*Proceedings of Indian Geotechnical Conference IGC-2014*
*December 18-20, 2014, Kakinada, India*

# THE SEISMIC DILATOMETER FOR IN SITU SOIL INVESTIGATIONS

**S. Marchetti,** Prof., L'Aquila University – Italy, silvano@marchetti-dmt.it

**ABSTRACT:** The last decades have seen a massive migration from laboratory testing to in situ testing. Often today in situ testing is the major part of a geotechnical investigation. In situ tests are fast, economical, reproducible, informative, provide many data, involve reduced scatter, cost much less than sampling & testing. This is particularly true in sand, where recovering samples is difficult. Field tests are therefore today the state-of-practice for everyday design. Laboratory tests remain fundamental for research and in big jobs. Scope of this paper is to describe the DMT, the obtained information and the engineering applications. The paper also describes the recently developed Seismic Dilatometer (SDMT) which includes an add-on seismic module for measuring also the shear wave velocity $V_S$. DMT and SDMT have been found helpful in projects where soil stiffness and settlements predictions are critical to the design. In the recent years DMT has been increasingly used for liquefaction resistance estimates.

## 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 $G$-$\gamma$ curves, i.e. the decay of the shear modulus $G$ with the shear strain $\gamma$.

## 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

(a) (b) (c)

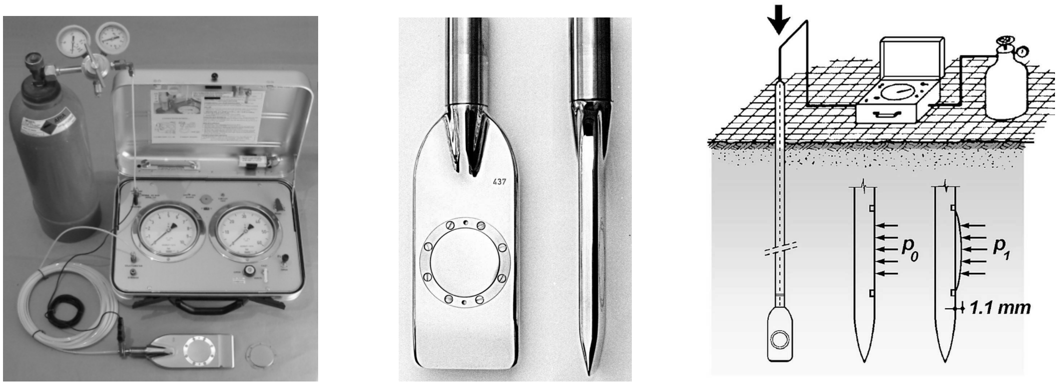


**Fig. 1** Flat Dilatometer: (a) Equipment (b) Dilatometer Blade (c) Schematic layout of the seismic dilatometer test.

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 by far 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 $\phi'$ (sands), bulk unit weight $\gamma$. 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 comprehensive Report by the ISSMGE Technical Committee TC16 [4].

