

Combined use of CPT & DMT: background, current trends and ongoing developments

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ABSTRACT: This paper aims to introduce and stimulate the discussion on the use of CPT & DMT and on the potential of their mutual integration for enhanced site characterization and geotechnical design. It provides a brief overview of background information, current trends and ongoing developments on the combined use of CPT & DMT testing. Specific issues addressed in the paper include: (a) CPT-DMT comparisons and inter-relationships; (b) derivation of soil parameters from combined CPT & DMT data; (c) applications based on combined CPT & DMT data.

1 INTRODUCTION

The use of in-situ testing for geotechnical site characterization has continued to expand over the past few decades, gaining an increasing role over the traditional practice based on drilling and sampling for laboratory testing. Often today in-situ tests represent the major part of a site investigation, particularly in geomaterials that are difficult to sample and test using conventional methods (e.g., sands, tailings, semi-liquid soils). Mayne et al. (2009) summarized the key advantages of in-situ tests: (a) they can be done relatively quickly as compared with laboratory tests, (b) results are available immediately, (c) large numbers of data are obtained, and (d) vertical and lateral variability can be assessed over the site.

In this context, the cone/piezcone penetration test (CPT/CPTu) and the flat dilatometer test (DMT) have proven to be particularly efficient and expedient for routine site investigations. In fact: (a) both are direct-push probes, which do not need a borehole for advancement, (b) multiple measurements are collected from a single sounding, (c) the data are obtained digitally and can be accessed for use immediately after completion of the sounding or even in real-time during advancement of the probe, (d) their instrumental accuracy is high, unlike “older” techniques such as the standard penetration test (SPT), (e) technological upgrades, such as additional sensors or full automation (e.g., Medusa DMT, Marchetti et al. 2019), can be easily implemented.

The use of direct-push in-situ tests providing multi-measurements was emphasized by Mayne et al. (2009) as a more efficient approach to geotechnical site characterization. Particularly beneficial and versatile is their “hybrid” configuration that combines the

advantages of full-displacement penetrometer probes with downhole geophysics (seismic piezocone SCPTu, seismic dilatometer SDMT), capable to provide information on soil behavior from the small- to the large-strain range.

A single SCPTu sounding provides up to five independent measurements: the basic CPTu measurements (cone resistance q_t , sleeve friction resistance f_s , pore pressure u_2), the shear wave velocity V_S , and information on soil consolidation / permeability parameters if dissipation tests are performed by monitoring the u_2 decay with time (e.g., time to reach 50% degree of consolidation, t_{50}). A single SDMT sounding provides a comparable number of independent measurements: the basic DMT pressure measurements (A , B and optional C corrected to p_0 , p_1 , p_2 respectively), the shear wave velocity V_S , as well as the compression wave velocity V_P when using the SPDMT configuration equipped with two pairs of receivers for S- and P-wave (Amoroso et al. 2020), and information on soil consolidation / permeability parameters if dissipation tests by monitoring the A -pressure decay with time are performed (e.g., reference time in the A -decay curve, t_{flex}).

For these reasons, Mayne et al. (2009) suggested that the SCPTu and SDMT direct-push tests should serve as the basis for the minimum required level of effort in routine and daily site investigation practices by the profession, in order that adequate amounts and sufficiently different types of data are collected for a given project. These data are complemented with sampling and laboratory testing.

The CPT and the DMT have in common the same equipment for insertion (push rig, rods) and a similar range of soil type applications (clays, silts, sands). Both tests are utilized in site investigations to obtain

information on stratigraphy, soil types and parameters to be used with general or dedicated design methods. However, each test has advantages and limitations and may prove more adequate in specific applications. E.g., the CPT is commonly used for pile design and liquefaction assessment, the DMT generally provides good predictions of settlements of shallow foundations.

In common practice, the CPT is often the preferred primary in-situ test, supported by a much larger consolidated use. On the other hand, the DMT can provide distinctive contributions in a routine site investigation: (1) information on stress history, which has a dominant influence on soil behavior; (2) being an in-situ pressure-displacement test, the DMT results are more closely related to “working strain” soil stiffness than penetration tests.

Some questions that may arise are then: are the two in-situ tests equivalent? Is one test (CPT or DMT alone) self-standing and sufficient for exhaustive geotechnical site characterization? Are there any advantages in the combined use of CPT & DMT?

One notable emerging trend (Marchetti 2015, Marchetti & Monaco 2018) is the increasing diffusion in site investigation practice of a “multi-parameter / multi-test” approach, based on the combination of CPT & DMT. This approach benefits, besides from the multiple measurements provided by a single CPT or DMT sounding, also from the combination of the different measurements obtained from nearby CPT and DMT soundings. Examples of application of a multi-parameter / multi-test approach based on the combined use of CPT & DMT are illustrated in this paper, aiming to stimulate the discussion on the potential of the mutual integration of these two in-situ tests for enhanced site characterization and geotechnical design. The terms ‘CPT’ and ‘DMT’ are herein intended in a general sense, referring to any equipment configurations (i.e., CPT(u), SCPT(u); DMT, SDMT, Medusa (S)DMT).

2 CPT-DMT CORRELATIONS

Interrelationships between CPT & DMT parameters can be helpful to expand and improve correlations and applications by using existing experience and databases from one test and extrapolating to the other (Robertson 2012).

Robertson (2009a) reviewed published records of data from nearby CPT and DMT soundings, as well as existing correlations for geotechnical parameters, in an effort to identify possible intercorrelations. The key in this approach was the recognition that, since the main DMT interpreted parameters are normalized, they should be correlated with normalized CPT parameters. Correlations were tentatively established between the three “intermediate” DMT parameters, i.e., the material index I_D , the horizontal stress index K_D and the dilatometer modulus E_D (Marchetti 1980), and the CPT normalized cone resistance Q_{t1} ,

normalized friction ratio F_r and Soil Behavior Type (SBT) Index I_c , defined as follows:

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \quad (1)$$

$$K_D = \frac{p_0 - u_0}{\sigma'_{v0}} \quad (2)$$

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

$$Q_{t1} = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \quad (4)$$

$$F_r = \left[\frac{f_s}{(q_t - \sigma_{v0})} \right] 100(\%) \quad (5)$$

$$I_c = \left[(3.47 - \log Q_{t1})^2 + (\log F_r + 1.22)^2 \right]^{0.5} \quad (6)$$

where p_0 = corrected first DMT pressure reading, p_1 = corrected second DMT pressure reading, q_t = corrected cone resistance, f_s = sleeve friction resistance, u_0 = pre-insertion in situ equilibrium pore pressure, σ_{v0} = in situ total vertical stress, σ'_{v0} = in situ effective vertical stress.

Robertson (2009a) explained that in most of the available published records the DMT K_D is normalized by σ'_{v0} as in the original formulation (Eq. 2) proposed by Marchetti (1980). Therefore, the CPT cone resistance Q_{t1} was normalized by σ'_{v0} in a consistent manner, i.e., assuming the exponent for stress normalization $n = 1$, as originally proposed by Robertson (1990), although currently used updated formulations (e.g., Robertson 2009b) refer to a normalized cone resistance Q_m that uses a variable n :

$$Q_m = \left[\frac{(q_t - \sigma_{v0})}{p_a} \right] \left(\frac{p_a}{\sigma'_{v0}} \right)^n \quad (7)$$

where p_a = atmospheric pressure in same units as q_t and σ_v , n = stress exponent that varies with SBT I_c (for $n = 1$, $Q_m = Q_{t1}$).

