Flat dilatometer (DMT). Applications and recent developments

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Abstract **– Since the original basic paper on the flat dilatometer (Marchetti 1980) a large number of papers, including manuals and standards, have been published. Aims of this paper are: (a) to briefly describe this in situ test; (b) to summarize the essential related content available in the literature; (c) to give an overview of its main applications; (d) to give information on the most recent developments, thereby permitting the unfamiliar reader to gain in a short time a basic knowledge of the DMT.**

I. 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 seismic dilatometer (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.
- Recent building codes based on the Eurocode 8 prescribe the determination of V_S in the top 30 m at all construction sites located in seismic zones.
- The 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.

II. 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 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. push rigs normally used for the cone penetration test (CPT). Pushing the blade with a 20 ton penetrometer truck is most effective (up to 80 m of profile per day). A drill rig is also usable, with the "torpedo" configuration [4], though with a lower productivity. The DMT can also be driven, e.g. using the SPT hammer and rods, but statical push is by far preferable.

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 undrained shear strength c_u = 2-4 kPa up to 1000 kPa (marls). The range of measurable moduli M is from 0.4 MPa up to 400 MPa.

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

Fig. 1. Flat dilatometer. (a) Equipment. (b) Dilatometer blade. (c) Schematic layout of the flat dilatometer test.
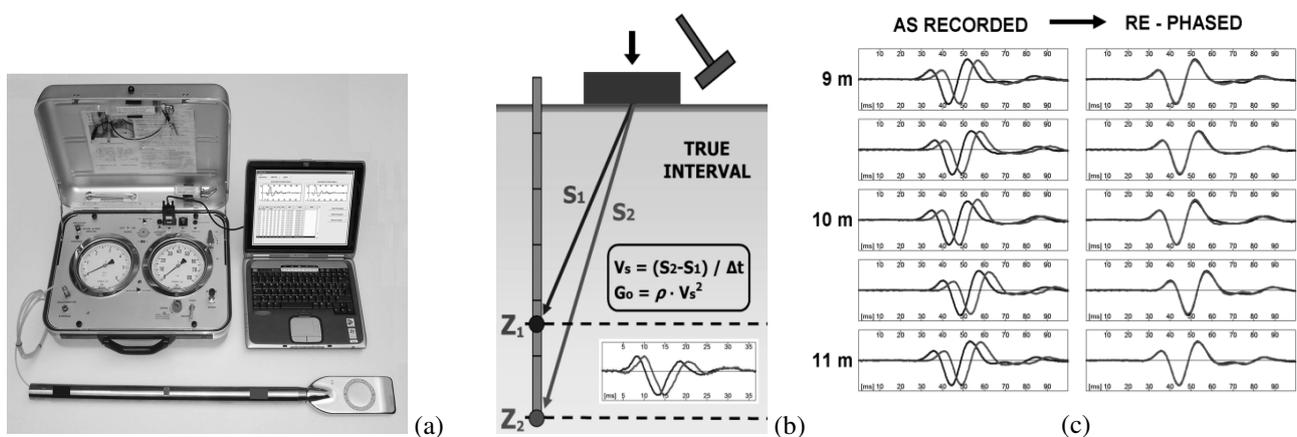

*Fig. 2. Seismic dilatometer. (a) DMT blade and seismic module. (b) Schematic layout of the seismic dilatometer test.
(c) Example of seismograms as recorded and rephased.*

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 (material index), K_D (horizontal stress index), E_D (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 c_u, coefficient of earth pressure in situ K_0 (clays), overconsolidation ratio 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 (also designated as M_{DMT}) is the vertical drained constrained modulus at geostatic stress;
- c_u 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. In clays $K_D \approx 2$ indicates OCR = 1, $K_D > 2$ indicates overconsolidation. 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 interpretation formulae may be found in the 2001 ISSMGE TC16 Report [4]. A comprehensive update of the above DMT Report, including information on developments in the last 15 years, has recently been published [5].

III. 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]. 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 ($S_2 - S_1$) and the
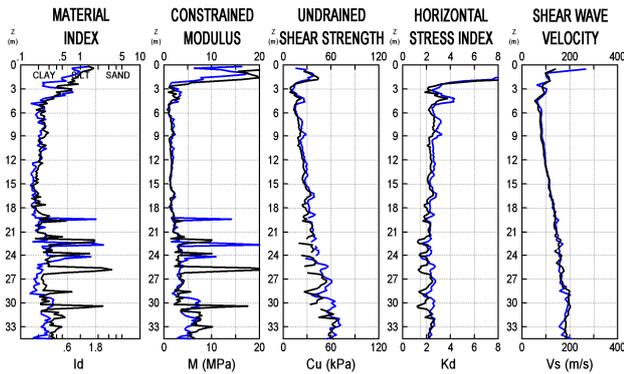
Fig. 3. Example of SDMT results (two nearby SDMTs).