## 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 [5-8]. 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

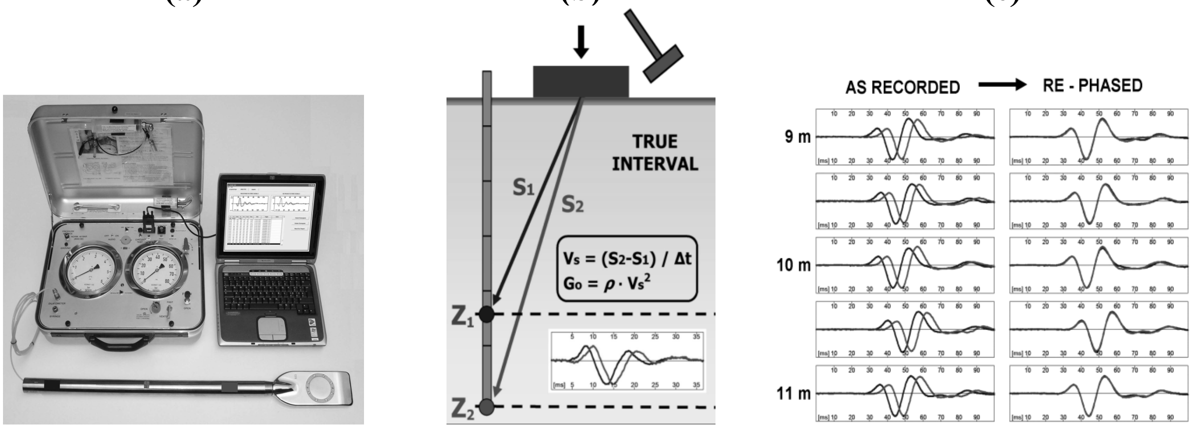


**Fig. 2** Seismic Dilatometer: (a) DMT blade and seismic module (b) Schematic layout of the seismic dilatometer test. (c) Example of seismograms as recorded and rephased.

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 $\Delta t$ 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 $\approx$ 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

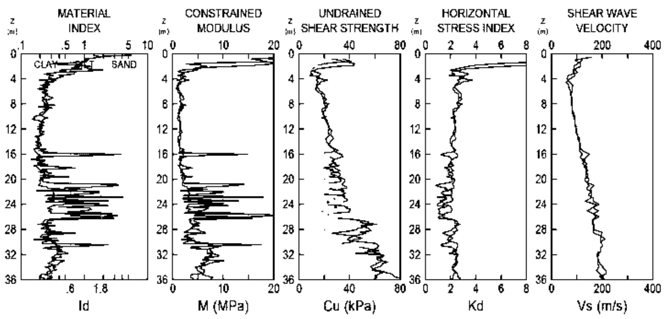


**Fig. 3** Example of SDMT results (from two nearby SDMTs).

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.

## SENSITIVITY OF $K_D$ TO STRESS HISTORY

It is a well established notion, supported by a large experimental base, 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. [9]) and in the field (e.g. [10], [11]).

As an example Fig. 4 shows results [12] 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 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 $Q_{cn}$. To the same normalized tip resistance $Q_{cn}$ 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

