,cs}$ and K_D, as follows:

$$Q_{tn,cs} = 25\ K_D \quad (13)$$

$Q_{tn,cs}$ is calculated using the approach described by Robertson and Wride (1998).

Robertson (2012) also suggested a link between DMT K_D and state parameter (ψ) and peak friction angle (ϕ'), in sandy soils ($I_D > 1.2$):

$$\psi = 0.56 - 0.33 \log (25\ K_D) \quad (14)$$

$$\phi' = \phi'_{cv} + 15.84\ [\log (25\ K_D)] - 26.88 \quad (15)$$

Equation 14 predicts smaller (i.e. denser) values for state parameter (ψ) than that suggested by Yu (2004). Yu (2004) would suggest that a $K_D = 4$ in a loose sand ($K_0 = 0.5$) when $\psi = 0$, whereas, equation 14 suggests a more reasonable value of $K_D = 2$ in a loose sand when $\psi = 0$. Equation 15 correctly predicts values for ϕ' that are slightly larger than the current method suggested my Marchetti et al (2001) for estimating the lower bound peak friction angle. Equation 15 has the advantage that it incorporates the importance of soil mineralogy via the constant volume (critical state) friction angle, ϕ'_{cv}.

5 DMT-BASED SOIL BEHAVIOR TYPE

Marchetti and Crapps (1981) suggested a chart to estimate soil type based on I_D and E_D, as shown in Fig. 3. Marchetti et al (2001) described that the parameter I_D was reflecting the mechanical behavior (i.e. SBT) and not the physical characteristics used in most classification systems (e.g. USCS). Marchetti et al (2001) also stated that the chart applies primarily to "normal" soils, (i.e. soils with little or no microstructure). Unfortunately, the original DMT-based chart is not dimensionless, since it uses the derived parameter E_D.

An alternate form of Fig. 3 is shown in Fig. 4 based on the dimensionless terms of I_D and E_D/σ'_{vo}. When represented in terms of dimensionless parameters (I_D and E_D/σ'_{vo}) contours of K_D can be added (using equation 8). At a depth where the vertical effective stress, σ'_{vo} = 100 kPa (= 1 bar), Fig. 3 and 4 are essentially the same.

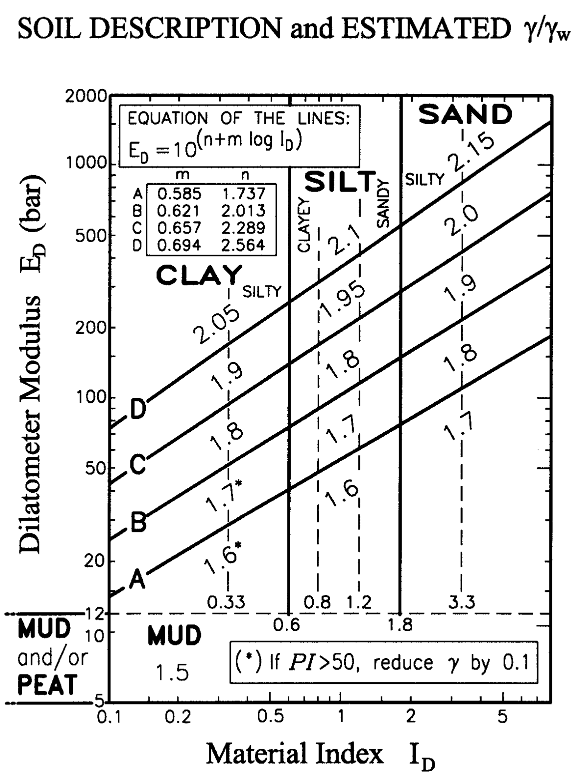


Fig. 3. DMT-based chart for soil type and unit weight based on I_D and E_D (After Marchetti and Crapps, 1981)