In addition, stress normalization for K_D is a debated issue. Robertson (2009a, 2015) suggested that a more complex normalization for K_D , similar to Q_m , would likely be more appropriate, especially in sands, and future CPT-DMT correlations could use more suitable normalized parameters. However, for typical stress levels in geotechnical engineering of about 65-200 kPa (i.e., ≈ 4 -20 m) the normalization method has little influence on the normalized parameters, hence updated CPT-DMT correlations using a different normalization may not change significantly. On the other hand, Marchetti (2015) remarked that a linear increase with depth of the DMT p_0 (i.e., a nearly constant K_D calculated using $n = 1$) is observed to large depths at

various test sites. In contrast, the increase of the CPT q_t with depth is generally less than linear, corresponding to $n < 1$. Such a different trend was attributed by Marchetti (2015) to the fact that the DMT blade, having a rectangular cross section with a width/thickness ratio ≈ 6 , is less affected by arching than a conical probe, resulting in a more linear trend of p_0 with depth which justifies $n = 1$ for K_D .

The preliminary set of average CPT-DMT correlations proposed by Robertson (2009a) is:

$$I_D = 10^{(1.67-0.67I_c)} \quad (8)$$

When $I_c \leq 2.60$ (i.e., for sand-like soils):

$$K_D = \frac{0.144Q_{t1}}{[10^{(1.67-0.67I_c)}]} \quad (9a)$$

When $I_c > 2.60$ (i.e., for clay-like soils):

$$K_D = \beta(Q_{t1})^{0.95} + 1.05 \quad (9b)$$

$$E_D/\sigma'_{v0} = 5Q_{t1} \quad (10)$$

where the constant β varies with soil sensitivity ($0.30 < \beta < 0.7$), with an average value $\beta = 0.3$.

The correlations for I_D , K_D (Eqs 8, 9a, 9b) depend on soil type, reflected in the CPT index I_c , which is a function of both Q_{t1} and F_r . These correlations are shown in Figure 1 in the form of contours of DMT I_D , K_D on the CPT normalized SBT chart $Q_{t1} - F_r$.

The relationship between DMT I_D and CPT I_c (Eq. 8) was established considering that both parameters are used to identify soil type. It is noted that I_D , likewise I_c , is a parameter reflecting the mechanical soil behavior, not a soil classification index based on real grain size distribution (Marchetti 1980). Robertson & Wride (1998) suggested that $I_c = 2.60$ can be assumed as an approximate boundary between sand-like and clay-like soils. Based on Eq. 8, $I_c = 2.60$ corresponds roughly to $I_D \approx 1$. In a general sense, CPT and DMT results are drained in sand-like soils ($I_c \leq 2.60$, $I_D > 1$) and undrained in clay-like soils ($I_c > 2.60$, $I_D < 1$). The correlation for K_D (Eqs 9a, 9b) can be sensitive to the cut-off $I_c = 2.60$ when CPT data fall close to the boundary between clay-like and sand-like soils. DMT results in the transition region of silt-mixture soils may also be influenced by partial drainage.

Robertson (2015), based on additional pairs of CPT & DMT (e.g., Togliani et al. 2015), suggested a more simplified link between CPT Q_{t1} and DMT K_D , I_D for young uncemented soils (i.e., soils with little or no microstructure):

$$Q_{t1} = (1.5 \log I_D + 7.5)I_D K_D \quad (11)$$

The (smoother) contours of DMT K_D corresponding to Eq. 11 are also plotted in Figure 1 (red dashed lines) on the CPT normalized SBT $Q_{t1} - F_r$ chart.

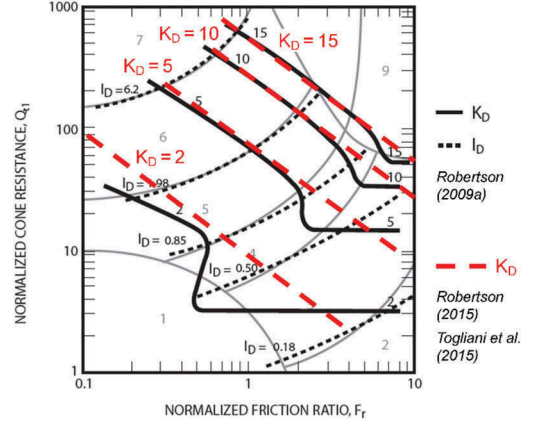


Figure 1. Contours of DMT K_D , I_D on the CPT normalized SBT $Q_{t1} - F_r$ chart for young uncemented soils (from Robertson 2017).

To stimulate a discussion on this topic, it is worth recalling what was observed by Robertson (2009a, 2015), i.e., the proposed CPT-DMT correlations are approximate and influenced by variations in in-situ stress state, soil density, stress and strain history, age, cementation, soil sensitivity. These correlations are unlikely to be unique for all soils, but they may form a framework for possible future refinements. Moreover, they 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 assessment). Marchetti (2011) recognized that procedures helpful for extracting as much information as possible from the field data represent a precious contribution since soil information is vital for the determination of reliable soil parameters for design, but costly to obtain. Correlations interconnecting CPT & DMT are useful in that translation formulas permit: (1) the use of interpretation methods or charts developed for one test with the results of the other test, (2) converting a database available for one test to a database for the other test. However, Marchetti (2011) stressed that intrinsic limits exist to the accuracy of the CPT-DMT translations, which, despite further refinements, are bound to remain of an approximate nature. These limits are mostly due to the different sensitivity to stress history

of the representative normalized CPT and DMT parameters, as will be discussed in the following.

A different theoretical approach for establishing interrelationships between the CPT and the DMT in soft clays has been explored by Mayne (2016), Ouyang & Mayne (2017, 2018) and earlier studies, based on a CPT-DMT compiled database in clays that progressively expanded over the years.

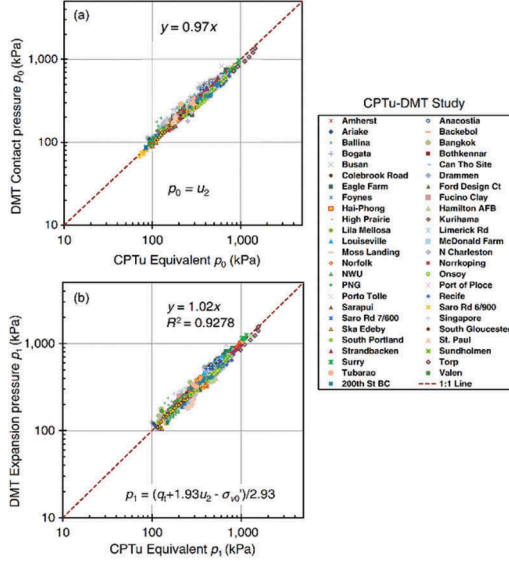


Figure 2. Comparison of DMT and CPTu-equivalent pressures p_0 (a) and p_1 (b) for 49 clays (adapted from Ouyang & Mayne 2018).

Mayne (2016) and Ouyang & Mayne (2017) established a theoretical nexus between CPTu readings (q_t and u_2) and DMT pressures (p_0 and p_1) based on spherical cavity expansion solutions for undrained penetration of both probes in soft firm clays. This nexus would permit an exchange of interpretations between the two tests, offering a complementary extension of methodologies. Data from paired sets of CPTu-DMT results in a variety of clays were used to support and validate the theoretical links. The net cone resistance, q_{net} , defined as:

$$q_{net} = q_t - \sigma_{v0} \quad (12)$$

was linked to the DMT pressure readings p_0 , p_1 by the following relationship:

$$q_{net} = 2.93p_1 - 1.93p_0 - u_0 \quad (13)$$

Ouyang & Mayne (2018) further expanded this concept and suggested that q_t and u_2 measured from

the CPTu can be utilized to duplicate equivalent DMT pressures p_0 and p_1 , and vice versa, according to the relationships:

$$p_0 = u_2 \quad (14)$$

$$p_1 = \frac{(q_t - 1.93u_2 - \sigma'_{v0})}{2.93} \quad (15)$$

Eq. 14 is in agreement with earlier studies (Mayne & Bachus 1989, Mayne 2006) that found the p_0 from DMT very similar to the pore pressures u_2 measured by CPTu in intact clays and clayey silts. Figure 2 shows a good agreement between the pressures p_0 , p_1 measured by DMT and their CPTu-equivalent p_0 , p_1 estimated by Eqs 14 and 15, based on 49 paired CPTu-DMT data sets in a variety of natural soft to firm clays and silts worldwide, having an overconsolidation ratio OCR between 1 to 2.5.

