CPT-DMT Correlations

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Abstract: Although the cone penetration test (CPT) and flat-plat dilatometer test (DMT) have been used for over 30 years, relatively little has been published regarding comprehensive correlations between the two in situ tests. This paper presents preliminary correlations between the main parameters of the CPT and DMT. The key to the proposed correlations is the recognition that the main DMT parameters are normalized and hence, should be correlated with normalized CPT parameters. The suggested correlations are developed and evaluated using published records and existing links to various other parameters as well as comparison profiles. The suggested correlations may guide future more detailed correlations between these two in situ tests.

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Introduction

The current electric cone penetration test (CPT) was developed in the Netherlands in the 1960s 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 other places around the world.

The flat-plat dilatometer test (DMT) was developed in Italy by Professor Silvano Marchetti in the 1980s and has become popular in some parts of the world. The DMT is simple, robust, repeatable and economical. However, the DMT is harder to push in very stiff ground compared to the CPT and the DMT is carried out every 20 cm whereas CPT readings are taken every 2–5 cm. The DMT requires a pause in the penetration to perform the test. Hence, the DMT produces less data than the CPT and is also slower than the CPT. 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 appears to correlate well with particular geotechnical parameters. For example, the CPT provides correlations with undrained shear strength and overconsolidation ratio (OCR) in fine-grained soils and peak friction angle in coarse-grained soils. The CPT is commonly used for pile design and to evaluate the potential for soil liquefaction. The DMT also provides correlations with undrained shear strength and OCR in fine-grained soils and correlations with one-dimensional constrained modulus for a wide range of soils. Both tests can be used to estimate consolidation/drainage parameters such as the coefficient of consolidation and permeability from dissipation tests. However, in the past 30 years relatively little has been published regarding comprehensive links between the CPT and DMT parameters.

The objective of this paper is to review published records of nearby CPT and DMT soundings as well as existing correlations for geotechnical parameters in an effort to identify possible correlations between normalized in situ test parameters. The key in the approach is the recognition that DMT interpretation parameters are normalized and will likely correlate with normalized CPT parameters.

Flat-Plat Dilatometer Test

The DMT was developed in Italy by Professor Silvano Marchetti. It was initially introduced in 1980 and is currently used in over 40 countries. Marchetti (1980) provided a detailed description of the DMT equipment, the test method, and the original correlations. Subsequently, the DMT has been used and calibrated in soil deposits all over the world. Various international standards and manuals are available for the DMT. Marchetti et al. (2001) prepared a comprehensive report on the DMT for Technical Committee 16, ISSMGE.

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, gauge zero offset, and feeler pin elevation in order to determine the pressures p_0 and p_1. Readings are taken every 20 cm during a pause in the penetration and the corrected pressures p_0 and p_1 are subsequently used for interpretation. The original correlations (Marchetti 1980) were obtained by calibrating DMT results with high quality soil parameters from several test sites in Europe. 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)

$$\text{Material index, } I_D = (p_1 - p_0)/(p_0 - u_0) \qquad (1)$$

$$\text{Horizontal stress index, } K_D = (p_0 - u_0)/\sigma'_{vo} \qquad (2)$$

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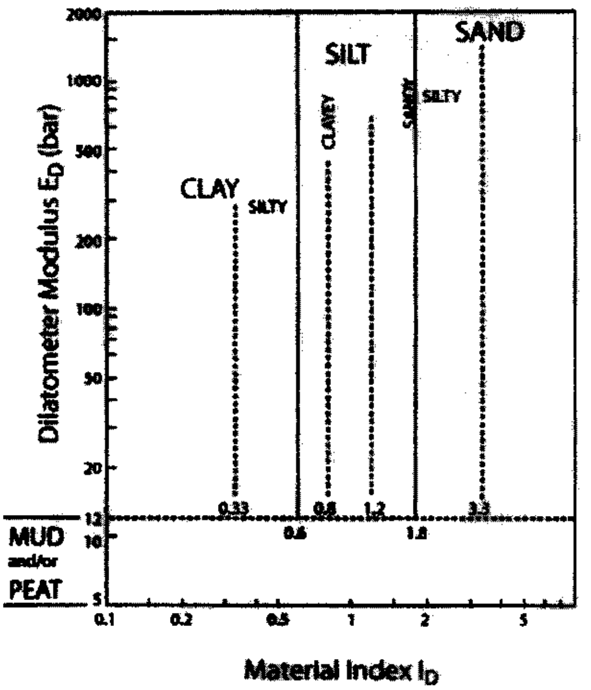

Fig. 1. Chart for estimating soil type and unit weight γ using the DMT [normalized to $\gamma_w = \gamma$ water; modified from Marchetti et al. (2001)]. Note that 1 bar = 100 kPa.

$$\text{Dilatometer modulus, } E_D = 34.7(p_1 - p_0) \tag{3}$$

where u_0=preinsertion in situ equilibrium water pressure and σ'_{vo}=preinsertion in situ vertical effective stress.

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

$$E_D/\sigma'_{vo} = 34.7 I_D K_D \tag{4}$$

The key DMT design parameters are I_D and K_D. Both parameters 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. Although alternate methods have been suggested to normalize K_D, the original normalization suggested by Marchetti (1980) using the in situ vertical effective stress is still the most common and is used in this paper. 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).

According to Marchetti (1980), the soil type can be identified as follows:

- Clays $I_D < 0.6$
- Silt mixtures $0.6 < I_D < 1.8$
- Sands $I_D > 1.8$

Marchetti (1980) suggested that I_D is a parameter reflecting the mechanical behavior of the soil and not a soil classification based on grain size distribution and plasticity. The link between I_D and soil type is shown in Fig. 1, which shows that I_D can range from 0.1 to 10 and is often presented on a log scale.

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 aging, structure, cementation) the value of K_D is $K_{D,\text{NC}} \approx 2$. 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 in clays (Marchetti 1980).