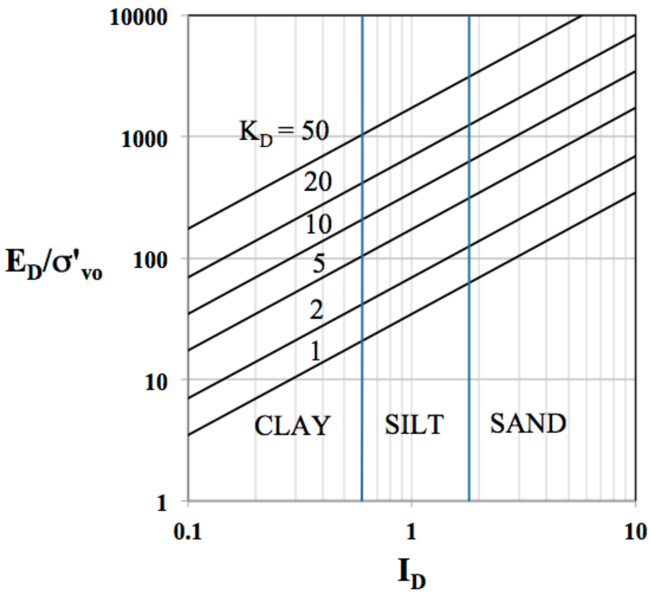


Fig. 4. Modified DMT-based chart for soil type based on dimensionless I_D and E_D/σ'_{vo}

Ideally any DMT-based chart for soil type should be based on the main dimensionless parameters of K_D and I_D. Fig. 5 presents a proposed modified chart to estimate soil type (or SBT) based on the main DMT parameters, K_D and I_D.

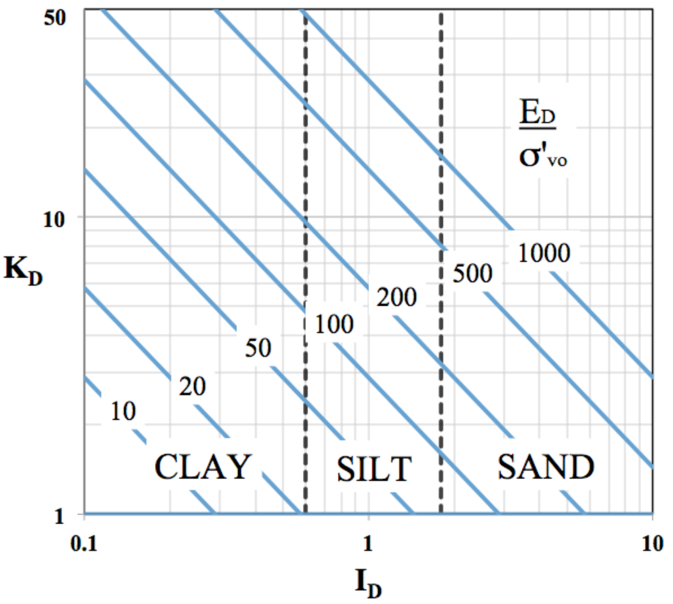


Fig. 5. Proposed modified DMT-based chart for soil type based on I_D and K_D

Marchetti (1980) had suggested a correlation to estimate the 1-D constrained modulus, M_{DMT} from the DMT. Although the original correlation is based primarily on linking M_{DMT} with E_D, it's possible to show the relationship (in normalized form) on the modified chart using equation 8, as shown on Fig. 6.

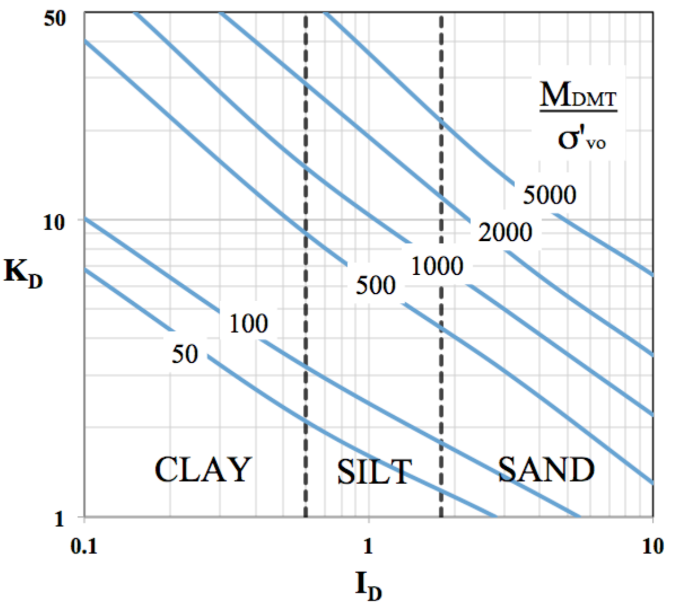


Fig. 6. Contours of M_{DMT}/σ'_{vo} plotted on modified DMT-based chart for soil type based on I_D and K_D (based on Marchetti, 1980)

