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FLAT DILATOMETER (DMT). APPLICATIONS AND RECENT DEVELOPMENTS

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ABSTRACT : Many designers, today, consider an investigation composed by CPT and DMT adequate for day-to-day jobs. The DMT, introduced 40 years after the CPT, is the most recent penetration probe. Its use has been spreading fast. DMT is currently used in over 70 countries. The main applications of the DMT are :
Settlement prediction. Many top experts worldwide consider DMT the best presently available tool for predicting settlements, notoriously not well predicted by conical probes.
Compaction control. DMT has been recognized to be more than twice more sensitive than CPT to compaction. For this reason before-after DMTs are increasingly used to monitor the gain in modulus and the gain in OCR due to the compaction.
Liquefaction. A chart has been recently (2015) developed to estimate the liquefaction resistance CRR based at the same time on CPT and DMT. An estimate of CRR based on two parameters is expected to be better than estimates based on just one parameter.
Detecting slip surfaces in clay slopes. Values of Kd ≈ 2 found in a slope indicate the presence of slip surfaces in the slope, active or quiescent.

INTRODUCTION

The Flat Dilatometer (DMT) is an in situ testing tool developed some 40 years ago [1]. The DMT is currently used in practically all industrialized countries. It is standardized in the ASTM [2] and the Eurocode [3]. The DMT has been object of a detailed monograph by the ISSMGE Technical Committee TC16 [4]. ISO/CEN is currently working on a Flat Dilatometer standard.

Some key features of the DMT are:

- The DMT is a penetration test. As such, it has the advantage of not requiring a borehole.
- The DMT, being a load-displacement test, provides information on soil stiffness, an information unobtainable by penetration tests, that essentially measure "rupture" characteristics, i.e. strength. Moreover the insertion distortions caused by the DMT blade are substantially less than the distortions caused by conical probes.
- The DMT equipment is robust, easy to use and remarkably operator-independent and repeatable.
- The DMT provides information on Stress History, which has a dominant influence on soil behaviour. In particular information on Stress History permits better estimates of settlements and of liquefaction resistance.

As to the SDMT, the add-on module has added to the parameters measurable by DMT the shear wave velocity V_S. V_S is today increasingly measured because of:

- More frequent requirement of seismic analyses, for which V_S is a basic input parameter.
- The newly introduced Eurocode 8 seismic regulations prescribe the determination of V_S in the top 30 m at all construction sites located in seismic zones.
- SDMT provides both the small strain shear modulus $G_0 = \rho V_S^2$ and the stiffness at operative strains (as represented by the constrained modulus M_{DMT}). Such two stiffnesses may offer guidance when selecting the G-γ curves, i.e. the decay of the shear modulus G with the shear strain γ.

DILATOMETER TEST (DMT)

The flat dilatometer consists of a steel blade having a thin, expandable, circular steel membrane mounted on one face. When at rest, the membrane is flush with the surrounding flat surface of the

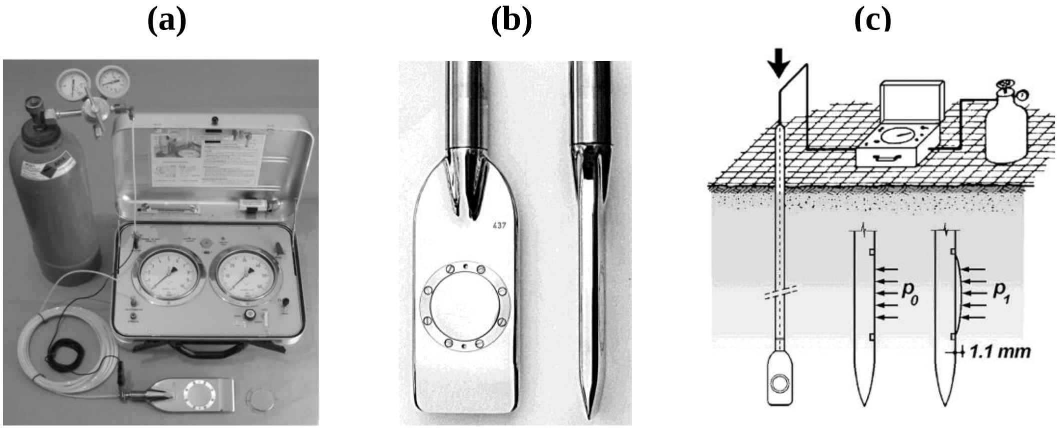

Fig. 1 Flat Dilatometer: (a) Equipment (b) Dilatometer Blade (c) Schematic layout of the seismic dilatometer test.

blade. The blade is connected, by an electro-pneumatic tube running through the insertion rods, to a control unit on the surface (Fig. 1).