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.

IV. SEAFLOOR DILATOMETER

The seafloor dilatometer (Fig. 4) has been developed to execute DMT/SDMT soundings from the seabed. It is composed by an upper pushing section of weight 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 four bolts. The seafloor dilatometer can operate down to a water depth of 100 m. The maximum test depth depends on soil consistency (it is the depth penetrable with 7 ton push). Six or seven push rods are already charged vertically ontop, 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.

V. 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 q_c. The higher sensitivity to stress history of K_D has been observed by numerous researchers, either in the large calibration chamber (e.g. [7]) and in the field (e.g. [8], [9]). As an example Fig. 5 [10] shows results 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. 5, OCR produces a substantial increase of K_D but an almost negligible increase of q_c. The two diagrams in Fig. 5 confirm that K_D is considerably more reactive to OCR than the normalized tip resistance $Q_{cn} = q_c /(\sigma'_v)^{0.5}$. 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. If stress history is not sensed, and therefore ignored, the benefits are wasted. Stress history is a substantial economical resource, permitting more economical design.

VI. 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 (i.e. plain, non seismic) DMT. Once K_D and M_{DMT} have been determined by mechanical DMT, Fig. 6 provides estimates of G_0 and then of V_S.

Fig. 4. Seafloor dilatometer for executing DMT or SDMT from the seafloor.
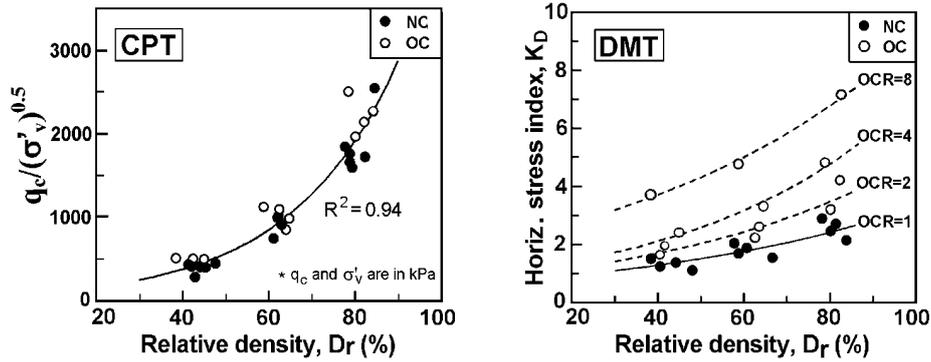
Fig. 5. Sensitivity of CPT and DMT to stress history [10].

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. 6 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. 6 is quite stable, having been constructed using SDMT results from 34 different sites world-wide in a variety of soil types [11]. Obtaining datapoints in Fig. 6 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.

The V_S comparisons shown in Fig. 7 [12] 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. 6 (dashed lines in Fig. 7). The relative error, calculated as (V_S measured – V_S estimated) / V_S measured, is about 20% on average.

Amoroso (2014) [13] compared the DMT correlations for estimating V_S with the similar correlations by CPT. Amoroso concluded that V_S estimates based on DMT are

closer to the measured V_S and attributed the better quality V_S by DMT to the fact that DMT is a genuine two parameter test.
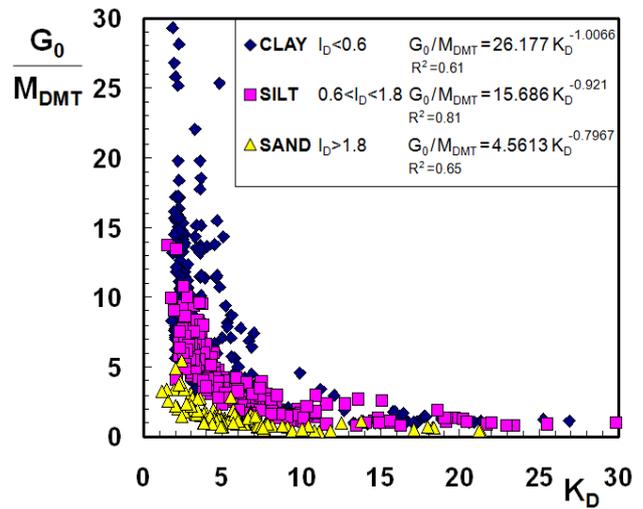