Cone Penetration Test

The CPT was first introduced in The Netherlands in the 1930s as a mechanical test and in the 1960s the cone was updated to incorporate electric strain-gauged load cells. Various international standards and manuals are available for the CPT and Lunne et al. (1997) presented a comprehensive book on the CPT.

The CPT is a cylindrical probe pushed into the ground at 2 cm/sec with essentially continuous readings of the tip stress, q_c, sleeve friction stress, f_s and sometimes the penetration pore pressure, u_2, typically measured behind the cone. The tip stress, q_c is corrected for unequal end area effects to a total cone stress of q_t. (Campanella and Robertson 1982). Although a similar correction can be made to the sleeve stress, f_s, the correction is rarely made when the cone has an equal end-area sleeve (Lunne et al. 1997).

Robertson (1990), based on the work of Wroth (1984), suggested using the following normalized CPT parameters to identify soil behavior type (SBT)

$$Q_{t1} = (q_t - \sigma_{vo})/\sigma'_{vo} \tag{5}$$

$$F_r = [f_s/(q_t - \sigma_{vo})]100\% \tag{6}$$

$$B_q = (u_2 - u_0)/(q_t - \sigma_{vo}) = \Delta u/(q_t - \sigma_{vo}) \tag{7}$$

where σ_{vo}=preinsertion in situ total vertical stress; σ'_{vo}=preinsertion in situ effective vertical stress; u_0=preinsertion in situ equilibrium water pressure; u_2=measured pore pressure (behind the cone); and $\Delta u = (u_2 - u_0)$=excess penetration pore pressure.

In the original paper by Robertson (1990) the normalized cone resistance was defined using the term Q_t. 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. Although alternate methods to normalize CPT results have been suggested (e.g., Olsen and Malone 1988; Jefferies and Davies 1991; Robertson and Wride 1998; Moss et al. 2006; Cetin and Isik 2007), especially in sands, and are more appropriate for a wide range of soils, the original normalization suggested by Wroth (1984), and shown in Eq. (5), will be used here to be consistent with the simple normalization used by Marchetti (1980) for DMT K_D results. Hence, DMT K_D and CPT Q_{t1} parameters are normalized in a consistent manner using the vertical effective stress. In the fullness of time, it is likely that DMT data will become normalized using more complex techniques and that future CPT-DMT correlations can use more appropriate normalized parameters. However, for typical stress levels in geotechnical engineering of about 65–200 kPa (i.e., about 4–20 m), the normalization method has little influence on the normalized parameters.

Similar to Marchetti (1980), Robertson (1990) suggested that the CPT parameters reflect the mechanical behavior of the soil and not a soil classification based on grain size distribution and plasticity. Robertson (1990) suggested the term SBT to reflect the mechanical characteristics of the soil measured using the CPT.

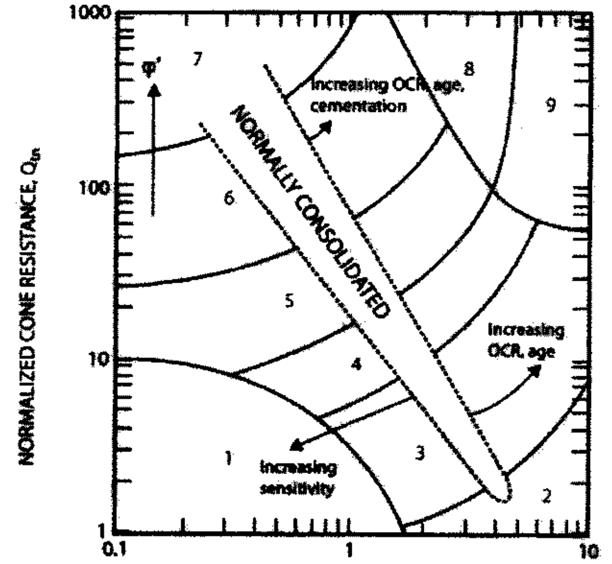

Fig. 2. Normalized SBT charts for CPT (after Robertson 1990)

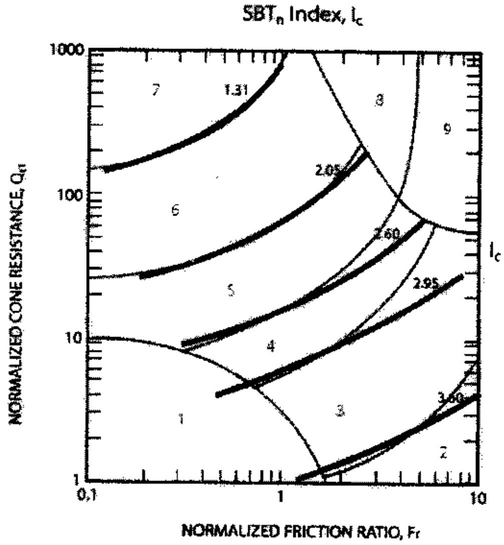

Fig. 3. Contours of SBT index, I_c on CPT normalized SBT $Q_{t1}-F_r$ chart

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, as shown in Fig. 2.

Jefferies and Davies (1993) identified that a SBT index, I_c, could represent the SBT zones in the $Q_{t1}-F_r$ chart where I_c is essentially the radius of concentric circles that define the boundaries of soil type. Robertson and Wride (1998) modified the definition of I_c to apply to the $Q_{t1}-F_r$ chart, as defined by

$$I_c = [(3.47 - \log Q_{t1})^2 + (\log F_r + 1.22)^2]^{0.5} \tag{8}$$

Contours of the SBT index I_c, are shown on Fig. 3, where Q_{t1} is based on Eq. (5).

The CPT SBT index I_c can be used to represent the boundaries between different soil types, where (Robertson and Wride 1998)

- Clays $I_c > 2.95$.
- Silt mixtures $2.05 < I_c < 2.95$.
- Sands $I_c < 2.05$.