The control unit is equipped with pressure gauges, an audio-visual signal, a valve for regulating gas pressure (provided by a tank) and vent valves. The blade is advanced into the ground using common field equipment, i.e. penetrometers normally used for the cone penetration test (CPT) or drill rigs. The DMT can also be driven, e.g. using the SPT hammer and rods, but statical push is preferable. Pushing the blade with a 20 ton penetrometer truck is most effective (up to 80 m of profile per day). The test starts by inserting the dilatometer into the ground. When the blade has been advanced to the desired test depth, the penetration is stopped. Without delay the operator inflates the membrane and takes, in about 30 sec, two readings: the A pressure, required to just begin to move the membrane (lift-off pressure), and the B pressure, required to expand the membrane center 1.1 mm against the soil. A third reading C (closing pressure) can also optionally be taken by slowly deflating the membrane soon after B is reached. The blade is then advanced to the next test depth, with a depth increment of typically 20 cm.

The interpretation proceeds as follows. First the field readings are converted into the DMT intermediate parameters I_D, K_D, E_D (Material index, Horizontal stress index, Dilatometer modulus). Then I_D, K_D, E_D are converted, by means of commonly used correlations [4] to: constrained modulus M, undrained shear strength Cu, K_0 (clays), OCR (clays), friction angle ϕ' (sands), bulk unit weight γ. Consolidation and permeability coefficients may be estimated by performing dissipation tests [4]. The C-reading, in sand, approximately equals the equilibrium pore pressure. An example of the profiles obtained by DMT is shown ahead in the paper in Fig. 3, where:

- I_D is the material index, that gives information on soil type (sand, silt, clay)
- M is the vertical drained constrained modulus (at geostatic stress)
- Cu is the undrained shear strength
- K_D is the Horizontal Stress Index. The profile of K_D is similar in shape to the profile of the overconsolidation ratio OCR. $K_D \approx 2$ indicates in clays OCR = 1, K_D > 2 indicates over-consolidation. The K_D profile often provides, at first glance, an understanding of the Stress History of the deposit.

More detailed information on the DMT equipment, test procedure and all the interpretation formulae may be found in the DMT 2001 Report by the ISSMGE Technical Committee TC16 [4]. A comprehensive update of the above DMT Report, including information on developments in the last 15 years, has recently been published (Marchetti 2015 [5]).

(a) **(b)** **(c)**

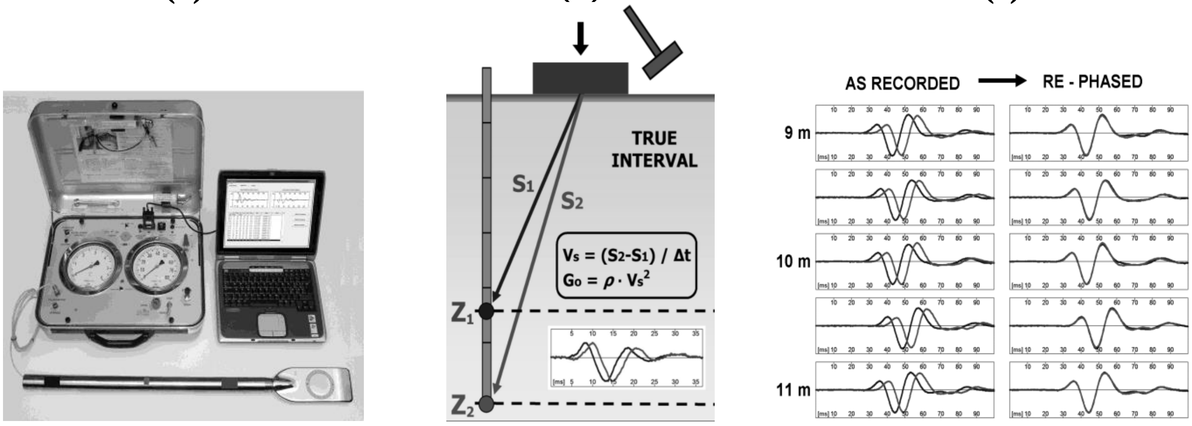

Fig. 2 Seismic Dilatometer: (a) DMT blade and seismic module (b) Schematic layout of the seismic dilatometer test. (c) Example of seismograms as recorded and rephased