With a growing database from seismic DMT (SDMT) Marchetti (2014) suggested a relationship between DMT parameters and the small strain shear modulus, G_o derived from the measured shear wave velocity. Based on this relationship, it is also possible to develop approximate contours of normalized G_o/σ'_{vo} on the modified chart, as shown on Fig. 7.

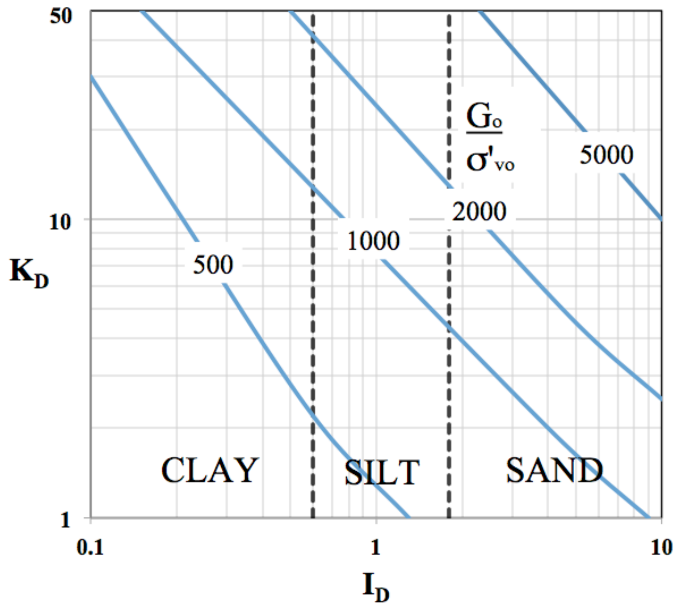


Fig. 7. Contours of G_o/σ'_{vo} plotted on modified DMT-based chart for soil type based on I_D and K_D (based on Marchetti, 2014)

The modified chart for soil type provides a framework to evaluate both existing and new correlations based on basic DMT parameters.

K_D provides the basis for several soil parameter correlations and is a key parameter from the DMT. Marchetti (1980) suggested that K_D could be regarded as the in-situ horizontal stress ratio, K_0, amplified by the DMT penetration. In genuinely normally consolidated clays (i.e. no microstructure) the value of K_D is $K_{D(NC)} \approx 2$. The K_D profile is similar in shape to the *OCR* profile and hence, is generally helpful for understanding the soil deposit and its stress history (Marchetti 1980).

Marchetti (1980) showed that K_D is strongly influenced by the overconsolidation ratio (OCR) and proposed that OCR in fine-grained soils can be estimated from the DMT using:

$$OCR = (0.5\ K_D)^{1.56} \qquad (16)$$

Hence, the contours of K_D shown in Fig. 4 also reflect contours of OCR (based on equation 16) when $I_D < 1.0$.

Robertson (2012) suggested that for fine-grained soils with little or no microstructure, the boundary between contractive and dilative behavior at large strains occurs when OCR ≈ 4. Based on Marchetti (1980) and equation 16, 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 14, this corresponds to a $K_D \approx 3$. A contour between $3 < K_D < 5$ is shown on Fig. 8 to represent the approximate boundary between dilative and contractive behavior at large strains for soils with little or no microstructure.

Fig. 8 is preliminary and will need further evaluation but is presented here as a possible future direction to evaluate soil behavior type (SBT) based on DMT data.