In general terms, the CPT SBT I_c can vary from 1 to 4.

Cone Penetration Test–Dilatometer Test Correlations

Relatively few comprehensive correlations have been published between the DMT and normalized CPT parameters. Campanella and Robertson (1991) suggested a link between normalized cone resistance, q_t/σ'_{vo} and K_D, in sands. Marchetti et al. (2001) suggested there was a link between the DMT constrained modulus (M_{DMT}) and cone resistance, q_t. Mayne and Liao (2004) suggested a link between I_D and friction ratio (F_r) and between E_D and q_t, based on DMT and CPT data in Piedmont residuum soils. Mayne (2006) suggested interrelationships between the basic DMT measurements (p_0 and p_1) and the CPTu measurements (q_t and u_2) in soft clays.

Many indirect correlations exist between DMT and CPT results, since both tests are used to estimate various geotechnical parameters. The main correlations used for both CPT and DMT results to estimate geotechnical soil parameters are for OCR, undrained shear strength, peak friction angle and soil modulus. Correlations also exist for hydraulic permeability and shear wave velocity.

The literature has been reviewed for published records of documented sites where adjacent CPT and DMT results are available. Table 1 shows a summary of the published records from adjacent CPT and DMT profiles in a wide range of soils. The depth range for the data shows that the methods used to normalized the results generally had little influence on the parameters. Unfortunately, some of the published records do not include access to the digital records of either CPT or DMT results and therefore, estimates were made of the range in parameters from the published plots. Fortunately, digital records were available for some of the published sites, and these are identified in Table 1.

Soil Type

Since DMT I_D and CPT I_c are both used to identify soil type, there is a strong possibility that a link exists between these normalized parameters. It is recognized that both parameters have the following range:

- DMT $0.1 < I_D < 10$.
- CPT $1.0 < I_c < 4.0$.

Fig. 4 presents a summary of the published records in terms of log I_D versus I_c. Included on Fig. 4 are the common soil type regions that overlap for both the CPT and DMT. Although individual values at each depth within a profile could be presented, the plots become crowded and confusing with many data points. Comparison between individual values from nearby in situ test profiles at the same depth often show considerable scatter due to variations in soil stratigraphy and consistency since many sites are not uniform. Hence, adjacent in situ test data from the same depth may not always represent the same soil. Any comparison between in situ tests should be done in terms of the near continuous profiles with depth so that any variation in soil stratigraphy can be identified from the profiles. However, when there are a large number of sites for comparison it is common to compare

Table 1. Published Records from Adjacent DMT-CPT Profiles

No.	Site	Soil	Reference	Depth range (m)	DMT range I_D	DMT range K_D	DMT range E_D/σ'_v	CPT range Q_{t1}	CPT range F_r (%)	CPT range I_c
1a	McDonald's Farm, BC, Canada	Deltaic sand	Campanella and Robertson 1991	5–12	3.0–8.0	2–6	200–600	40–120	0.3–0.6	1.6–1.9
1b	McDonald's Farm, BC, Canada	Soft silty clay	Campanella and Robertson 1991	17–30	0.2–0.3	2–3	14–30	2–4	1.5–2.5	3.3–3.6
2[a]	Bothkennar, U.K.	Soft clay	Mayne 2006	3–15	0.3–0.4	2–3	15–35	4.5–6	1.0–2.0	2.9–3.2
3[a]	Amherst, MA, U.S.A.	Soft varved sensitive clay	Mayne 2006	6–10	0.2–0.3	3.5–5	20–40	4–6	1.0–2.5	3.1–3.3
4[a]	Ford Center, IL, U.S.A.	Soft glacial clay	Mayne 2006	7–16	0.1–0.3	3–5	10–40	4–6	1.5–3.0	3.1–3.3
5a	Venice Lagoon, Italy	Medium dense sand	Marchetti et al. 2006	4–5	4.0–6.0	3–6	400–600	80–100	0.4–0.6	1.6–1.8
5b	Venice Lagoon, Italy	Soft clayey silt	Marchetti et al. 2006	29–30	0.3–0.5	2–3	20–50	5–7	2.0–3.0	3.0–3.3
6	Zelezny Mine, Poland	Loose silty sand–tailing	Mlynarek et al. 2006	5–20	2.0–4.0	1.2–2.5	130–200	40–80	0.5–0.9	1.8–2.1
7	Hydraulic Fill, Brazil	Loose silt and fine sand–fill	Penna 2006	4–8	0.2–0.3	2–3	14–30	5–8	1.5–3.0	2.9–3.3
8[a]	Baton Rouge, LA, U.S.A.	Stiff fissured clay	Mayne 2006	10–30	0.5–0.8	4–10	80–175	10–20	2.5–3.0	2.8–3.0
9[a]	Georgia Piedmont, U.S.A.	Stiff silty sand to sandy silt—residual soil	Mayne and Liao 2004	4–12	1.2–1.8	2.7–5.0	110–300	25–55	1.4–2.2	2.3–2.5
10[a]	Alabama Piedmont, U.S.A.	Stiff silty sand, sandy silt—residual soil	Mayne and Liao 2004	2–10	1.1–1.6	4–5	150–250	35–45	4.0–5.0	2.5–2.7
11[a]	North Carolina Piedmont, U.S.A.	Stiff silty sand to clayey silt—residual soil	Mayne and Liao 2004	2–12	0.7–0.9	3–6	70–180	12–30	7.0–9.0	2.9–3.2
12[a]	Cooper Marl, SC, U.S.A.	Stiff cemented silt	Meng et al. 2006	20–30	0.2–0.4	6–10	40–140	15–20	0.9–1.2	2.5–2.7
13[a]	Tainan, Taiwan	Silty sand	C. H. Juang and D.-H. Lee, personal communication, 2008	6–12	1.5–2.5	4–8	300–500	80–150	0.9–1.0	1.7–2.2
14[a]	Tainan, Taiwan	Silty clay	C. H. Juang and D.-H. Lee, personal communication, 2008	4–8	0.3–0.6	2–4	30–50	8–12	2–3	2.9–3.1
15	Cowden, U.K.	Very stiff clay	Powell and Uglow 1988	4–10	0.5–0.7	5–10	100–150	20–60	1.5–2.5	2.5–2.7
16	Brent Cross, U.K.	Very stiff clay	Powell and Uglow 1988	2–10	0.4–0.8	5–15	100–200	20–45	2.0–3.5	2.6–2.8
17	Madingley, U.K.	Very stiff clay	Powell and Uglow 1988	2–12	0.5–0.8	8–16	100–300	30–50	3.5–6.0	2.6–2.9
18	Pisa Clay	Soft sensitive clay	M. Jamiolkowski, personal communication, 2008	12–20	0.2–0.3	3–4	30–50	5–7	0.4–1.0	2.9–3.1
19	Univ of Central Florida, U.S.A.	Sand to silty sand	Anderson et al. 2007	3–5	2.0–5.0	4–8	300–800	80–150	0.4–1.0	1.5–1.8