SEISMIC DILATOMETER TEST (SDMT)

The SDMT is the combination of the flat dilatometer with an add-on seismic module for the measurement of the shear wave velocity [6-9]. The seismic module (Fig. 2a) is a tubular element placed above the DMT blade, equipped with two receivers located at 0.5 m distance. When a shear wave is generated at surface, it reaches first the upper receiver, then, after a delay, the lower receiver. The seismograms acquired by the two receivers, amplified and digitized at depth, are transmitted to a PC at the surface, that determines the delay. V_S is obtained (Fig. 2b) as the ratio between the difference in distance between the source and the two receivers (S2 - S1) and the delay Δt from the first to the second receiver. The true-interval test configuration with two receivers avoids possible inaccuracy of the "zero time" at the hammer impact, sometimes observed in the pseudo-interval one-receiver configuration.

Moreover, the couple of seismograms recorded by the two receivers at a given test depth corresponds to the same hammer blow. The repeatability of the V_S measurements is remarkable (observed V_S repeatability ≈ 1 %, i.e. a few m/s).

Fig. 2c shows an example of seismograms obtained by SDMT at various test depths at the site of Fucino. Fig. 3 shows an example of SDMT results. The fifth diagram is the V_S profile obtained by the seismic module. It can be seen that the repeatability of V_S is similar to the repeatability of the other four DMT parameters.

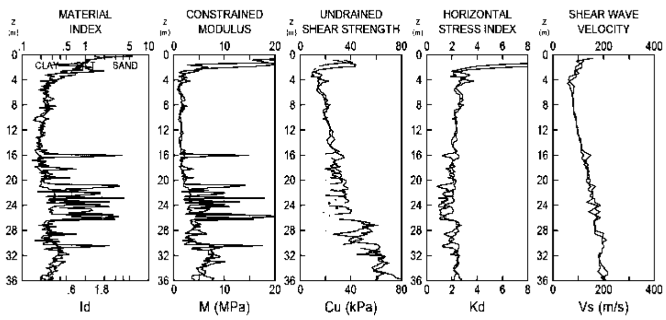

Fig. 3 Example of SDMT results (from two nearby SDMTs)

SENSITIVITY OF K_D TO STRESS HISTORY

It is well established that the DMT's K_D parameter is considerably more sensitive to Stress History than penetration resistance. The higher sensitivity to Stress History of K_D has been observed by numerous researchers, either in the large calibration chamber (e.g. [10]) and in the field (e.g. [11], [12]).

As an example Fig. 4 shows results [13] from a recent calibration chamber research carried out in Korea, comparing the reactivity of CPT and DMT to Stress History. Forty large specimens of Busan silica sand were preconsolidated to OCR in the range 1 to 8. Then half of the specimens were tested by CPT, the other half by DMT. As it can be seen in Fig. 4 OCR produces a substantial increase