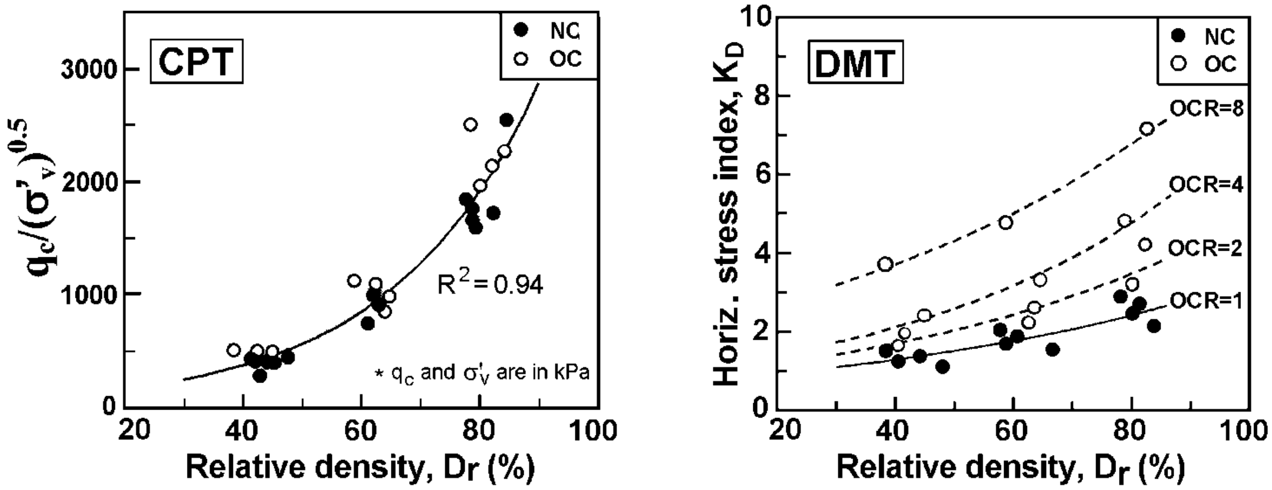


**Fig. 4** Sensitivity of CPT and DMT to Stress History (Lee et al. 2011 [12]).

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

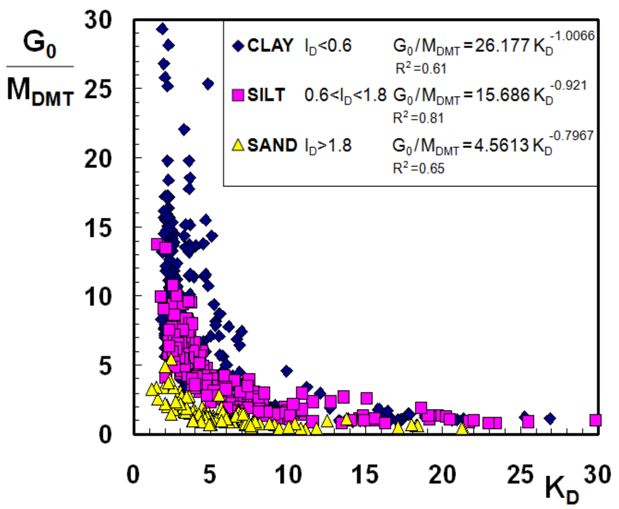


**Fig. 5** Ratio $G_0/M_{DMT}$ vs. $K_D$ (OCR) for various soil types [8]. It can provide estimates of $G_0$ (and $V_S$) from the results of the "mechanical" DMT.

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.

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 [8]. 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 $G_0$.

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). The relative error, calculated as ($V_S$ measured – $V_S$ estimated) / $V_S$ measured, is about 20% on average.

Fig. 5 highlights the dominant influence of $K_D$ - which reflects stress history - on the ratio $G_0/M_{DMT}$. In case of non availability of $K_D$, all the experimental data points would cluster on the vertical axis. On the other hand the poor direct

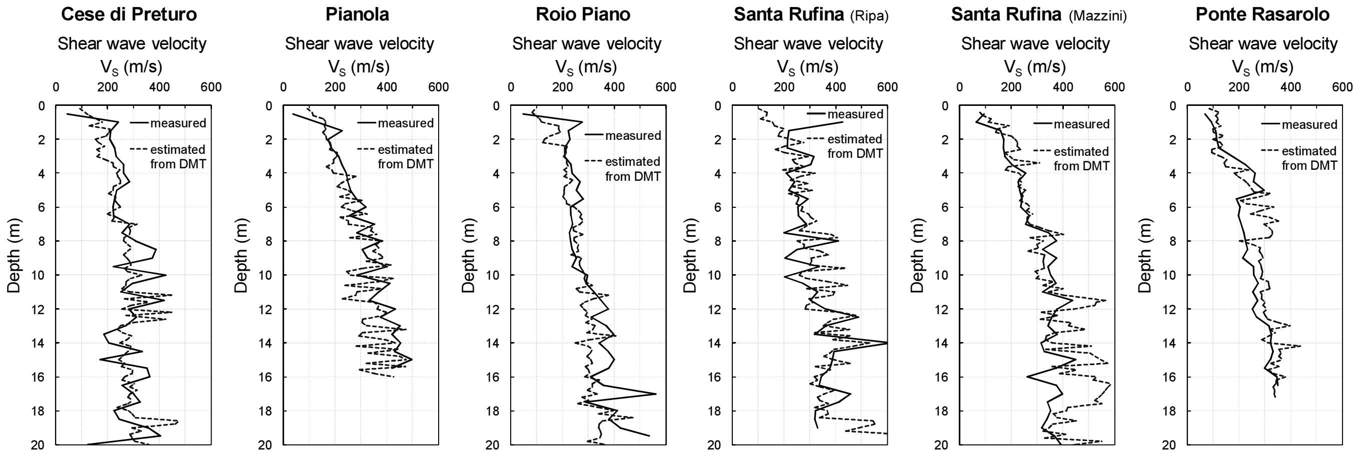


**Fig. 6** Comparison of profiles of $V_S$ measured by SDMT and estimated from mechanical DMT data, by use of the correlations in Fig. 5, at six sites in the area of L'Aquila (Monaco at al. 2013 [13]).

correlability $M_{DMT}$ to $G_0$, in absence of $K_D$, is expectable. $M_{DMT}$ and $G_0$ are inherently different parameters, since at small strains the soil tendency to dilate or contract is not active yet. Such tendency substantially affects the operative modulus $M_{DMT}$, but does not affect $G_0$. Moduli $M$ are substantially increased by Stress History, $V_S$ (or $G_0$) much less (see e.g. Fig. 7). In conclusion correlations for predicting $V_S$ that do not include $K_D$ or Stress History are expected to be highly imprecise.