[a]Sites where digital data for both CPT and DMT were available.

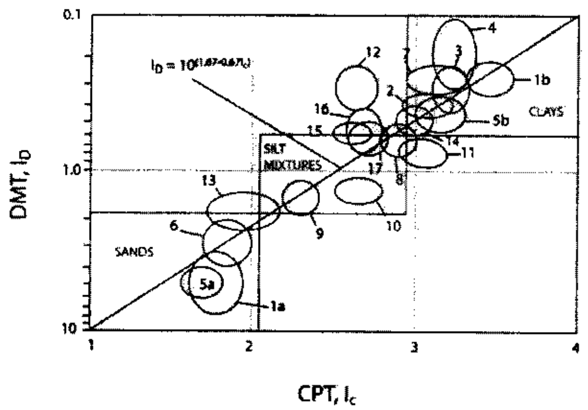

Fig. 4. Summary of published average values from adjacent CPT and DMT profiles of I_D versus I_c (see Table 1 for site details)

values obtained at the same depth within relatively uniform sections of a deposit. Sand deposits tend to be highly variable in consistency (e.g., relative density and grain characteristics) and plots of individual data points from nearby in situ tests can show large scatter. To simplify the presentation of comparison data a range of values are shown that represent the approximate average values within each relatively uniform section of a deposit. Some sites have more than one relatively uniform deposit within the profile and these are represented by a set of values for each uniform deposit. Presentation of average values also aids in the inclusion of published records where digital results were not available and where only estimates of average values were made from published plots.

Fig. 4 shows a trend between I_D and I_c that can be defined using the following simple relationship:

$$I_c = 2.5 - 1.5 \log I_D \tag{9}$$

or

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

Mayne and Liao (2004) suggested a correlation between DMT I_D and CPT F_r for Piedmont residuum in the form

$$I_D = 2.0 - 0.14\, F_r \tag{11}$$

The published records, as presented in Table 1, do not support this relationship over a wider range of soils. However, for some soils there can be a site specific or geologic link between I_D and F_r, since natural soils tend to plot within one region of the $Q_{t1}-F_r$ chart and normally to lightly overconsolidated soils tend to plot down the center of the chart, as indicated in Fig. 2. The proposed correlation between I_D and I_c, represented by Eq. (10), would appear to be more general than the relationship between I_D and F_r proposed by Mayne and Liao (2004).

Robertson and Wride (1998) had suggested that the boundary between sand-like and clay-like soils (sandy silt to silty clay) occurs at about I_c=2.60. Fig. 1 shows that the same soil type boundary for the DMT is about I_D=1.0 (Marchetti 1980), which, based on Eq. (10), corresponds to I_c=2.50. Hence, the boundary between sand-like and clay-like soils corresponds approximately to I_c=2.60 and I_D=1.0. In a general sense, CPT and DMT results are drained in sand-like soils and undrained in clay-like soils.

Clay-Like Soils (I_c>2.60, I_D<1.0)

Douglas and Olsen (1981) and Robertson et al. (1986) identified that F_r decreases with increasing soil sensitivity, as indicated in Fig. 2. In fine-grained clay-like soil, the CPT normalized friction ratio, F_r, is strongly influenced by soil sensitivity, whereas the normalized cone resistance, Q_{t1} is strongly influenced by OCR, but with a small influence from soil sensitivity (Robertson 2009). In fine-grained soils it appears that the DMT K_D is also strongly linked to OCR but with a small influence from soil sensitivity (Marchetti 1980). There is evidence that K_D increases slightly as soil sensitivity increases due to the higher pore pressures generated around the DMT probe during penetration (Robertson et al. 1988). Therefore, in fine-grained clay-like soils, there is likely a strong link between K_D and Q_{t1}, but essentially independent of F_r.

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

$$\mathrm{OCR} = (0.5\, K_D)^{1.56} \tag{12}$$

Mayne and Martin (1998) presented a summary of published studies linking K_D with OCR and showed that most have a form similar to that suggested by Marchetti (1980). Analytical studies for the DMT (e.g., Mayne and Bachus 1989; Smith and Houlsby 1995; Mayne 2001) confirm the general form of the relationship in Eq. (12), and show that the relationship is influenced by the shear strength, stiffness and compressibility of the soil.

Kulhawy and Mayne (1990) showed that the normalized cone resistance, Q_{t1}, was also strongly influenced by OCR and proposed that OCR in fine-grained soils could be estimated from the CPT using

$$\mathrm{OCR} = 0.3\, Q_{t1} \tag{13}$$

Mayne (2001) and Yu (2004) summarized analytical solutions for the CPT linking Q_{t1} with OCR and showed that most have the same general form as suggested by Kulhawy and Mayne (1990) and show that the relationship is also influenced by shear strength, stiffness, and compressibility of the soil.