The approach proposed by Ouyang & Mayne (2017, 2018) is valid only for undrained penetration conditions, which are generally accepted to occur for both CPTu and DMT in low permeability clays at a standard penetration rate of 20 mm/s. The approach could be invalidated in intermediate permeability soils, such as silts, where drainage conditions may be different. The CPTu readings q_t and u_2 are taken during penetration (at time $t = 0$), whereas the DMT readings p_0 and p_1 are obtained at approximately $t = 15$ s and $t = 30$ s after penetration respectively, hence some pore pressure dissipation may have occurred prior to obtaining the DMT readings.

3 CPT VS. DMT DATA COMPARISONS

3.1 Sensitivity to stress history of DMT vs. CPT

The horizontal stress index K_D is a key parameter obtained from DMT interpretation. K_D reflects cumulatively various stress history effects (overconsolidation, aging, in-situ horizontal earth pressure, K_0), as summarized by Marchetti (2010).

Numerous researchers have observed that the DMT K_D is considerably more sensitive than the CPT cone resistance q_c in monitoring compaction in the field. The higher sensitivity of the DMT to stress history is confirmed by comparisons CPT-DMT in controlled calibration chamber (CC) testing conditions. Jamiolkowski & Lo Presti (1998), in CC tests in Ticino sand, found the DMT K_D much more sensitive to stress-strain history (including aging-like effects) than the CPT q_c . Lee et al. (2011) investigated the effects of stress history on CPT and DMT in CC testing on 40 large specimens of Busan sand having different relative density D_r and OCR in the range 1 to 8. The overconsolidation produced an almost negligible increase in the normalized cone resistance $q_c / (\sigma'_{v0})^{0.5}$ (Figure 3a), but a substantial increase in K_D (Figure 3b). It appears

that, while the normalized q_c reflects essentially D_r , and only to a minor extent OCR ,

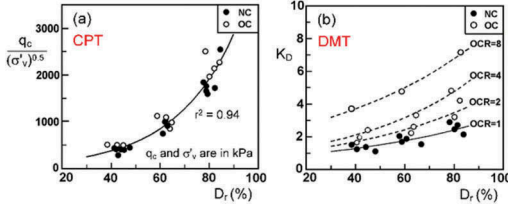


Figure 3. Effect of stress history on (a) normalized q_c from CPT, and (b) K_D from DMT in CC testing on Busan sand (modified from Lee et al. 2011).

K_D reflects not only D_r , but also stress history effects. The higher reactivity of K_D to OCR indicated by Figure 3, in agreement with other available experiences, implies that to the same normalized q_c may correspond different values of K_D (Marchetti 2016). In Figure 3a the coefficient of determination r^2 close to 1 for data points of any OCR suggests poor ability of the normalized q_c to distinguish OC from NC sands, hence estimating OCR from CPT alone appears problematic. This example supports the necessity of a multi-parameter/multi-test approach based on both DMT & CPT for estimating OCR in sand, as will be discussed in the following.

3.2 Soil parameters estimated from DMT vs. CPT

Many indirect correlations exist between DMT and CPT results, since both tests are used to estimate various geotechnical parameters.

The DMT interpretation is commonly based on the original correlations developed by Marchetti (1980) for “textbook” soils, although several updates, reviewed by Marchetti et al. (2001), have been proposed. Among the various parameters obtained from DMT, the 1-D constrained modulus M (M_{DMT}) is the most generally appreciated. According to Marchetti (1980) M_{DMT} is obtained from E_D (Eq. 3), which links soil stiffness to the p_0 and p_1 measured during membrane expansion (a “mini load test”), corrected as a function of I_D (soil type) and K_D (OCR). Several favorable comparisons in terms of both M_{DMT} vs. reference M and DMT-predicted vs. measured settlements have shown that, in general, M_{DMT} is a reasonable estimate of the “operative” or “working strain” modulus.

Numerous correlations have been proposed to estimate the constrained modulus M from CPT in various soil types. Typically, M is obtained by multiplying the cone resistance (q_c or q_t), or the net cone resistance ($q_t - \sigma_{v0}$), by an empirical coefficient α which depends on soil type and other soil properties, and may vary in a rather large range (e.g., 1 to 10).

Comparisons of moduli M estimated from DMT vs. CPT have been published by several authors. As an example, Amoroso et al. (2022a) compared the

depth profiles of M estimated from DMT and CPTu before/after ground improvement with Rammed Aggregate Piers (RAP) in silty and sandy soils at the Bondeno test site, Italy. In natural soils they found a rather good agreement between M estimated from DMT (Marchetti 1980) and from CPTu using the correlations proposed by Robertson (2009b), as shown in Figure 4, while other CPT-based correlations (Lunne & Christophersen 1983, Senneker et al. 1988) provided M equal to about half the values of M obtained from DMT and from Robertson (2009b). The agreement between the latter two methods is not surprising. In fact, the development of the CPT correlations for M by Robertson (2009b) was partly “guided” by the author’s correlations between normalized DMT and CPT parameters (Robertson 2009a), based on the recognition that M estimated from DMT has often been shown to provide excellent estimates of settlement (e.g., Monaco et al. 2006). However, Figure 4 also shows that in treated soils, using the same correlations, the increase in M from DMT was found much more evident than the increase in M from CPTu, suggesting higher ability of M_{DMT} to reflect the benefit of soil treatment.

As to the undrained shear strength (s_u) in clay, available comparisons of s_u from DMT vs. other tests at well-documented sites have often found that the depth profiles of s_u estimated from DMT (Marchetti 1980) plot in an intermediate position, in particular in between the s_u profiles obtained from CPT(u) assuming variable values of the cone bearing capacity factor (N_k or N_{kt}). An example is shown in Figure 5 (Marchetti et al. 2022), where the s_u values obtained in Fucino clay by Medusa DMT are compared with the s_u from CPT(u) and from other tests.

Comparisons CPT-DMT are also available in terms of pore pressure index and consolidation/drainage parameters inferred from dissipation tests. The DMT, though non provided with a pore pressure sensor as the CPTu, permits to determine the pre-insertion in-situ equilibrium pore pressure u_0 in sand and to discern layers of different permeability based on the closing pressure p_2 . As described by Marchetti et al. (2001), in sand $p_2 \approx u_0$, while in clay $p_2 > u_0$ due to some excess pore pressure induced by penetration persisting at the time of the p_2 measurement. The pore pressure index U_D (Lutenegger & Kabir 1988) is defined as:

$$U_D = \frac{(p_2 - u_0)}{(p_0 - u_0)} \quad (16)$$

The parameter U_D is the DMT equivalent of the pore pressure ratio B_q from CPTu:

$$B_q = \frac{(u_2 - u_0)}{(q_t - \sigma_{v0})} \quad (17)$$

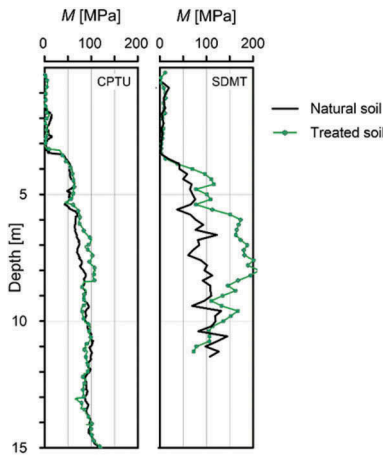


Figure 4. Comparison of constrained moduli M estimated from CPTu (Robertson 2009b) and SDMT (Marchetti 1980) in natural and treated soils at the Bondeno test site (modified from Amoroso et al. 2022a).