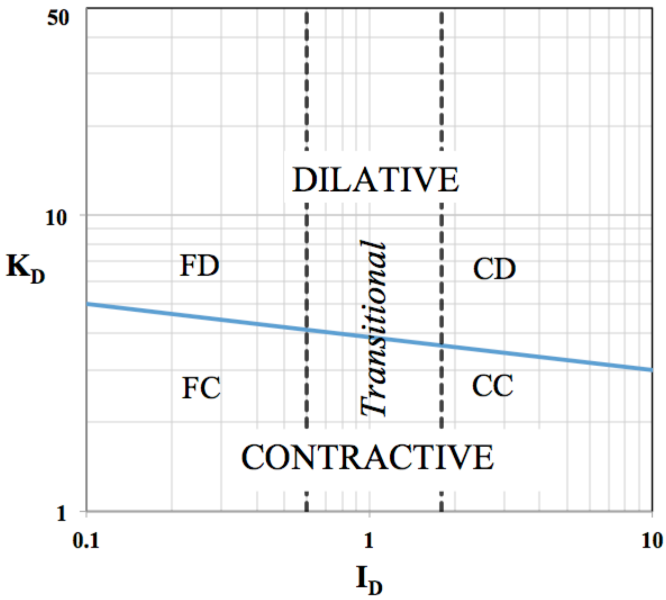


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Fig. 8. Proposed DMT-based soil behavior type (SBT) chart for soils with little or no microstructure

It is interesting to note that the suggested boundary between contractive and dilative soils is not defined by a single value for K_D for all soils. Marchettit (1980) had suggested the original K_D normalization using the in-situ vertical effective stress. It is likely that a more complex normalization for K_D would be more appropriate, especially in coarse-grained soils, similar to the manner in which the CPT normalized penetration resistance Q_{tn} is normalized (Robertson, 2009a).

6 COMBINED CPT-DMT

Experience suggests that K_D is more sensitive to factors that cause microstructure, such as stress and strain history, age, cementation (bonding) than the normalized cone resistance, Q_{t1}. Since most empirical correlations for penetration tests are based on case histories from soils with little or no microstructure, it is helpful if the existence of microstructure in soils (e.g. age, cementation, etc.) can be estimated from in-situ tests.

Robertson (2012) suggested that the seismic CPT (SCPT) be used to identify soils with microstructure. A similar potential is possible using the SDMT (Marchetti, 2014), and Fig. 7 is one approach. If the measured G_o (based on measured shear wave velocity) is significantly larger than the estimated value based on Fig. 7, the soils likely have some microstructure. The larger the difference between measured and estimated G_o, the larger the influence of microstructure. An alternate approach is to use a combination of CPT and DMT. Tsai et al (2009) presented data from a number of sites in Taiwan that experienced soil liquefaction and showed a relationship between the CPT normalized clean sand equivalent cone resistance, $Q_{tn,cs}$ and K_D. The data from Tsai et al (2009) is reproduced in Fig. 9. The data was from predominately young uncemented sandy soils with $I_D > 1.2$. Robertson (2012) had suggested an average relationship given by equation 12. In general, it appears that young uncemented sandy soils generally have $Q_{tn,cs} > 16\ K_D$. Soils with significant microstructure tend to have $Q_{tn,cs} < 16\ K_D$.

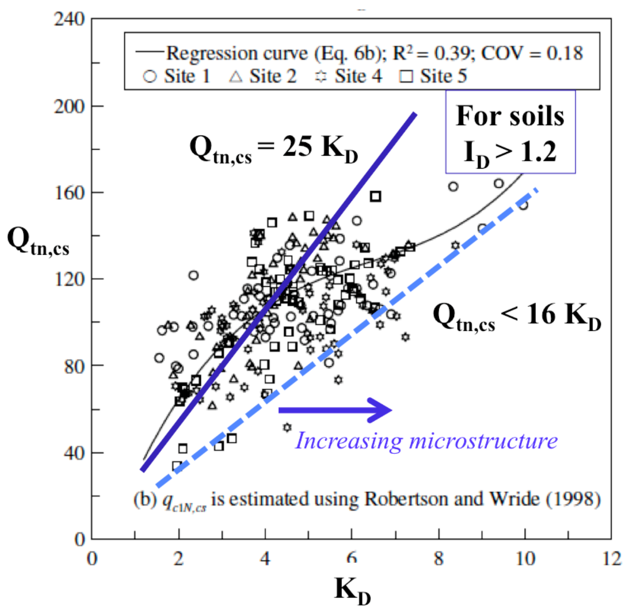

Fig. 9. Relationship between CPT $Q_{tn,cs}$ and K_D for young, uncemented sandy soils ($I_D > 1.2$) (data from Tsai et al, 2009)