Combining Eqs. (12) and (13) gives

$$K_D = 0.88(Q_{t1})^{0.64} \tag{14}$$

Based on the well-known relationship between undrained shear strength ratio and OCR (Wroth 1984; Ladd 1991), a slightly modified CPT method can be developed to estimate OCR in fine-grained soils using

$$\mathrm{OCR} = 0.24(Q_{t1})^{1.25} \tag{15}$$

Combining Eqs. (12) and (15) gives

$$K_D = 0.8(Q_{t1})^{0.80} \tag{16}$$

Robertson et al. (1988), Campanella and Robertson (1991), and Mayne (2006) showed that, in soft clays, the DMT corrected lift-off pressure (p_0) is dominated by the excess pore pressures around the DMT probe, and that the excess pore pressure around the DMT is similar to the excess pore pressure around the CPT (i.e., u_2). Recently Schneider et al. (2008) suggested an alternate CPT soil type chart based on normalized pore pressure, in the form of $\Delta u_2/\sigma'_{vo}$ versus Q_{t1}. Using critical state soil mechanics and a cavity expansion model, Schneider et al. (2008) developed a series of relationships between $\Delta u_2/\sigma'_{vo}$ and Q_{t1} for insensitive clays in the form

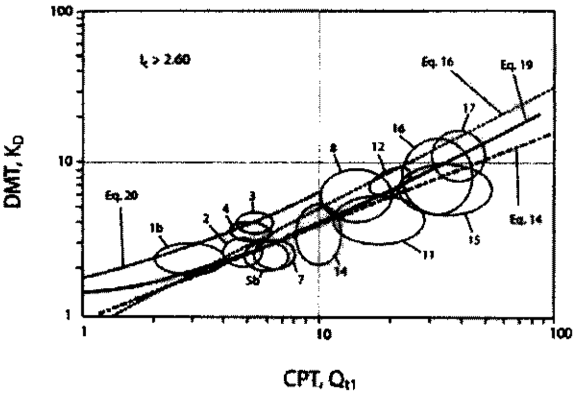

Fig. 5. Summary of published average values from adjacent CPT and DMT profiles of Q_{t1} versus K_D in fine-grained soils where $I_c > 2.60$ (see Table 1 for site details)

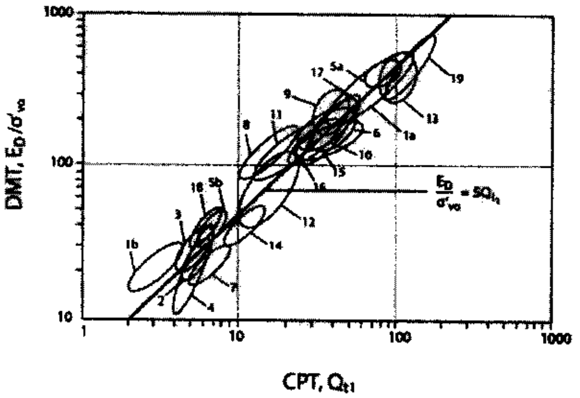

Fig. 6. Summary of published average values from adjacent CPT and DMT profiles of Q_{t1} versus E_D/σ'_{vo} (see Table 1 for site details)

$$\Delta u_2/\sigma'_{vo} = \beta(Q_{t1})^{0.95} + 1.05 \tag{17}$$

The constant β varies between $0.2 < \beta < 0.5$ as the assumed values for the undrained shear strength ratio for normally consolidated soils varies between $0.20 < (s_u/\sigma'_{vo})_{NC} < 0.30$ and soil rigidity index varies between $30 < I_R < 200$, with an average $\beta = 0.3$ that represents

$$(s_u/\sigma'_{vo})_{NC} = 0.25 \text{ and rigidity index, } I_R = 200 \tag{18}$$

Based on the observation that the corrected lift-off pressure (p_0) is essentially equal to the excess pore pressures (u_2) around the probe in clays, it follows that

$$K_D = (u_2 - u_0)/\sigma'_{vo} = \Delta u_2/\sigma'_{vo} = \beta(Q_{t1})^{0.95} + 1.05 \tag{19}$$

where, on average, $\beta = 0.3$.

Hence, K_D should have similar values as the CPT parameter $\Delta u_2/\sigma'_{vo}$ in soft clays. The relationship in Eq. (19) produces values for K_D that are remarkably similar to and are essentially bounded by values from Eqs. (14) and (16), when $0.5 > \beta > 0.2$, respectively. Eq. (19) was developed using a hybrid critical state-cavity expansion model for the CPT and assuming that the corrected DMT lift-off pressure (p_0) is essentially equal to the CPT pore pressures (u_2) around the probe. Eqs. (14) and (16) were developed empirically based on case history observations with OCR.

Fig. 5 presents a summary of the published records in terms of log K_D versus log Q_{t1}, when $I_c > 2.60$. Included on Fig. 5 are the relationships represented by Eqs. (14), (16), and (19). Eq. (19) (with $\beta = 0.3$) appears to provide the best overall fit to the field comparison data over the full range of values. Eq. (19) also shows the correct trend in very soft clays (i.e., at low values of Q_{t1}), where $1.0 < K_D < 2.0$. The slightly higher measured values for K_D in the region where $Q_{t1} < 10$, may be due to high penetration pore pressures around the DMT probe in sensitive soils, since more sensitive soils generate higher pore pressures during probe penetration (Schneider et al. 2008). Schneider et al. (2008) also developed a relationship for excess CPT pore pressures in sensitive clays of the form

$$\Delta u_2/\sigma'_{vo} = 0.67(Q_{t1})^{0.91} + 1.1 \tag{20}$$

Eq. (20) can be related to K_D (assuming $K_D = \Delta u_2/\sigma'_{vo}$) and is also shown on Fig. 5 in the region where $Q_{t1} < 10$. Eq. (20) represents an approximate upper bound to the measured values. The clays from sites 1b, 3, and 4 are somewhat sensitive and plot closer to Eq. (20), as predicted.