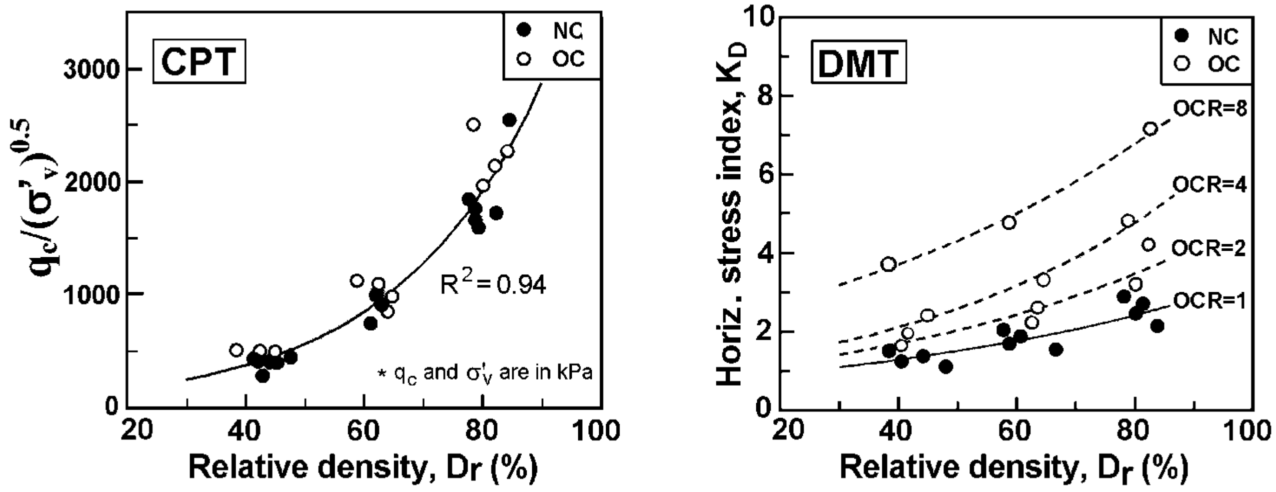

Fig. 4 Sensitivity of CPT and DMT to Stress History (Lee et al. 2011 [13])

of K_D but an almost negligible increase of q_c. The two diagrams in Fig. 4 confirm that K_D is considerably more reactive to OCR than the normalized tip resistance Q_{cn}. To the same Q_{cn} correspond many values of K_D. K_D permits to distinguish sands with Stress History, penetration tests much less.

Sensitivity to Stress History is important because not many in situ methods are available to sense it. On the other hand Stress History is fundamental for realistic estimates of settlements and liquefaction resistance, it makes the soil much "stronger". If Stress History is not sensed, and therefore ignored, the benefits are wasted. Stress History is a substantial economical resource, permitting a more economical design.

ESTIMATING V_S FROM MECHANICAL DMT (NON SEISMIC) RESULTS.

If V_S has not been measured directly, approximate estimates of V_S and G_0 can be obtained from the three DMT parameters I_D, K_D, M_{DMT} obtained by mechanical DMT (i.e. plain, non seismic DMT). Once K_D and M_{DMT} have been determined by mechanical DMT, Fig. 5 provides estimates of G_0 and then of V_S. Note that the ratio G_0/M_{DMT} on the vertical axis is the ratio between the small strain modulus and the operative modulus. It can be seen that such ratio varies in a quite wide range , say from 0.5 to 25. Fig. 5 negates the possibility, sometimes suggested, to estimate the operative modulus by dividing G_0 by a constant, considering that the "constant" varies in the range 0.5 to 20.

The experimental relationship in Fig. 5 is quite stable, having been constructed using SDMT results from 34 different sites world-wide in a variety of soil types [9]. Obtaining datapoints in Fig. 5 does not require a specific research. Datapoints are obtained whenever a SDMT is executed, because SDMT provides routinely at each test depth either K_D, I_D, M_{DMT} and G_0.

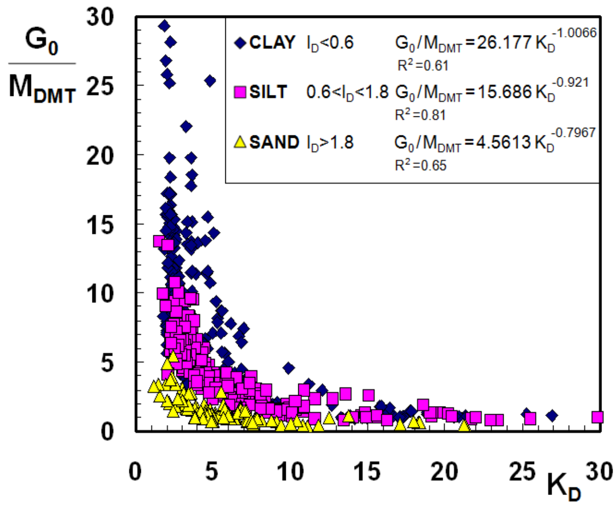

Fig. 5 Ratio G_0/M_{DMT} vs. K_D (OCR) for various soil types [8]. It can provide estimates of G_0 (and V_S) from the results of the "mechanical" DMT