Fig. 6. Ratio G_0/M_{DMT} vs. K_D (OCR) for various soil types [11]. It can provide estimates of G_0 (and V_S) from the results of the "mechanical" DMT.
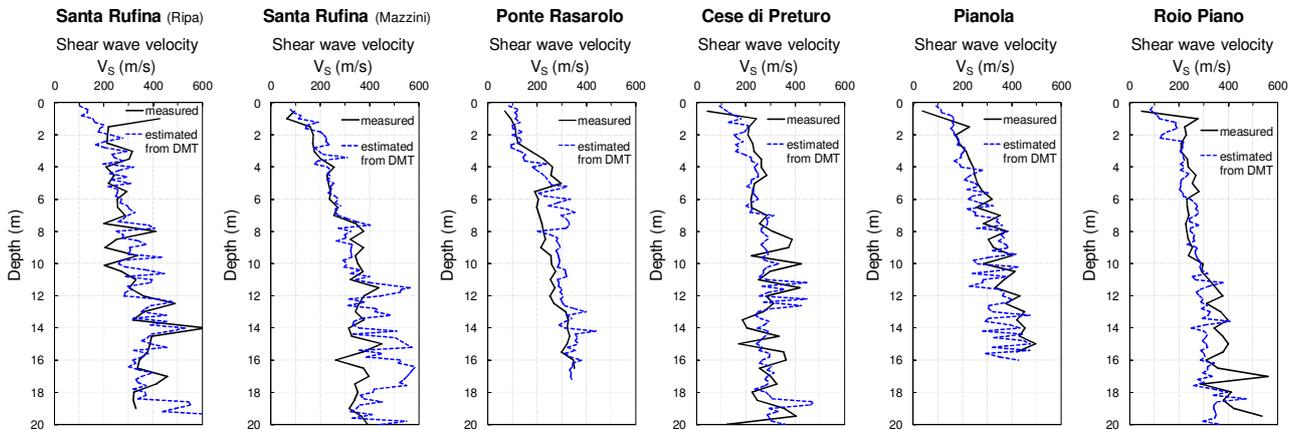

Fig. 7. Comparison of profiles of V_S measured by SDMT and estimated from mechanical DMT data, by use of the correlations in Fig. 6, at six sites in the area of L'Aquila [12].

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VII.   APPLICATIONS TO ENGINEERING PROBLEMS

A. Design via parameters

In most cases the DMT estimated parameters, in particular the undrained shear strength c_u and the constrained modulus M, are used with common design methods of geotechnical engineering for evaluating bearing capacity, settlements, etc. However, for a number of applications, specific comments may be opportune.

B. 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 cases of agreement between measured and DMT-predicted settlements. Fig. 8b [14] compares the insertion distortions caused by probes of different shape.

C. Laterally loaded piles

Methods have been developed for deriving P-y curves from DMT results [15], [16]. 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.

D. 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.

E. Compaction control

The 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 et al. (1986) [8] 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) [9] 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. 9a). 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 and Kurek (2015) [17]: *"The mean increase of M_{DMT} within the compacted sandy layer is about 2.3 times higher than corresponding increase of q_c"* (Fig. 9b).

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) [18] equation:

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

or its graphical equivalent Fig. 10.

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.
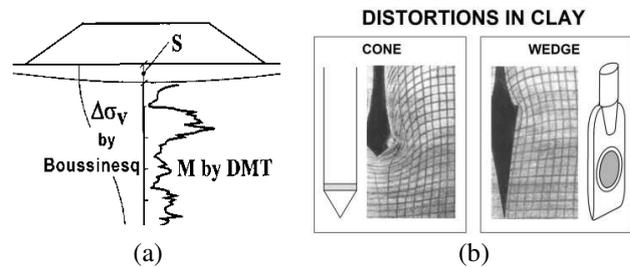

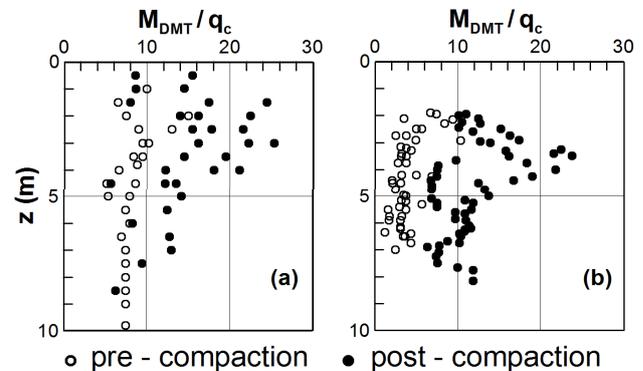*Fig. 8. (a) Settlement prediction by DMT. (b) Soil distortions caused by tips of different shape [14].*