Sand-Like Soils ($I_c \leq 2.60$, $I_D > 1.0$)

The DMT parameter K_D is used extensively in many correlations for the DMT. Marchetti (1980) noted that for most normally consolidated, uncemented, young soils, $K_D \sim 2.0$. Robertson (1990) noted that most normally consolidated, uncemented, young soils plot down the center of the $Q_{t1} - F_r$ chart, as shown in Fig. 2. Hence, there is a possibility that, in coarse-grained soils, K_D varies with both Q_{t1} and F_r and likely follows approximately the region marked "normally consolidated" on Fig. 2.

Possible $E_D - Q_{t1}$ Relationship

Mayne and Liao (2004) presented CPT and DMT data from three sites with Piedmont residual soils that are silty sands to sandy silts with very high small strain stiffness that is possibly associated with cementation and suggested a correlation between E_D and q_t, as follows:

$$E_D = 5\, q_t \tag{21}$$

Professor Mayne kindly made the digital CPT and DMT records available for these and other published sites. The data from these three sites fit equally well in terms of net cone resistance, $q_{net} = (q_t - \sigma_{vo})$, since $q_t \gg \sigma_{vo}$ at these sites. Hence

$$E_D = 5(q_t - \sigma_{vo}) \tag{22}$$

The normalized form then becomes

$$E_D/\sigma'_{vo} = 5\, Q_{t1} \tag{23}$$

Fig. 6 presents a summary of the published records for all the soils in terms of E_D/σ'_{vo} versus Q_{t1} (both on log scales), and shows that Eq. (23) provides a reasonable average fit to the data. The range of values presented in Fig. 6 suggests that the relationship can be represented in a more general manner by

$$E_D/\sigma'_{vo} = \alpha Q_{t1} \tag{24}$$

Based on Fig. 6, it would appear that $2 < \alpha < 10$, where α may vary with relative density, age, and stress history in a manner similar to the variation of the CPT modulus factor, α_E, with these factors (Baldi et al. 1989; Lunne et al. 1997). Based on the published field records shown in Fig. 6, it would appear that a value of $\alpha=5$ is a reasonable average for a wide range of soils where $5<Q_{t1}<200$.

The data presented on Fig. 6 span a wide range of soils, from coarse-grained soils where the CPT and DMT results are essentially drained, to fine-grained soils where the test results are essentially undrained. Fig. 6 also includes some "unusual soils" (Schnaid et al. 2004) where the small strain stiffness (G_o) is significantly higher than would be expected from the cone resistance (i.e., high G_o/q_t ratios). This confirms the observation made by Campanella and Robertson (1991) that the DMT modulus E_D is essentially a large strain response.

Since E_D/σ'_{vo} is also a function of I_D and K_D [Eq. (4)], it follows that:

$$34.7 I_D K_D = 5\ Q_{t1} \tag{25}$$

hence

$$K_D = 0.144\ Q_{t1}/I_D \tag{26}$$

Using the link between I_D and I_c [Eq. (10)], this becomes

$$K_D = 0.144\ Q_{t1}/[10^{(1.67-0.67Ic)}] \tag{27}$$

hence, there appears to be an approximate relationship between DMT K_D and CPT Q_{t1} for different values of I_c in a wide range of soils where $5<Q_{t1}<200$. Since Eq. (27) is based on an average value of $\alpha=5$, the relationship between K_D and Q_{t1} will not be unique for all soils, since α may vary with soil type, relative density, age, and stress history. However, Eq. (27) may represent a framework for future refinements, as more well-documented comparison data becomes available. Although alternate normalization techniques could be used to normalize both K_D and Q_{t1}, any influence on the correlation in Eq. (27) will likely be small, provided consistent normalization is applied to both parameters. Also for typical stress levels in geotechnical engineering of about 65–200 kPa (about 4–20 m), the normalization has little influence on the CPT SBT index, I_c. When $I_c>2.60$ ($I_D<1.0$) the relationship between K_D and Q_{t1} may be better captured by Eq. (19) (see Fig. 5).

Proposed Cone Penetration Test–Dilatometer Test Correlations

With the above observations as a framework [i.e., Eqs. (10), (19), and (23)], approximate contours of DMT I_D and K_D were developed on the normalized CPT soil behavior chart $Q_{t1}-F_r$, as shown in Fig. 7. Fig. 7 shows that K_D varies with both normalized Q_{t1} and F_r, except in the region defined by $I_c>2.60$ ($I_D<0.85$), where K_D likely becomes essentially independent of F_r.

The proposed correlations can be summarized, as follows:

$$I_D = 10^{(1.67-0.67Ic)} \tag{28}$$

$$K_D = 0.3(Q_{t1})^{0.95} + 1.05 \quad \text{when } I_c > 2.60 \tag{29}$$

$$E_D/\sigma'_{vo} = 5\ Q_{t1} \tag{30}$$

The correlation for K_D can be sensitive to the cutoff for I_c when CPT data fall on or close to the boundary between fine-grained and coarse-grained soils. The suggested cutoff in Eq. (29) is $I_c>2.60$. However, some soils can straddle this value which can result in a rapid variation in estimated DMT K_D values depending on the values for Q_{t1} and F_r. If this occurs the cut-off