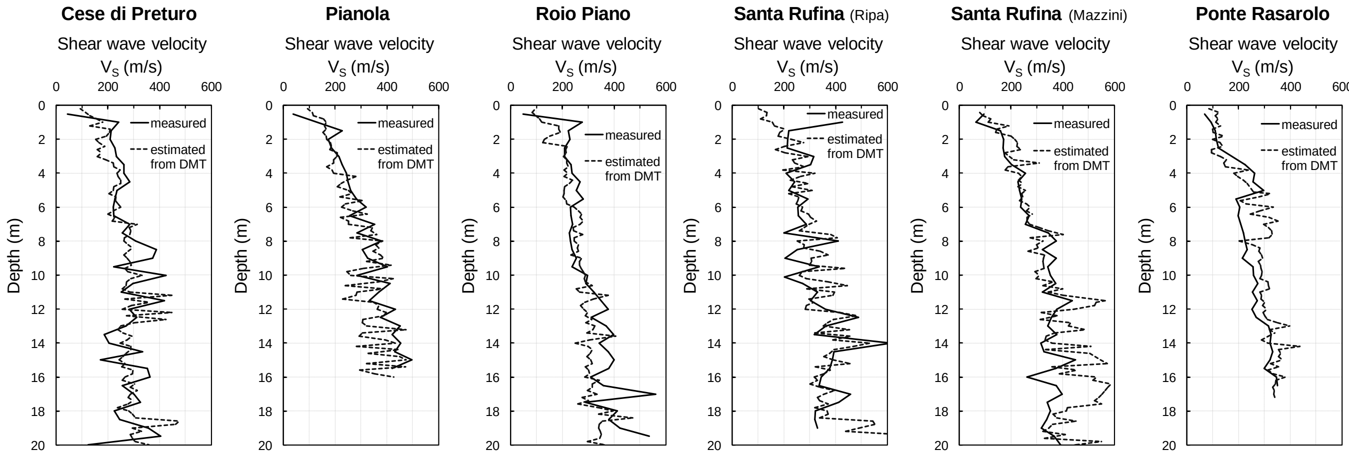

Fig. 6 Comparison of profiles of V_S measured by SDMT and estimated from mechanical DMT data, by use of the correlations in Fig. 5, at six sites in the area of L'Aquila (Monaco at al. 2013 [14])

The V_S comparisons shown in Fig. 6 indicate a fair agreement between the V_S values determined by SDMT (solid lines) and the V_S values inferred by entering K_D, I_D, M_{DMT} in Fig. 5 (dashed lines in Fig. 6). The relative error, calculated as (V_S measured – V_S estimated) / V_S measured, is about 20% on average.

Amoroso et al. (2013) [15] compare the DMT correlations for estimating V_S with the similar correlations by CPT. Amoroso concludes that V_S estimates based on DMT are closer to the measured V_S and attributes the better quality V_S by DMT to the fact that DMT is a genuine two parameter test.

TESTABLE SOILS

The soils that can be investigated by DMT range from extremely soft to hard soils to soft rocks. The DMT readings are accurate even in nearly liquid soils. On the other hand the blade is very robust and can penetrate even in soft rock. Clays can be tested from *Cu* = 2-4 kPa up to 1000 kPa (marls). The range of measurable moduli *M* is from 0.4 MPa up to 400 MPa.

The DMT blade can be inserted by a variety of penetration machines. Truck-mounted penetrometers are the fastest. A drill rig is also usable, with the "Torpedo" configuration [4], though at a lower productivity. Penetration by percussion, e.g. using the SPT hammer (Fig. 7), is also possible. Though dynamic insertion using an SPT rig is not the preferred way, in some countries, e.g. Switzerland, driving is the most common insertion method.

APPLICATIONS TO ENGINEERING PROBLEMS

Design via Parameters

In most cases the DMT estimated parameters, in particular the undrained shear strength *Cu* and the constrained modulus *M*, are used with the common design methods of Geotechnical Engineering for evaluating bearing capacity, settlements etc.

Fig. 7 DMT blade advanced by an SPT rig

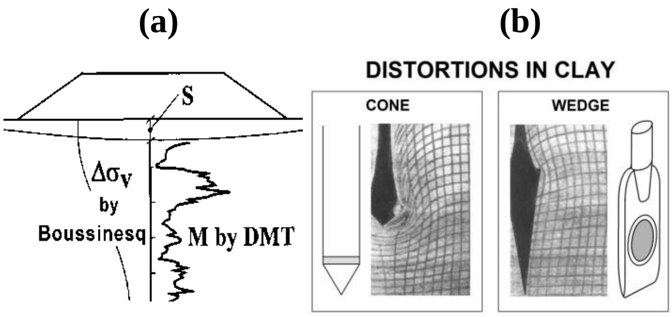

Fig. 8 (a) Settlement prediction by DMT (b) Soil distortions caused by tips of different shape (Baligh & Scott 1975 [16])

However, for a number of applications, specific comments may be opportune.