7 SIMPLIFIED CPT-DMT LINK

Robertson (2010) suggested a link between CPT and DMT, as shown in Fig. 2. Recent pairs of CPT and DMT (e.g. Togliani et al, 2015) suggest a more simplified link that applies to young, uncemented soils (i.e. soils with little or no microstructure) that can be represented by the following simple expression:

$$Q_{t1} = A\, I_D\, K_D \qquad (17)$$

Where A appears to vary primarily with soil type and can be approximated, as follows:

$$A = (1.5\log I_D + 7.5) \qquad (18)$$

This simplified relationship can be represented by contours of Q_{t1} on the DMT K_D - I_D SBT chart, as shown in Fig. 10.

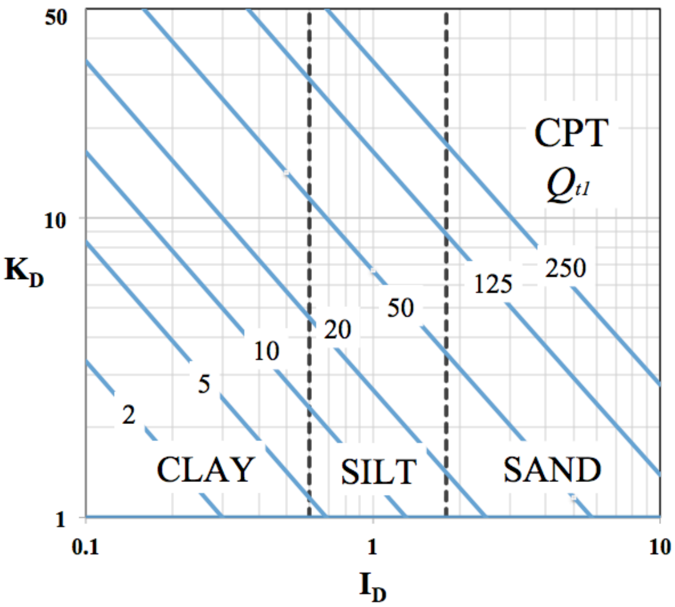

Fig. 10. Simplified link between CPT Q_{t1} and DMT K_D - I_D for young, uncemented soils
$Q_{t1} = (1.5\log I_D + 7.5)\, I_D\, K_D$

8 CONCLUSIONS

The CPT and DMT are the most promising in-situ penetration tests currently used in practice. Each test has advantages and limitations. Relationships between the two in-situ tests can be used to expand and improve correlations and applications using experience and databases from one test and extrapolating to the other test. Since the CPT is faster, less expensive and provides a near continuous profile, it is often used more than the DMT, especially for smaller, low risk projects. However, the DMT has been shown to be more sensitive to factors that cause microstructure in soils, such as, age, cementation, stress and strain history, etc. Hence, there are advantages of combining both tests. Depending on the size, scope and risk of the project, it is recommended that about 80% of the penetration testing be performed using the CPT (ideally the SCPTu) and about 20% using the DMT. At some locations the CPT and DMT should be performed adjacent (within 1m) to provide better correlation. Since each test is not at exactly the same location (i.e. same soil) care is required when comparing data within the same soil deposit to ensure valid correlation. Average values should be used in each stratigraphic unit.

The correlations presented in this paper hopefully provide some insight into the links between the CPT and DMT. A modified chart to estimate soil type using the main DMT normalized parameters (I_D, K_D) is presented. Existing correlations for normalized M_{DMT} and G_o are presented as contours on the modified DMT chart to provide insight into the correlations. A new soil behavior type (SBT) chart is also presented using generalized soil behavior descriptions (e.g. coarse-grained dilative, fine-grained contractive, etc.). A method of combined CPT and DMT is suggested to evaluate if soils have significant microstructure that may influence the interpretation and application of the test results. A simplified link between CPT (Q_{t1}) and DMT (K_D and I_D) is also presented that applies to soils with little or no microstructure.

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