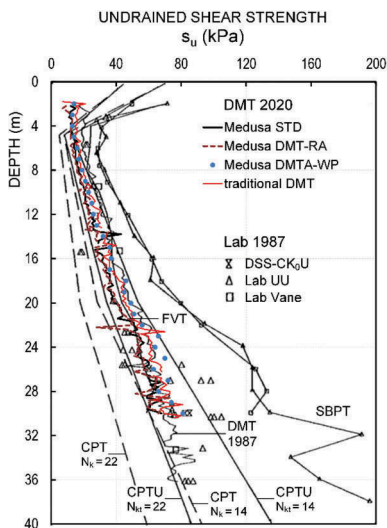


Figure 5. Comparison of profiles of the undrained shear strength s_u from standard/Medusa DMT, CPT/CPTu and other in-situ and laboratory tests (data from Burghignoli et al. 1991) at Fucino-Telespazio (Marchetti et al. 2022).

Similar to B_q , U_D may help delineate soil stratigraphy, particularly in highly stratified deposits. In free-draining soils $U_D \approx 0$, in non free-draining soils $U_D > 0$. The example in Figure 6 (Benoit 1989) shows a good agreement between DMT U_D and CPTu B_q .

The use of the DMT in intermediate soils (silty sands, silts, sandy silts) is being increasingly investigated (Schnaid et al. 2016, 2018). Monaco et al. (2021) presented preliminary results of tests carried out using the Medusa DMT adopting variable

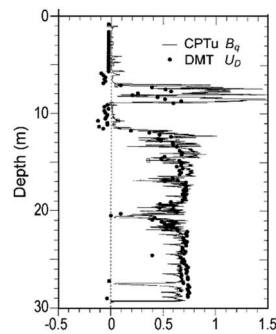


Figure 6. Comparison of U_D from DMT and B_q from CPTu (Benoit 1989, from Marchetti et al. 2001).

pressurization and penetration rates in intermediate soils in the Po river valley, Italy, combined with CPTus at variable penetration rates. In these soils, the highly accurate and repeatable time-for-reading facility of the Medusa DMT permitted to identify some trends in the variation of DMT pressure measurements in response to variable-rate testing conditions, i.e., a slower penetration/pressurization rate ‘shifts’ the interpretation towards drained behavior, while a faster penetration/pressurization rate ‘shifts’ the interpretation towards undrained behavior. In sand, a fully drained response was found for any penetration/pressurization rate. U_D appears as a suitable independent parameter to discern between drained, undrained or partially drained soil behavior and may be usefully combined with I_D to obtain some ‘soil behavior type’. Ongoing research investigates the potential of combining variable-rate Medusa DMT and CPTu tests as an innovative approach for characterizing the in-situ behavior of intermediate soils.

The DMT is also used to estimate in-situ consolidation/permeability parameters by means of dissipation tests. Differently from CPTu, the decay with time monitored by the DMT is not that of the pore pressure, but of the total contact A -pressure. This involves lack of worry over desaturation or poor saturation of a porous element, which may affect the u_2 measurement in CPTu dissipation tests. The Medusa DMT technology, which permits to acquire up to 3 repeated A -pressure readings per second, has extended the range of soil types in which A -dissipations are feasible from low permeability soils (clays, silty clays) to intermediate permeability soils (silts, silty sands).

4 DERIVATION OF SOIL PARAMETERS BY COMBINED USE OF CPT & DMT

4.1 Estimating OCR in sand from DMT & CPT

The combined use of DMT & CPT may provide estimates of the OCR in sand. Marchetti et al. (2001) suggested to use the ratio between the constrained

modulus from DMT M_{DMT} and the cone resistance q_c from CPT as an indicator OCR in sand:

$$M_{DMT}/q_c = 5 - 10 \text{ in NC sands} \quad (18a)$$

$$M_{DMT}/q_c = 12 - 24 \text{ in OC sands} \quad (18b)$$

The above preliminary indications were based on available CPT-DMT data before/after compaction of sand fills (e.g., Jendebly 1992), where M_{DMT}/q_c was found to increase with the overconsolidation achieved by compaction, combined with data from CC research and from other tests.

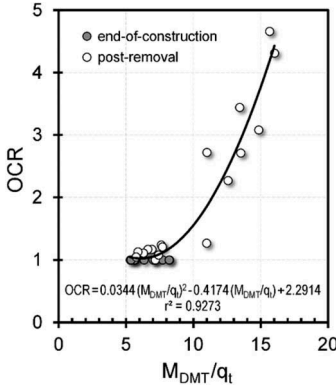


Figure 7. Correlation $OCR-M_{DMT}/q_t$ in sands obtained from paired DMT-CPTu data at the Treporti trial embankment test site (modified from Monaco et al. 2014).

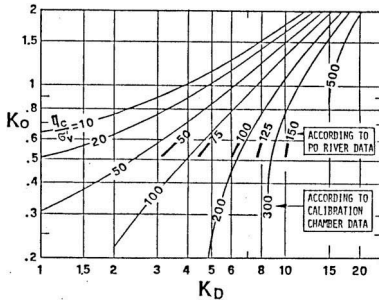


Figure 8. Chart for evaluating $K_0 = f(K_D, q_c/\sigma'_v)$ proposed by Marchetti (1985).

The possibility to estimate OCR in sand by the combined use of DMT and CPT was investigated by Monaco et al. (2014) as part of an extensive experimental study carried out at the Treporti Test Site, Venice, Italy. At this site, a full-scale cylindrical trial embankment (40 m diameter, 6.7 m height, applied pressure 106 kPa) was built and monitored from the beginning of its construction until its complete removal, four years later. Using same-depth values of M_{DMT} and q_t obtained in sand layers from paired DMT and CPTu soundings carried out at

the times when reference “imparted OCR ” were known, i.e. at end-of-construction and post-removal, Monaco et al. (2014) derived the correlation (Figure 7):

$$OCR = 0.0344(M_{DMT}/q_t)^2 - 0.4174(M_{DMT}/q_t) + 2.2914 \quad (19)$$

Using the same data set, Monaco et al. (2014) also constructed a correlation $OCR-K_D$ based only on DMT. However the $OCR-K_D$ correlation is not unique, but likely depending also on the relative density D_r . In fact, going back to the CC results shown in Figure 3b (Lee et al. 2011), it can be deduced that for a given D_r there is a one-to-one correspondence between K_D and OCR values (i.e., a vertical line having constant D_r in the diagram intersects each OCR curve for a unique K_D value), but if D_r is not constant the same OCR may result from a different combination of K_D and D_r . Hence a given K_D may be due either to a low D_r and a high OCR , or to a high D_r and a low OCR . In order to separate the D_r effect from the OCR effect, i.e., to pinpoint the right OCR, D_r pair and then to estimate OCR , the normalized q_c (Figure 3a) is also necessary to provide an indication of D_r on the horizontal axis. Hence both q_c and K_D would be needed to estimate OCR in sand, i.e., CPT alone or DMT alone are insufficient. The $OCR-K_D$ correlation by Monaco et al. (2014) works well at the Treporti test site where it was calibrated because in these sands D_r is almost uniform, but it may not work at sites where D_r is variable. Based on CC tests on Busan sand samples having different D_r and OCR , Choo et al. (2015) proposed a correlation to estimate OCR in sand based on K_D and D_r , with D_r also estimated from DMT, hence using only DMT data. This $OCR-K_D$ correlation needs to be calibrated for each specific sand.

The $OCR-M_{DMT}/q_t$ correlation (Eq. 19) by Monaco et al. (2014), based on both DMT and CPTu data, appears to have more general validity and may provide broad OCR estimates in different sands. Additional research is encouraged to investigate the dependency of the correlation $OCR-M_{DMT}/q_t$ on D_r , stress level and possibly sand type.

4.2 Estimating K_0 in sand from DMT & CPT

Similar considerations may be extended to the estimation of K_0 in sand. The $K_0 - q_c - K_D$ chart in Figure 8, elaborated by Marchetti (1985), is probably the first example of combined use of CPT & DMT. The chart permits to estimate K_0 once q_c and K_D are known. Figure 8 shows, besides the continuous curves obtained from CC tests, an additional scale for q_c/σ'_v based on 25 data points in Po river sand, where an average value $K_0 = 0.55$ was estimated.