Settlements of Shallow Foundations

Predicting settlements of shallow foundations is probably the No. 1 application of the DMT, especially in sands, where undisturbed samples cannot be retrieved. Settlements are generally calculated by means of the one-dimensional formula (Fig. 8a) :

$$S_{1-DMT} = \sum \frac{\Delta\sigma_v}{M_{DMT}} \Delta z \qquad (1)$$

with $\Delta\sigma_v$ calculated according to Boussinesq and M_{DMT} constrained modulus estimated by DMT. The validity of the method has been confirmed by a large number of observed agreement between measured and DMT-predicted settlements. Fig. 8b compares the insertion distortions caused by probes of different shape.

Laterally Loaded Piles

Methods have been developed for deriving P-y curves from DMT results [17,18]. A number of independent validations (NGI, Georgia Tech and tests in Virginia sediments) have indicated that the two methods provide similar predictions, and that the predictions are in quite good agreement with the observed behavior. Note that all methods are for the case of first time monotonic loading.

Detecting Slip Surfaces in OC Clay

The $K_D \approx 2$ method [4] permits to detect active or old slip surfaces in overconsolidated (OC) clay slopes, based on the inspection of the K_D profiles. In essence, the method consists in identifying zones of normally consolidated (NC) clay in a slope which, otherwise, exhibits an OC profile. The NC clay bands, remoulded by the sliding, then reconsolidated under the weight of the overlying soil, are recognized by using $K_D \approx 2$ as the identifier of the NC zones. Note that the method involves searching for a specific numerical value ($K_D \approx 2$) rather than for simply weak zones, which could be detected just as easily by other in situ tests. The $K_D \approx 2$ method permits to detect even quiescent surfaces, which could reactivate e.g. due to a cut.

Compaction Control

DMT has been found to be more than twice more sensitive than CPT to compaction. For this reason before-after DMTs are increasingly used to monitor the gain in modulus and the gain in OCR due to compaction. Schmertmann (1986) [11] found that the compaction produced on average an M_{DMT} gain 2.3 times the q_c gain. A similar trend was observed by Jendeby (1992, [12]) who found, upon compaction of a loose sandfill, an increase of the ratio M_{DMT} / q_c from a pre-compaction M_{DMT} / $q_c \approx$5-12 to a post-compaction M_{DMT} / $q_c \approx$ 12-24 (Fig. 10a). The fact that M_{DMT} / q_c increases with compaction - which is a way of applying stress history - confirms that OCR increases M_{DMT} at a faster rate than q_c. The higher sensitivity of DMT to compaction has been confirmed by many researchers, e.g. Balachowski (2015 [19]) : "The mean increase of M_{DMT} within the compacted sandy layer is about 2.3 times higher than corresponding increase of q_c ".

Many designers like to know not only the gain in M, but also the gain in OCR due to compaction. OCR in granular soils can be estimated, before and after compaction, from the ratio M_{DMT} / q_c using the Monaco et al. (2014 [20]) equation :

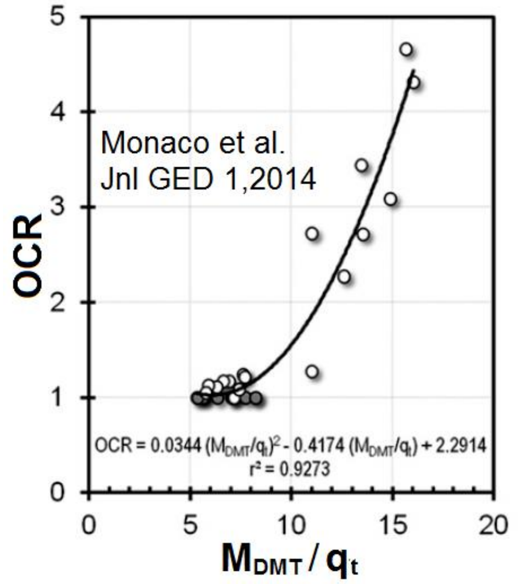

Fig. 9 Correlation OCR= f(M_{DMT} / q_c) for Sandy layers (Monaco et al. 2014 [20])

$$OCR = 0.0344\,(M_{DMT}/q_c)^2 - 0.4174\,(M_{DMT}/q_c) + 2.2914 \qquad (2)$$

or its graphical equivalent Fig. 9.