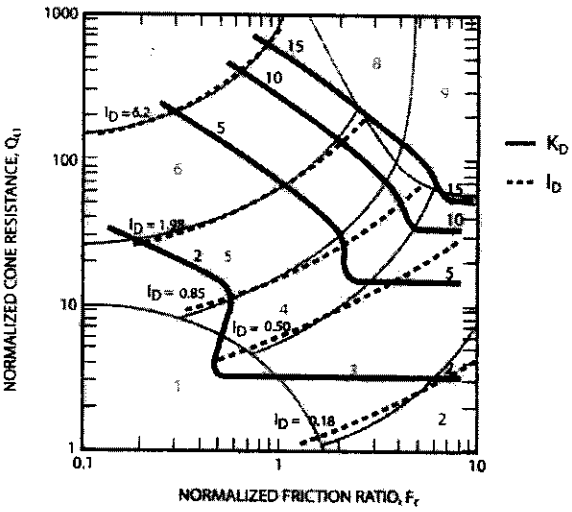

Fig. 7. Proposed contours of DMT K_D and I_D on the CPT normalized SBT $Q_{t1}-F_r$ chart

value for I_c can be modified slightly to obtain a more smooth profile of predicted K_D. The suggested correlations for K_D shown in Fig. 7 identifies a possible transition zone in the region comprised of silt mixture soils where $2.40<I_c<2.90$ (i.e., $1.2>I_D>0.60$). This region represents a transition from primarily drained CPT and DMT in sands ($I_c<2.40$ and $I_D>1.2$) to primarily undrained CPT and DMT in clays ($I_c>2.90$ and $I_D<0.60$). DMT results in this transition region of silt-mixture soils can be further influenced by possible drainage during the pause between penetration and testing.

The contours for K_D shown in Fig. 7 where $I_c<2.60$ ($I_D>0.85$) were based on $E_D/\sigma'_{vo}=5\ Q_{t1}$. This relationship could be extended to stiff soils, where $I_c>2.60$ ($I_D<0.85$) and $Q_{t1}>20$, since the suggested contours change little in form in this region. This is confirmed by the results presented by Mayne and Liao (2004) for the stiff Piedmont soils that included one site (site 11) where $I_c>2.60$.

The suggested contours for K_D in Fig. 7 may partly explain the somewhat poor published correlations between K_D and relative density (D_r) and peak friction angle (ϕ'_p) in coarse-grained soils.

The proposed correlations between normalized CPT parameters (Q_{t1} and F_r) and DMT parameters (I_D, K_D, and E_D) are approximate and will likely be influenced by variations in in situ stress state (i.e., Ko), soil density, stress history, age, cementation, and soil sensitivity. The general relationship for K_D in Eq. (29) for fine-grained soils where $Q_{t1}<10$ will tend to under predict K_D in sensitive fine-grained soils, as illustrated in Fig. 5. The proposed correlations are unlikely to be unique for all soils but the contours shown in Fig. 7 may form a framework for future refinements.

The profiles of measured cone resistance (q_t) may also differ slightly from those of adjacent DMT since the CPT senses soil slightly ahead and behind the cone tip due to the size of the zone of influence. Ahmadi and Robertson (2005) showed that the cone can sense a soil interface up to 15 cone diameters ahead and behind, depending on the strength/stiffness of the soil and the in situ effective stresses. The DMT appears to be less influenced by soil layers ahead and behind since the probe is stopped and the membrane expanded in a horizontal direction. Hence, in interbed-

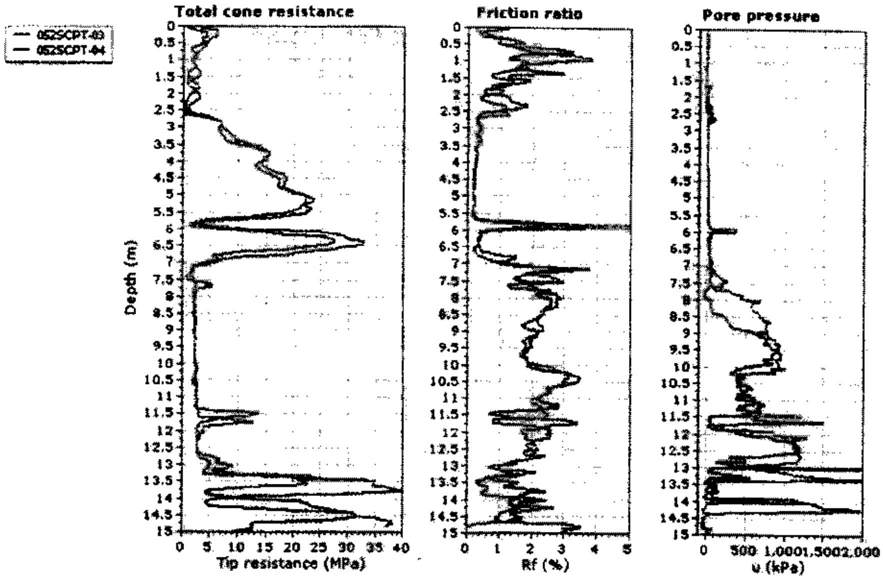

Fig. 8. CPT profile at Moss Landing site (Woodward Marine), California

ded soils the CPT may be influenced by adjacent soil layers somewhat more than the DMT.