Baldi et al. (1986) enriched such $K_0 - q_c - K_D$ chart with additional CC work and converted it into the following equations:

$$K_0 = 0.376 + 0.095K_D - 0.0017q_c/\sigma'_{v0} \quad (20a)$$

$$K_0 = 0.376 + 0.095K_D - 0.0046q_c/\sigma'_{v0} \quad (20b)$$

Eq. 20a was determined as the best fit of CC data, obtained on pluviated artificial sand, while Eq. 20b was obtained by modifying the last coefficient to predict “correctly” K_0 for the natural Po river sand.

Marchetti et al. (2001) recommended using Eqs 20a and 20b (Baldi et al. 1986) with the following values of the last coefficient: -0.002 in “freshly deposited” sand, -0.005 in “seasoned” sand. In this way, the influence of OCR on K_0 is incorporated by the choice of the last coefficient, which involves appreciable subjectivity (e.g., a sand could be assumed as “fresh” if $K_D = 1-2$, “seasoned” if $K_D = 5-6$).

Choo et al. (2015), based on CC testing on Busan sand, proposed a correlation to estimate K_0 in sand from DMT only, but similarly to OCR this correlation requires specific calibration for different sands.

Based on the CC data set by Baldi et al. (1986), Hossain & Andrus (2016) proposed to estimate K_0 in sand by use of the following correlation:

$$K_0 = 0.72 + 0.456 \log OCR + 0.035K_D - 0.194 \log(q_c/\sigma'_v) \quad (21)$$

in which the influence of OCR on K_0 is explicitly taken into account. Eq. 21 could be used in combination with OCR estimated by Eq. 19.

All the above considerations imply that the challenging task of estimating OCR and K_0 in sands requires a multi-parameter/multi-test approach, based on the combined use of DMT and CPT.

5 APPLICATIONS BASED ON COMBINED USE OF CPT & DMT DATA

5.1 Use of DMT & CPT in monitoring ground improvement

Several comparisons of pre-post CPT & DMT executed for monitoring ground improvement are available. Various studies have found the increase in M_{DMT} after soil treatment approximately twice the increase in q_c . For instance, Jendebay (1992) found an increase of the ratio M_{DMT}/q_c from $\approx 5-12$ pre-compaction to $\approx 12-24$ post-compaction of a loose sand fill (Figure 9a). Bałachowski & Kurek (2015) found the mean increase in M_{DMT} after vibroflotation of sand about 2.3 times higher than the corresponding increase in q_c and an increase of M_{DMT}/q_c from $\approx 2-10$ pre-compaction to $\approx 10-24$ post-compaction

(Figure 9b). Amoroso et al. (2022a, b), using paired DMT and CPTu data before/after ground improvement with Rammed Aggregate Piers (RAP) at the Bondeno test site, found a similar trend of the ratio M_{DMT}/q_t (Figure 10), consistent with the observed increase in M_{DMT} higher than M from CPTu in treated soils (Figure 4). This evidence suggests that the DMT is more sensitive to stiffness variations as a consequence of the increase in horizontal stress produced by soil treatment, as reflected by the increase in K_0 (and OCR), also shown in Figure 10. Similar pre-post comparisons were reported by Amoroso et al. (2018). The finding that compaction (a sort of “imparted overconsolidation”) increases both M_{DMT} and q_c , but M_{DMT} at a faster rate, inspired the use of the ratio M_{DMT}/q_c as a “proxy” of OCR , as previously discussed.

5.2 Liquefaction assessment based on DMT & CPT

The use of the DMT for liquefaction assessment is receiving increasing attention. Much of the interest on the development of simplified methods based on the DMT K_D derives from its high sensitivity to stress history, besides to other factors (e.g., D_r , K_0 , aging) that influence liquefaction resistance. Numerous researchers (e.g., Pyke 2003, Leon et al. 2006 and many others) have pointed out that past stress-strain history (overconsolidation, aging) is likely to have a much greater effect on increasing liquefaction resistance than penetration resistance.

Simplified methods for estimating the cyclic resistance ratio (CRR) based on DMT K_D have been proposed over the years, including the most recent by Monaco et al. (2005), Tsai et al. (2009), Robertson (2012), Marchetti (2016), Chiaradonna & Monaco (2022) shown in Figure 11 (valid for magnitude $M = 7.5$ and clean uncemented sand).

All these methods have in common a strong link with CPT-based methods in their origin, in an effort to relate in some way to the field performance database that provides a vast experimental validation for current methods based on CPT, but is currently limited for DMT-based methods.

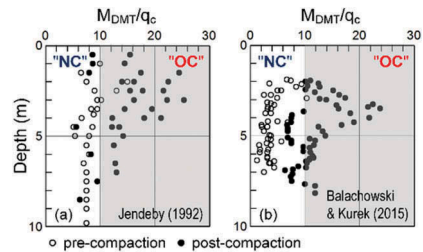


Figure 9. Ratio M_{DMT}/q_c before-after compaction of sand fills/deposits: data from (a) Jendebay (1992), (b) Bałachowski & Kurek (2015).

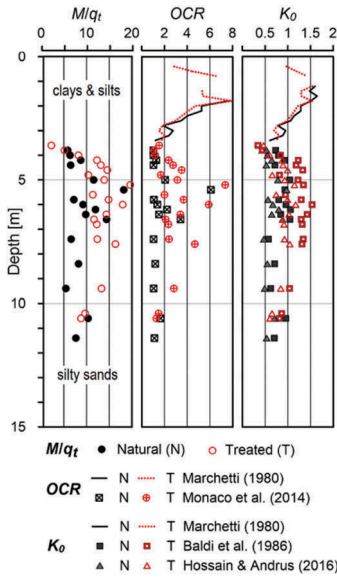


Figure 10. Profiles of M_{DMT}/q_t , OCR and K_D obtained from combined DMT-CPTu data in natural and treated soils at the Bondeno test site (modified from Amoroso et al. 2022b).

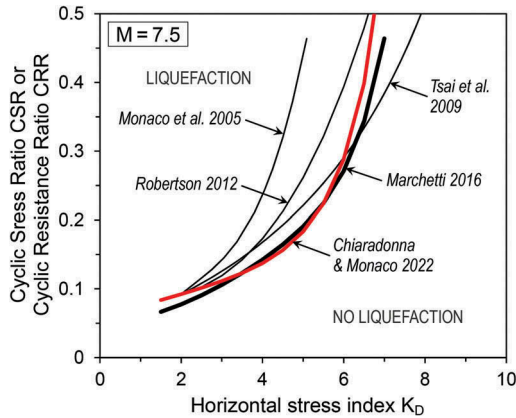


Figure 11. Recent $CRR-K_D$ correlations for clean sand.

The $CRR-K_D$ curve by Monaco et al. (2005) was obtained by translating “consensus” CPT (and SPT) curves, namely the CPT curve by Robertson & Wride (1998), using the relative density D_r as intermediate parameter. This approach is inevitably affected by some uncertainty in estimating D_r from the in-situ tests. Differently, Tsai et al. (2009) obtained a $CRR-K_D$ curve by translating “consensus” CPT (and SPT) curves, again Robertson & Wride (1998) for CPT, by using direct correlations between the CPT normalized clean sand equivalent cone resistance and the DMT K_D , established using data from paired CPT-DMT

soundings at five saturated loose sand sites in Taiwan that experienced liquefaction.

Using a similar approach, independently, Robertson (2012) re-elaborated the CPT-DMT data set collected by Tsai et al. (2009) and proposed, for young uncemented sands ($I_D > 1.2$ and $2 < K_D < 6$), an average relationship between the normalized clean sand equivalent cone resistance $Q_{m,cs}$, defined as:

$$Q_{m,cs} = K_c \cdot Q_m \quad (22)$$

where K_c = correction factor for fines content estimated using I_c , and the DMT K_D :

$$Q_{m,cs} = 25K_D \quad (23)$$

Based on Eq. 23, Robertson (2012) converted the Robertson & Wride (1998) $CRR-Q_{m,cs}$ curve into a $CRR-K_D$ curve. Later Marchetti (2016) obtained a new $CRR-K_D$ curve by combining the same Eq. 23 with the CPT curve by Idriss & Boulanger (2006).