It is noted that, in order to estimate OCR, both CPT and DMT are necessary, because both q_c and K_D increase with D_r and Stress History - though in a different proportion. Dr and Stress History are two unknowns, it is therefore impossible to estimate OCR in granular soils from CPT or DMT alone.

Profiles of OCR - or of its proxy M_{DMT} / q_c - are often plotted (Fig. 10) by designers wishing to confirm the gain in OCR of the compacted fill.

In 1986 Schmertmann [11] observed that, since the primary objective of the ground improvement is to limit settlements, it appears more rational to establish the acceptance criterion in terms of minimum modulus rather than of minimum D_r , as modulus relates more closely to the objective than D_r. In the job described by Schmertmann the designers replaced the q_c to D_r criterion to a minimum M_{DMT} acceptance criterion. Similarly Balachowski (2015,[19]) describes a compaction job where "the minimum average M_{DMT} = 80 MPa was fixed as an acceptance criterion for the post-treated subsoil".

A collateral advantage of using the minimum M_{DMT} acceptance criterion is avoiding the in situ D_r determination, often problematic, because there is no unique mapping q_c to D_r applicable to all sands (e.g. Robertson and Campanella 1983 [21]).

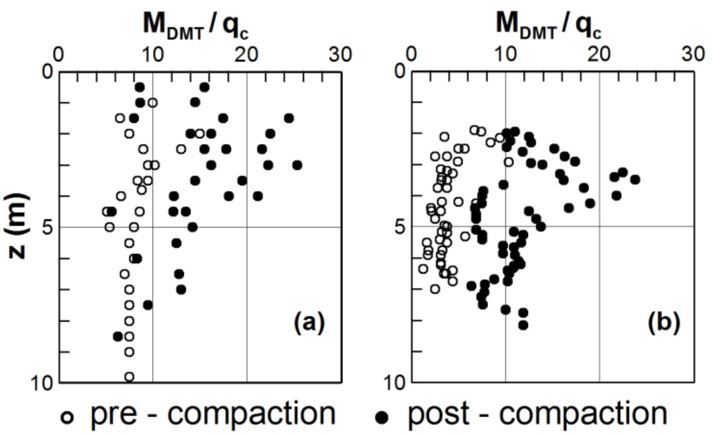

Fig. 10 M_{DMT}/ q_c ratio before/ after compaction. (a) Jendeby (1992) [12] (b) Balachowski and Kurek (2015 [19])

Subgrade Compaction Control

DMT has been used for verifying the compaction of the natural ground surface (i.e. the subgrade) to support the road superstructure [22]. DMT has been used as an economical production tool for quality control of the compaction, with only occasional verifications by the originally specified methods.

Estimating liquefaction resistance CRR from the DMT's parameter K_D

In the last decades various CRR-K_D correlations have been developed. They appear to converge towards a narrow central band. Much of the interest on the CRR-K_D correlation derives from the fact that the Stress History increases significantly CRR and K_D, but only slightly the normalized tip resistance Q_{cn} (Fig. 4). Hence it is possible that a correlation K_D-CRR will be stricter than Q_{cn} - CRR. A collection of recent CRR-K_D correlations is shown in Fig. 11.

As today (end of 2015), the recommended CRR-K_D correlation is the correlation composed by the two equations combined:

$$CRR = \exp\left[(Q_{cn}/540) + (Q_{cn}/67)^2 - (Q_{cn}/80)^3 + (Q_{cn}/114)^4 - 3\right] \quad (3a)$$

$$\text{with } Q_{cn} = 25\, K_D \quad (3b)$$

Eq. (3a) is the Idriss and Boulanger (2006 [23]) correlation to estimate CRR from Q_{cn}.
Eq. (3b) is the Robertson (2012 [24]) average interrelationship $Q_{cn} \approx 25\, K_D$.
The recommended CRR-K_D correlation, defined analytically by the combination of Eqs. (3a) and (3b), is plotted in Fig. 11, identified with the label RIB.
If both DMT and CPT results are available, it is possible to obtain two independent estimates of CRR, one from CPT using Eq. (3a), the second one from DMT using Eq. (3a) and Eq. (3b) combined. The two above mentioned CRR estimates are however obtained each one by one-to-one correlations, one providing CRR just from DMT, the second one providing CRR just from CPT. A recent chart (Marchetti 2015 [25]), rather than providing two CRR estimates from two distinct one-to-one CRR correlations, presents a correlation providing just one estimate of CRR, based at the same time on Q_{cn} & K_D, in the form CRR=f(Q_{cn}, K_D), as shown in Fig. 12.