Recently, two CPTs and one DMT were carried out at adjacent locations only 1 m apart at the Moss Landing site (Woodward Marine) in California. Details about the Moss Landing site are provided by Boulanger et al. (1997). The results from two adjacent CPT soundings at Moss Landing are shown in Fig. 8. The site is composed of about 2.6 m of silty sand to silt over about 4.4 m of sand. Below the sand is a deposit of firm plastic clay extending to a depth of 13.4 m. A thin soft clay layer is at a depth of 6 m within the sand deposit. The ground water level is at a depth of about 2.2 m below ground surface but fluctuates somewhat with the tide. The two CPT profiles show good repeatability in terms of tip resistance (q_t) and friction ratio (R_f) down to about 11 m, after which the sand layers show considerable differences in terms of depth, thickness, and density, especially the sand layers between 13 and 15 m. Some soil liquefaction was observed at shallow depth at the site during the 1989 Loma Prieta earthquake (Boulanger et al., 1997). A comparison between measured and predicted DMT parameters (I_D, K_D, and E_D) with depth based on one of the CPT profiles (CPT-04), using Eqs. (28)–(30), is shown in Fig. 9. Note that the Moss landing data were not used in developing the correlations shown in Figs. 4–6. The comparison plots for I_D and E_D are presented on log scales to present the range of values more clearly. In general, the comparison between measured DMT parameters and those predicted from the CPT using the proposed correlations show reasonable trends. The rapid and large variations in both I_D and E_D are fully captured. It is interesting to note the small scale effect where the CPT appears to sense the soft clay layer at a depth of about 6 m, which is earlier than the DMT responds to the same layer. Eq. (19) underpredicts K_D in the clay layer between 7.5 and 13 m where I_c values are close to or slightly larger than 2.60. In places, (e.g., at 8.7 and 12 m) the CPT I_c values fall just below the cutoff of 2.60 which produces a sudden change in predicted K_D. This illustrates the sensitivity of the proposed correlations for K_D in transition (silt-mixture) soils where $2.40 < I_c < 2.90$. The predicted DMT values are significantly different from the measured values between 12.5 and 14 m, which may, in part, be due to rapid variations in these sand layers, as indicated from the two CPT profiles shown in Fig. 8. In general, the Moss Landing site provides a good test for the proposed correlations since the soils range from soft to firm clay and loose to dense sand.

Marchetti (1997) has suggested that the DMT is more sensitive to a "surface crust" than the CPT. However, previous published comparisons were carried out using non-normalized CPT parameters. It is possible that the CPT may also be sensitive to a surface crust when the comparison is carried out using normalized values, since the normalized cone resistance (Q_{t1}) increases close to the ground surface due to the low vertical effective stresses.

Conclusions

The CPT and DMT have been used worldwide for over 30 years. Each test has certain advantages and limitations (Mayne et al. 2002). A preliminary set of correlations is proposed that links the key DMT parameters (I_D, K_D, and E_D) to normalized CPT parameters (Q_{t1} and F_r). The proposed correlations are approximate and will likely be influenced by variations in in situ stress state, soil density, stress history, age, cementation, and soil sensitivity. The proposed correlations are unlikely to be unique for all soils but the suggested relationships may form a framework for future refinements. The proposed general relationship for K_D in fine-grained soils ($I_c > 2.60$) will tend to under predict K_D in sensitive soils. The trends in the proposed correlations illustrated in Fig. 7 may provide further insight into possible future correlations for the DMT with other geotechnical parameters and design applications since the CPT has a somewhat more extensive theoretical background compared to the DMT as well as a larger database of documented case histories for certain applications (e.g., liquefaction evaluation).

The correlations presented are based on a simple but consistent normalization of the key parameters (K_D and Q_{t1}). The resulting correlations between normalized CPT and DMT parameters

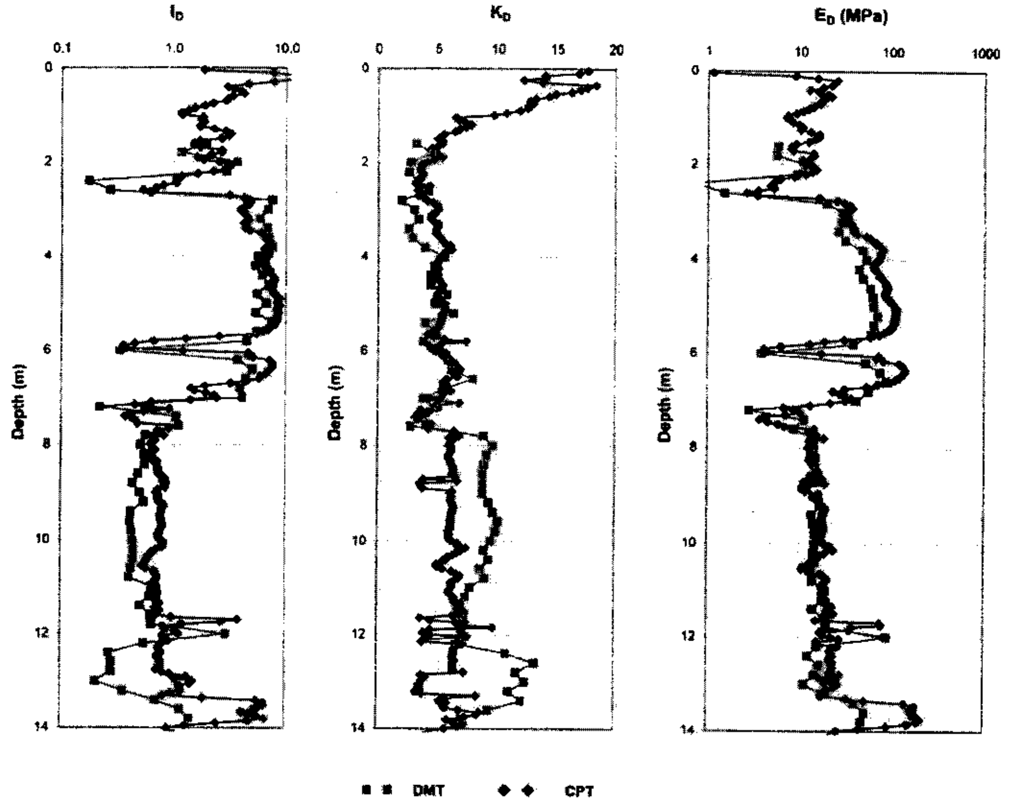

Fig. 9. Comparison between measured DMT parameters (I_D, K_D, and E_D) with depth and predicted parameters using the CPT at Moss Landing site, California. Note that I_D and E_D are presented on log scale.

may be somewhat influenced by the normalization technique. However, provided consistent normalization methods are applied to each in situ test the correlations may not change significantly, although further research will be required to verify this assumption.

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