## 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 by far 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, is also possible, although not recommended.

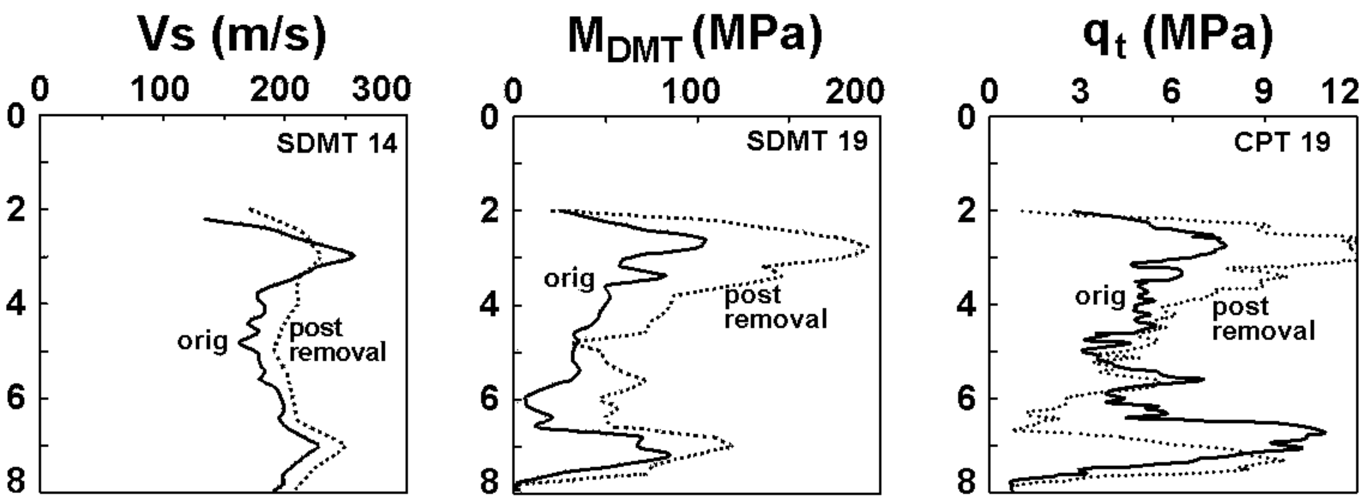


**Fig. 7** Profiles of $V_S$, $M_{DMT}$ and $Q_t$ in the Treporti-Venezia nearly normally consolidated site before-construction and after-removal of a 100 kPa cylindrical embankment 40 m in diameter [14].

## 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. However, for a number of applications, additional 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 [16,17]. 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.

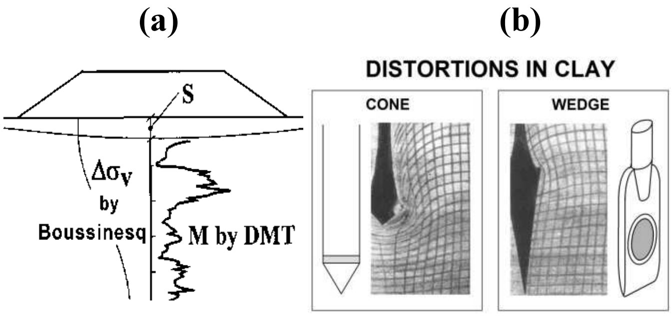


**Fig. 8** (a) Settlement prediction by DMT (b) Soil distortions caused by tips of different shape (Baligh & Scott 1975 [15]).

### 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 ($K_D = 2$) rather than for simply weak zones, which could be detected just as easily by other in situ tests. The $K_D = 2$ method permits to detect even quiescent surfaces, which could reactivate e.g. due to an excavation.