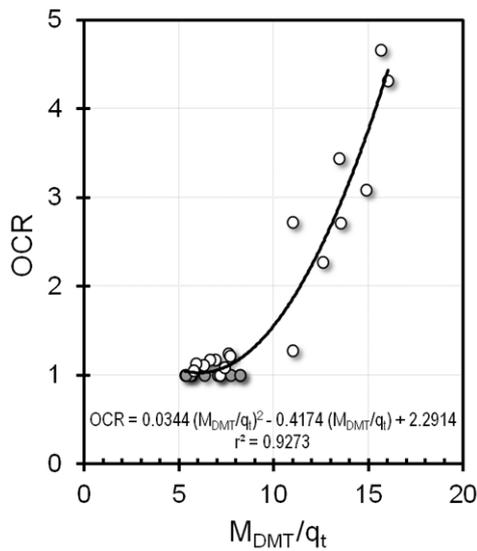*Fig. 9. M_{DMT}/q_c ratio before/after compaction [9] (a), [17] (b).*

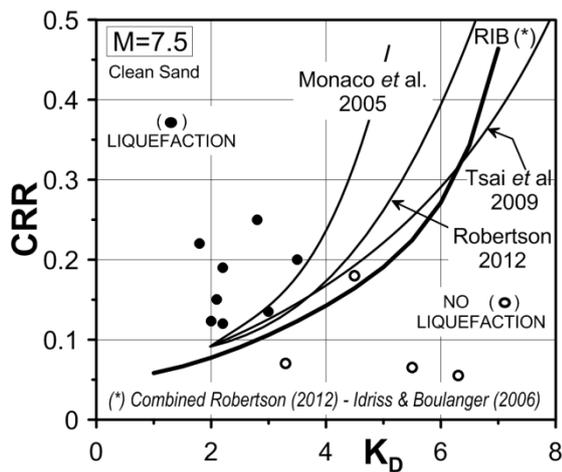*Fig. 10. Correlation OCR = f(M_{DMT}/q_c) for sands [18].*

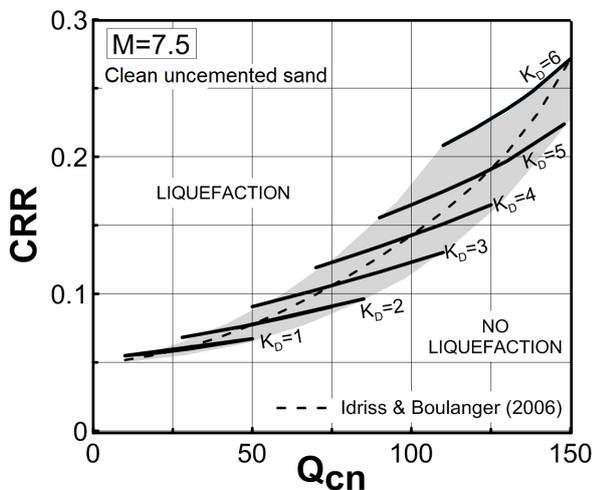*Fig. 11. Recent clean sand K_D - CRR correlations.*

Fig. 12. Correlation for estimating CRR based on both Q_{cn} and K_D, for clean uncemented sand [25].

D_r 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. 9) by designers wishing to confirm the gain in OCR of the compacted fill. Schmertmann et al. (1986) [8] 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 in [8] the designers replaced the q_c to D_r criterion with a minimum M_{DMT} acceptance criterion. Similarly Balachowski and Kurek (2015) [17] describe 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. [19]).

F. Subgrade compaction control

The DMT has been used for verifying the compaction of the natural ground surface (i.e. the subgrade) to support the road superstructure as an economical production tool for quality control of the compaction [20], with only occasional verifications by the originally specified methods.

G. 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. 5). 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 [21], [22], [23] is shown in Fig. 11.

As today, the recommended CRR-K_D correlation is the correlation composed by the two equations combined:

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

(3a)

with

$$Q_{cn} = 25\,K_D \tag{3b}$$

Eq. (3a) is the Idriss and Boulanger (2006) [24] correlation to estimate CRR from Q_{cn}. Eq. (3b) is the Robertson (2012) [23] average interrelationship Q_{cn} - 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 by Marchetti (2016) [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.

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.

VIII. 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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