Chiaradonna & Monaco (2022) proposed an update of the $CRR-K_D$ curve adopting the CPT-based framework by Boulanger & Idriss (2014). Using the CPT-DMT data set by Tsai et al. (2009), considering only CPT data having I_c between 1.5 and 2.6, a direct correlation was established between K_D and the clean sand equivalent cone resistance q_{c1Ncs} defined according to Boulanger & Idriss (2014):

$$q_{c1Ncs} = q_{c1N} + \Delta q_{c1N} \quad (24)$$

where q_{c1N} is the normalized cone resistance and Δq_{c1N} accounts for the effect of fines content.

Despite the dispersion, the data set (Figure 12) is well described by a linear trend with a slope of 20. Figure 12 also shows a second data set from the Scortichino site, Italy, where both CPT and SDMT data were available (Tonni et al. 2015), which is better interpreted by a linear trend with a slope of about 30. Based on this limited data, Chiaradonna & Monaco (2022) adopted an average coefficient of 25:

$$q_{c1Ncs} = 25K_D \quad (25)$$

which is compatible with Eq. 23 by Robertson (2012), also used by Marchetti (2016). By substituting Eq. 25 into the $CRR-q_{c1Ncs}$ curve by Boulanger & Idriss (2014), a new $CRR-K_D$ curve was obtained.

Average CPT-DMT correlations such as Eq. 23 (Robertson 2012) and Eq. 25 (Chiaradonna & Monaco 2022) may be useful to convert CPT- into DMT-based liquefaction triggering curves. On the other hand, the example in Figure 12 suggests that the $q_{c1Ncs} - K_D$ relationship varies from one site to another, presumably as a consequence of the higher sensitivity of K_D to stress

history. Two sites may have similar q_{c1Ncs} , but different K_D depending on different stress history (Marchetti 2016). This implies that q_{c1Ncs} and K_D do not contain equivalent information, and may also explain in part the high dispersion of the CPT-DMT correlations (Marchetti 2015). Robertson (2015), recognizing the higher sensitivity of K_D to factors that cause soil microstructure (stress and strain history, age, cementation/bonding), suggested using the $Q_{m,cs} - K_D$ relationship to assess microstructure, noting that in young uncemented sands generally $Q_{m,cs} > 16 K_D$, while soils with significant microstructure tend to have $Q_{m,cs} < 16 K_D$.

In perspective, the DMT could offer a valuable integration to current methods for liquefaction assessment based on CPT, SPT or V_S , also given the general recommendation towards the use of “redundant” correlations based on different in-situ techniques / parameters. The main drawbacks of current DMT-based methods are: (1) lack of any correction factor for the fines content, and (2) limited experimental validation based on field performance data from real earthquakes. Ongoing research is attempting to fill these gaps. The implementation of an adequate case-history database for validation of the DMT-based approach could support the introduction of more consistent liquefaction triggering curves, considering also the fines content influence.

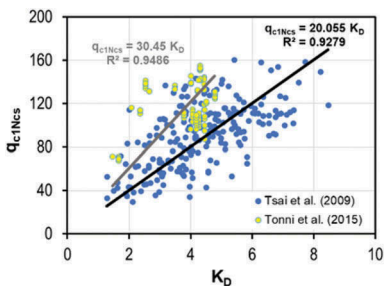


Figure 12. Relationship $q_{c1Ncs} - K_D$ from published CPT-DMT data records at two test sites (Chiaradonna & Monaco 2022).

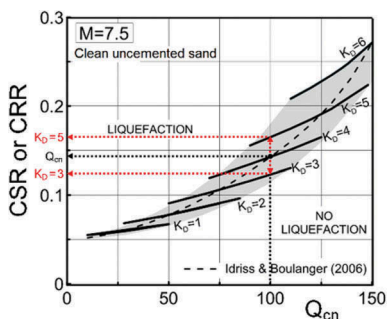


Figure 13. Correlation for estimating CRR based on both DMT & CPT for clean sand (modified from Marchetti 2016).

Besides the $CRR-K_D$ curve, Marchetti (2016) also proposed a method to estimate CRR based on the combined use of DMT & CPT (Figure 13), aiming to complement the higher sensitivity of K_D to stress history with the much larger field performance support of CPT-based methods. The conceptual framework is the following: (1) estimate CRR using a “consensus” CPT liquefaction curve; (2) increase (shift upwards) the CRR predicted by CPT if K_D is high, reduce it (shift downwards) if K_D is low. As an example, Figure 13 for a normalized cone resistance $Q_{cn} = 100$ and $K_D = 3$ provides $CRR = 0.125$ (i.e., lower than predicted by the dashed CPT curve), while for the same $Q_{cn} = 100$ and $K_D = 5$ the chart provides $CRR = 0.17$ (i.e., higher than predicted by CPT). The method proposed by Marchetti (2016) for estimating CRR from both DMT & CPT is another example of multi-parameter / multi-test approach. It is expectable that an estimate based on two measured independent parameters could be more accurate than an estimate based on just one parameter.

6 PROPER MATCHING OF CPT & DMT DATA

One specific issue that arises when using any interpretation or design approach that requires the combination of CPT & DMT results is the proper matching of corresponding data. In fact, the CPT measurements are taken every 10-20 to 50 mm, whereas the DMT pressure readings are taken every 200 mm. Data from paired CPT & DMT soundings shall be matched at respective elevations. Care must be adopted even when nearby soundings are carried out at the same ground elevation, particularly in non uniform, highly stratified deposits.

Comparisons between individual same-depth values from nearby CPT & DMT profiles often show considerable scatter due to variations in soil stratigraphy and consistency, hence adjacent data from the same depth may not always represent the same soil. Sand deposits are often characterized by high variability in grain size distribution and D_r , then plots of individual data points from nearby CPT & DMT may show large scatter. The profiles of q_t may also differ slightly from those of adjacent DMT since the CPT senses soil slightly ahead and behind the cone tip (up to 15 cone diameters, depending on soil strength / stiffness and in-situ effective stresses, Ahmadi & Robertson 2005). The DMT appears to be less influenced by soil layers ahead and behind since the probe is stopped and the membrane expanded in horizontal direction. Hence, in interbedded soils the CPT may be influenced by adjacent soil layers somewhat more than the DMT (Robertson 2009a).

Any comparison between adjacent CPT & DMT 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. It is also common to compare values obtained at the same depth within relatively uniform sections of a deposit. As an example, at the highly stratified Treporti test site (Monaco et al. 2014) the paired CPTu-DMT

data, including the data pairs $M_{DMT} - q_t$ shown in Figure 7, were carefully selected by retaining only pairs from uniform soil layers of significant thickness to avoid any possible mismatching of data.

In general, the following matching criteria may be adopted: (1) match paired CPT & DMT profiles accounting for respective ground elevations, if not coincident; (2) correct both CPT & DMT test depths for inclination; (3) select soil type (e.g., sand-like, $I_c \leq 2.60$ and $I_D > 1$, or clay-like, $I_c > 2.60$ and $I_D < 1$) and possibly depth range of interest; (4) identify “visually” or by cross-correlation of representative parameters (e.g., q_t and M_{DMT}) corresponding soil layers in CPT & DMT profiles, to detect any depth misalignment offset; (5) identify soil layers having a reasonable thickness (e.g., in which at least two DMT readings are present) and relatively uniform CPT & DMT parameters; (6) use average values of CPT & DMT parameters in each layer. It would be desirable that the matching algorithm is implemented in software tools, although some visual inspection and judgment may be still needed.