### Monitoring Densification/ Stress Increase

Before-after DMTs have been frequently used for monitoring soil densification treatments. Compaction is generally reflected by a brisk increase of both $K_D$ and $M_{DMT}$. Results by various authors (e.g. Schmertmann 1986 [10]) indicate that the percentage increase in $M_{DMT}$ is approximately twice the increase in $Q_c$. In other words densification increases both $Q_c$ and $M_{DMT}$, but $M_{DMT}$ increases at a faster rate. DMT appears therefore well suited to detect the benefits of the soil improvement.

It may be noted that, since densification is often aimed at reducing settlements, it would appear more direct to set the specifications in terms of *M* rather than of relative density *Dr* - a not precisely measurable parameter.

The DMT is suitable for detecting small horizontal stress variation, e.g. in the relaxing soil behind diaphragm walls during the excavation.

### 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 [20]. 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 OCR-$K_D$ correlation derives from the fact that the Stress History increases significantly CRR and $K_D$, but only slightly $Q_{cn}$ (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. 9.

As today (end of 2014), the recommended CRR-$K_D$ correlation is the correlation composed by the two equations combined:

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

$$\text{with } Q_{cn} = 25\, K_D \qquad (2b)$$

Eq. (2a) is the Idriss and Boulanger (2006 [18]) correlation to estimate CRR from $Q_{cn}$.

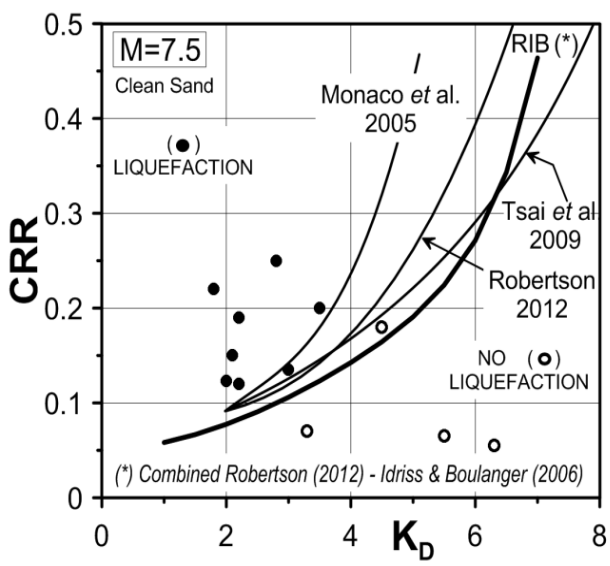


**Fig. 9**. Recent clean sand $K_D$ – CRR correlations

Eq. (2b) is the Robertson (2012 [19]) correlation to estimate $Q_{cn}$ from $K_D$.

The curve defined by the combination of Eqs. 2a and 2b is plotted in Fig. 9, 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. 2a, the second one from DMT using Eq. 2a and Eq. 2b combined (a third independent CRR estimate is possible if $V_S$ has also been measured by SDMT or SCPT). The two above mentioned CRR estimates are however obtained by one-to-one correlations, one providing CRR just from DMT, the second one providing CRR just from CPT. Recent research (2015), rather than predicting CRR from two distinct one-to-one CRR correlations, has developed 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 qualitatively in Fig. 10.

**The Seafloor Dilatometer**

The seafloor dilatometer (Fig. 11) 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

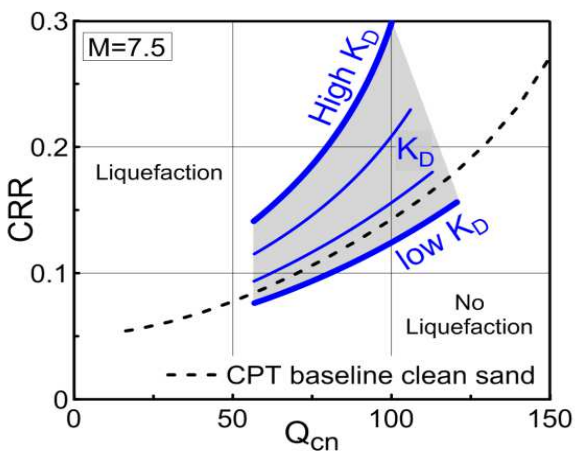


**Fig. 10** Correlation (qualitative) for estimating CRR based at the same time on $Q_{cn}$ and $K_D$


**Fig. 11** Seafloor Dilatometer for executing DMT or SDMT from the seafloor

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.