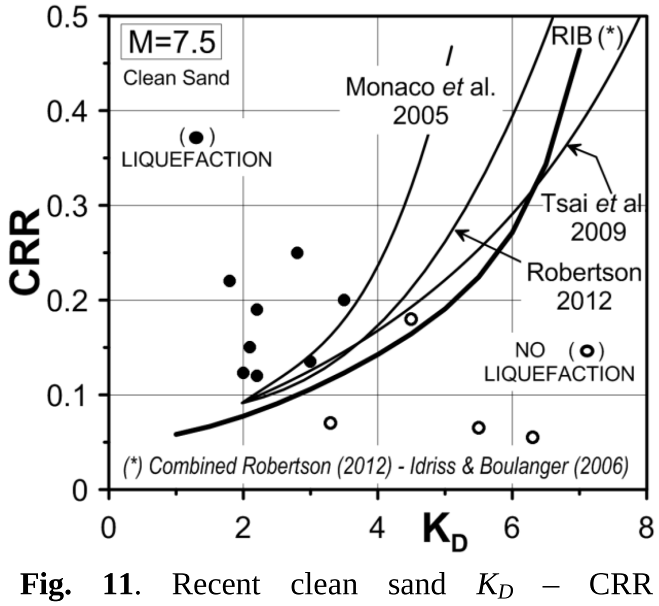

Fig. 11. Recent clean sand K_D – CRR correlations

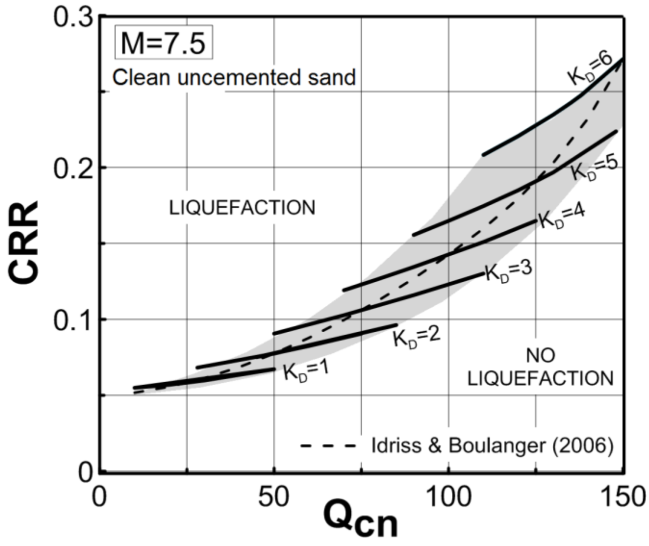

Fig. 12 Correlation for estimating CRR based at the same time on Q_{cn} and K_D - for clean uncemented sand (Marchetti 2015 [25])

A numerical example. For Q_{cn} =100 and K_D = 4, Fig. 12 provides CRR = 0.14. However, for the same Q_{cn} =100, if K_D =5, Fig. 12 provides CRR = 0.17. In other words, for the same Q_{cn}, Fig. 12 provides CRR estimates which are higher if K_D is more than average (i.e. > Q_{cn}/25) , are lower if K_D is less than average.

The Seafloor Dilatometer

The seafloor dilatometer (Fig. 13) has been developed to execute DMT soundings from the seabed. It is composed by an upper pushing section, whose weight is 60-80 Kg, easily transported and a lower heavy section, that can be ballasted 3 to 7 tons, easy to construct locally. The two sections can be quickly solidarized using 4 bolts. The seafloor dilatometer can operate up to a waterdepth of 100 m. The maximum test depth depends on soil consistency – it is the depth penetrable with 7 ton push. Six or seven pushrods are already charged vertically on top, before lowering the machine. More rods can be added by keeping the string vertical, sustaining the rodstring with a buoy - or a trestle fixed to the top of the ballast.

Fig. 13 Seafloor Dilatometer for executing DMT or SDMT from the seafloor

CONCLUSIONS

The Flat Dilatometer and the Seismic Dilatometer are relatively recent in situ tests. They provide estimates of a variety of design parameters. They are fast and simple to operate, and the measurements are reproducible and operator independent. The DMT most frequent application is to predict settlements. Other applications have been briefly described in the paper. The test is standardized in the ASTM and the Eurocode.

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(°) Many of the references can be downloaded from the site www.marchetti-dmt.it