7 CONCLUDING REMARKS

Direct-push in-situ tests such as the CPT and the DMT, particularly in their powerful seismic configurations, have proven to be remarkably expedient in geotechnical site investigations. Recent experience highlights an increasing awareness of researchers and practitioners that an adequate site investigation for a given project cannot rely solely on one isolated testing technique, delineating the trend of expanding diffusion of a multi-parameter / multi-test approach in site investigation practice.

The CPT and the DMT can be effectively combined to obtain more accurate information on stratigraphy and stress history of soil deposits, more reliable estimates of soil parameters (e.g., OCR and K_0 in sand) and for various design applications (e.g., monitoring ground improvement, liquefaction assessment). Moving towards an in-situ multi-parameter / multi-test approach appears a logical trend. In this respect, the availability of the DMT stress history parameter K_D is important not only “per se”, but also in combination with parameters obtained from CPT.

Each test has advantages and limitations. The CPT is often used more than the DMT, especially for smaller projects, being faster and less expensive (no pauses of penetration are required for obtaining the measurements, as for the DMT). However, the DMT has been shown to be more sensitive to stress history, which has a dominant influence on soil behavior. Hence, their mutual integration could helpfully merge the respective advantages and counterbalance their limitations. For instance, the CPT could be used for a “screening” of the site on a large scale, the DMT at locations of particular relevance for the project. Adjacent CPT & DMT at selected locations

should be planned. The increase in time and cost of a site investigation program including paired CPT & DMT soundings can be efficiently optimized considering that both tests can share the same insertion rig and rods, and even the same cable when using the Medusa DMT (i.e., only the probe connected to the bottom rod needs to be changed). Such “redundancy” would be largely compensated by substantial increase in soil information.

Interrelationships between CPT & DMT can be used to expand and improve correlations and applications by using experience and databases from one test and extrapolating to the other test. The accumulation and sharing of paired data sets from companion series of CPT & DMT soundings at well-documented and benchmark test sites is a desirable address for future research and practice.

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REFERENCES

- Ahmadi, M.M. & Robertson, P.K. 2005. Thin layer effects on the CPT q_c measurement. *Can. Geotech. J.* 42(9): 1302–1317.
- Amoroso, S., Comina, C. & Marchetti, D. 2020. Combined P- and S-Wave Measurements by Seismic Dilatometer Test (SPDMT): A Case History in Bondeno (Emilia Romagna, Italy). *Geotech. Testing J.* 43(2): 383–393.
- Amoroso, S., Garcia Martínez, M.F., Monaco, P., Tonni, L., Gottardi, G., Rollins, K.M., Minarelli, L., Marchetti, D. & Wissmann, K.J. 2022a. Comparative study of CPTU and SDMT in liquefaction prone silty sands with ground improvement. *J. Geotech. Geoenviron. Eng.* (accepted) [http://dx.doi.org/10.1061/\(ASCE\)GT.1943-5606.0002801](http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0002801)
- Amoroso, S., Martínez, M.F., Tonni, L., Gottardi, G., Monaco, P., Rollins, K.M., Minarelli, L., Marchetti, D. & Wissmann, K.J. 2022b. Monitoring ground improvement by Rammed Aggregate Piers using a combined CPTU and SDMT approach at a silty sand liquefaction-prone site in Emilia-Romagna. *Proc. 5th Int. Symp. Cone Penetration Testing CPT'22, Bologna*, 8-10 June 2022.
- Amoroso, S., Rollins, K.M., Monaco, P., Holtrigter, M. & Thorp, A. 2018. Monitoring Ground Improvement Using the Seismic Dilatometer in Christchurch, New Zealand. *Geotech. Testing J.* 41(5): 946–966.
- Balachowski, L. & Kurek, N. 2015. Vibroflotation Control of Sandy Soils. In S. Marchetti, P. Monaco & A. Viana da Fonseca (eds), *Proc. 3rd Int. Conf. Flat Dilatometer DMT'15, Rome*, 14-16 June 2015, 185–190.
- Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., Marchetti, S. & Pasqualini, E. 1986. Flat Dilatometer Tests in Calibration Chambers. *Proc. Spec. Conf. Use of*

- In Situ Tests in Geotech. Eng. In Situ '86, Blacksburg, 431-446.*
- Benoit, J. 1989. Personal communication to S. Marchetti.
- Boulanger, R.W. & Idriss, I.M. 2014. CPT and SPT liquefaction triggering procedures. *Report No UCD/GCM-14/01*, University of California at Davis.
- Burghignoli, A., Cavalera, L., Chieppa, V., Jamiolkowski, M., Mancuso, C., Marchetti, S., Pane, V., Paoliani, P., Silvestri, F., Vinale, F. & Vittori, E. 1991. Geotechnical characterization of Fucino clay. *Proc. 10th Eur. Conf. Soil Mech. Found. Eng., Florence*, 26-30 May 1991, 1: 27-40. Rotterdam: Balkema.
- Chiaradonna, A. & Monaco, P. 2022. Assessment of liquefaction triggering by seismic dilatometer tests: comparison between semi-empirical approaches and non-linear dynamic analyses. *Proc. 20th Int. Conf. Soil Mech. Geotech. Eng., Sydney*, 1-5 May 2022.
- Choo, H., Lee, W., Lee, C., Kim, Y.-S. & Lee, M.-J. 2015. Perception of Overconsolidated States of Coarse-Grained Soils Using DMT Results. In S. Marchetti, P. Monaco & A. Viana da Fonseca (eds), *Proc. 3rd Int. Conf. Flat Dilatometer DMT'15, Rome*, 14-16 June 2015, 205-212.
- Hossain, M.A. & Andrus, R.D. 2016. At-Rest Lateral Stress Coefficient in Sands from Common Field Methods. *J. Geotech. Geoenviron. Eng.* 142(12): 06016016.
- Idriss, I.M. & Boulanger, R.W. 2006. Semi-empirical procedures for evaluating liquefaction potential during earthquakes. *Soil Dyn. Earthquake Eng.* 26(2-4): 115-130.
- Jamiolkowski, M. & Lo Presti, D.C.F. 1998. DMT research in sand. What can be learned from calibration chamber tests. *1st Int. Conf. Site Characterization ISC '98, Atlanta*, 19-22 April 1998 (oral presentation).
- Jendebly, L. 1992. Deep Compaction by Vibrowing. *Proc. Nordic Geotech. Meeting NGM-92, Aalborg*, 1: 19-24.
- Lee, M.J., Choi, S.K., Kim, M.T. & Lee, W. 2011. Effect of stress history on CPT and DMT results in sand. *Eng. Geol.* 117(3-4): 259-265.
- Leon, E., Gassman, S.L. & Talwani, P. 2006. Accounting for Soil Aging When Assessing Liquefaction Potential. *J. Geotech. Geoenviron. Eng.* 132(3): 363-377.
- Lunne, T. & Christophersen, H.P. 1983. Interpretation of cone penetrometer data for offshore sands. *Proc. 15th Annual Offshore Technology Conf.*, 181-188.
- Lutenegger, A.J. & Kabir, M.G. 1988. Dilatometer C-reading to help determine stratigraphy. *Proc. Int. Symp. Penetration Testing ISOPT-1, Orlando*, 1: 549-554. Rotterdam: Balkema.
- Marchetti, D., Monaco, P., Amoroso, S. & Minarelli, L. 2019. In situ tests by Medusa DMT. *Proc. XVII Eur. Conf. Soil Mech. Geotech. Eng., Reykjavik*, 1-6 September 2019.
- Marchetti, D., Monaco, P., Totani, G., Totani, F. & Amoroso, S. (2022). Comparisons CPT-DMT in soft clay at Fucino-Telespazio GeoTest site. *Proc. 5th Int. Symp. Cone Penetration Testing CPT'22, Bologna*, 8-10 June 2022.
- Marchetti, S. 1980. In Situ Tests by Flat Dilatometer. *J. Geotech. Eng. Div.* 106(GT3): 299-321.
- Marchetti, S. 1985. On the Field Determination of K_0 in Sand. *Proc. 11th Int. Conf. Soil Mech. Found. Eng., San Francisco*, 5: 2667-2673. Rotterdam: Balkema.
- Marchetti, S. 2010. Sensitivity of CPT and DMT to stress history and aging in sands for liquefaction assessment. *Proc. 2nd Int. Symp. Cone Penetration Testing CPT'10, Huntington Beach*, 9-11 May 2010.
- Marchetti, S. 2011. Discussion of "CPT-DMT Correlations" by P.K. Robertson. *J. Geotech. Geoenviron. Eng.* 137(4): 441-442.
- Marchetti, S. 2015. Some 2015 Updates to the TC16 DMT Report 2001. In S. Marchetti, P. Monaco & A. Viana da Fonseca (eds), *Proc. 3rd Int. Conf. Flat Dilatometer DMT'15, Rome*, 14-16 June 2015, 43-65.
- Marchetti, S. 2016. Incorporating the Stress History Parameter K_D of DMT into the Liquefaction Correlations in Clean Uncemented Sands. *J. Geotech. Geoenviron. Eng.* 142(2): 04015072.
- Marchetti, S. & Monaco, P. 2018. Recent Improvements in the Use, Interpretation, and Applications of DMT and SDMT in Practice. *Geotech. Testing J.* 41(5): 837-850.
- Marchetti, S., Monaco, P., Totani, G. & Calabrese, M. 2001. The Flat Dilatometer Test (DMT) in Soil Investigations - A Report by the ISSMGE Committee TC16. Official version approved by ISSMGE TC16 reprinted in R. A. Failmezger & J.B Anderson (eds), *Proc. 2nd Int. Conf. Flat Dilatometer, Washington D.C.*, 2-5 April 2006, 7-48.
- Mayne, P.W. 2006. Interrelationships of DMT and CPT Readings in Soft Clays. In R.A. Failmezger & J. B Anderson (eds), *Proc. 2nd Int. Conf. Flat Dilatometer, Washington D.C.*, 2-5 April 2006, 231-236.
- Mayne, P.W. 2016. Evaluating effective stress parameters and undrained shear strengths of soft-firm clays from CPTu and DMT. *Australian Geomech. J.* 51(4): 27-55.
- Mayne, P.W. & Bachus, R.C. 1989. Penetration Pore Pressures in Clay by CPTU, DMT, and SBP. *Proc. 12th Int. Conf. Soil Mech. Geotech. Eng., Rio de Janeiro*, 291-294. Rotterdam: Balkema.
- Mayne, P.W., Coop, M.R., Springman, S.M., Huang, A.B. & Zornberg, J.G. 2009. Geomaterial behavior and testing. *Proc. 17th Int. Conf. Soil Mech. Geotech. Eng., Alexandria*, 5-9 October 2009, 4: 2777-2872. Amsterdam: IOS Press.
- Monaco, P., Amoroso, S., Marchetti, S., Marchetti, D., Totani, G., Cola, S. & Simonini, P. 2014. Overconsolidation and Stiffness of Venice Lagoon Sands and Silts from SDMT and CPTU. *J. Geotech. Geoenviron. Eng.* 140(1): 215-227.
- Monaco, P., Marchetti, S., Totani, G. & Calabrese, M. 2005. Sand Liquefiability Assessment by Flat Dilatometer Test (DMT). *Proc. 16th Int. Conf. Soil Mech. Geotech. Eng., Osaka*, 4: 2693-2697. Rotterdam: Millpress.
- Monaco, P., Tonni, L., Amoroso, S., Garcia Martinez, M.F., Gottardi, G., Marchetti, D. & Minarelli, L. 2021. Use of Medusa DMT in alluvial silty sediments of the Po river valley. *Proc. 6th Int. Conf. Geotech. Geophys. Site Characterisation ISC'6, Budapest*, 26-29 September 2021.
- Monaco, P., Totani, G. & Calabrese, M. 2006. DMT-predicted vs observed settlements: a review of the available experience. In R.A. Failmezger & J.B Anderson (eds), *Proc. 2nd Int. Conf. Flat Dilatometer, Washington D.C.*, 2-5 April 2006, 244-252.
- Ouyang, Z. & Mayne, P.W. 2017. Spherical cavity expansion nexus between CPTu and DMT in soft-firm clays. *Proc. 19th Int. Conf. Soil Mech. Geotech. Eng., Seoul*, 17-22 September 2017, 631-634.
- Ouyang, Z. & Mayne, P.W. 2018. Effective stress parameters of clays from DMT. *Geotech. Testing J.* 41(5): 851-867.
- Pyke, R. 2003. Discussion of "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF" by T.L. Youd et al., *J. Geotech. Geoenviron. Eng.* 129(3): 283-284.

- Robertson, P.K. 1990. Soil classification using the cone penetration test. *Can. Geotech. J.* 27(1): 151–158.
- Robertson, P.K. 2009a. CPT-DMT Correlations. *J. Geotech. Geoenviron. Eng.* 135(11): 1762–1771.
- Robertson, P.K. 2009b. Interpretation of cone penetration tests – a unified approach. *Can. Geotech. J.*, 46(11): 1337–1355.
- Robertson, P.K. 2012. The James K. Mitchell Lecture: Interpretation of in-situ tests – some insights. In R. Coutinho & P.W. Mayne (eds), *Proc. 4th Int. Conf. Geotech. Geophys. Site Characterization, Porto de Galinhas*, 1: 3–24.
- Robertson, P.K. 2015. Soil Behavior Type using the DMT. In S. Marchetti, P. Monaco & A. Viana da Fonseca (eds), *Proc. 3rd Int. Conf. Flat Dilatometer DMT'15, Rome*, 14-16 June 2015, 243–250.
- Robertson, P.K. 2017. DMT-CPT Correlations. *Prof. Silvano Marchetti Memorial Session on In-Situ Testing, 19th Int. Conf. Soil Mech. Geotech. Eng., Seoul, 17-22 September 2017* (oral presentation).
- Robertson, P.K. & Wride, C.E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. *Can. Geotech. J.* 35(3): 442–459.
- Schnaid, F., Belloli, M.V.A., Odebrecht, E. & Marchetti, D. 2018. Interpretation of the DMT in silts. *Geotech. Testing J.* 41(5): 868–876.
- Schnaid, F., Odebrecht, E., Sosnoski, J. & Robertson, P.K. 2016. Effects of test procedure on flat dilatometer test (DMT) results in intermediate soils. *Can. Geotech. J.* 53(8): 1270–1280.
- Senneset, K., Sandven, R., Lunne, T., By, T. & Amundsen, T. 1988. Piezocone Tests in Silty Soils. *Proc. Int. Symp. Penetration Testing ISOPT-1, Orlando*, 2: 955–966. Rotterdam: Balkema.
- Togliani, G., Calzolari, L. & Menghini, A. 2015. Governolo & Gonzaga (Mantua, Italy) Experimental Sites: In situ Test comparison. In S. Marchetti, P. Monaco & A. Viana da Fonseca (eds), *Proc. 3rd Int. Conf. Flat Dilatometer DMT'15, Rome*, 14-16 June 2015, 259–270.
- Tonni, L., Gottardi, G., Amoroso, S., Bardotti, R., Bonzi, L., Chiaradonna, A., d'Onofrio, A., Fioravante, V., Ghinelli, A., Giretti, D., Lanzo, G., Madiati, C., Marchi, M., Martelli, L., Monaco, P., Porcino, D., Razzano, R., Rosselli, S., Severi, P., Silvestri, F., Simeoni, L., Vannucchi, G. & Aversa, S. 2015. Interpreting the deformation phenomena triggered by the 2012 Emilia seismic sequence on the Canale Diversivo di Burana banks. *Rivista Italiana di Geotecnica* 49 (2):28–58 (in Italian).
- Tsai, P.-H., Lee, D.-H., Kung, G.T.-C. & Juang, C.H. 2009. Simplified DMT-Based Methods for Evaluating Liquefaction Resistance of Soils. *Eng. Geol.* 103(1-2): 13–22.