## 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.

## REFERENCES (°)


1. Marchetti, S. (1980), In Situ Tests by Flat Dilatometer, *Jnl GED, ASCE*, 106, GT3: 299-321.
2. ASTM D6635-01 (2001 & 2007), Standard Test Method for Performing the Flat Plate Dilatometer, *Book of Standards*, 14 pp.
3. Eurocode 7 (1997 & 2007), Geotechnical Design - Part 2, *Ground Investigation and Testing*, EN 1997-2:2007.
4. TC16 (2001), The Flat Dilatometer Test (DMT) in Soil Investigations, A *Report by the ISSMGE Committee TC16*. May 2001, 41 pp. Reprinted in Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington D.C. 2006 : 7-48.
5. Monaco, P., Marchetti, S., Totani, G. & Calabrese, M. (2005), Sand liquefiability assessment by Flat Dilatometer Test (DMT), *Proc. XVI ICSMGE*, Osaka, 4: 2693-2697.
6. Monaco, P. & Marchetti, S. (2007), Evaluating liquefaction potential by seismic dilatometer (SDMT) accounting for aging/stress history, *Proc. 4th Int. Conf. on Earthquake Geotechnical Engineering ICEGE*, Thessaloniki, 12pp.
7. Marchetti, S., Monaco, P., Totani, G. & Marchetti, D. (2008), In Situ Tests by Seismic Dilatometer (SDMT), *Proc. from Research to Practice in Geotechnical Engineering, ASCE Geotech. Spec. Publ. No. 180* (honoring J.H. Schmertmann): 292-311.
8. Monaco, P., Marchetti, S., Totani, G. & Marchetti, D. (2009), Interrelationship between Small Strain Modulus $G_0$ and Operative Modulus, *International Symposium IS-Tokyo 2009 on Performance-Based Design in Earthquake Geotechnical Engineering*, 8 pp.
9. Jamiolkowski, M. and Lo Presti, D.C.F. (1998), DMT Research in Sand. What can be learned from calibration chamber tests, *1st Int. Conf. on Site Characterization ISC'98*, Atlanta. Oral presentation.
10. Schmertmann, J.H., Baker, W., Gupta, R. and Kessler, K. (1986), CPT/DMT Quality Control of Ground Modification at a Power

Plant, *Proc. ASCE Spec. Conf. on Use of In Situ Tests in Geotechnical Engineering In Situ '86,* Virginia Tech, Blacksburg. ASCE Geotech. Spec. Publ. No. 6, 985-1001.

11. Jendeby, L. (1992), Deep Compaction by Vibrowing, *Proc. Nordic Geotechnical Meeting NGM-92,* 1, 19-24.
12. Lee, M., Choi, S., Kim, M. and Lee, W. (2011), Effect of Stress History on CPT and DMT results in Sand, *J .Engineering Geology, Elsevier*, 117, 259-265.
13. Monaco P., Totani G., Amoroso S., Totani F., Marchetti D. (2013), Site Characterization by Seismic Dilatometer (SDMT) in the City of L'Aquila, *Rivista Italiana di Geotecnica*, Year 47, 3, 8-22.
14. Marchetti S. (2010), Sensitivity of CPT and DMT to stress history and aging in sands for liquefaction assessment, *Proc. CPT 2010 Int.nl Symposium Huntington Beach*, California.
15. Baligh, M.M. & Scott, R.F. (1975), Quasi Static Deep Penetration in Clays, *ASCE Jnl GE*, 101, GT11 : 1119-1133.
16. Robertson, P.K., Davies, M.P. & Campanella, R.G. (1987), Design of Laterally Loaded Driven Piles Using the Flat Dilatometer, *Geot. Testing Jnl*, Vol. 12, No. 1: 30-38.
17. Marchetti, S., Totani, G., Calabrese, M. & Monaco, P. (1991), P-y curves from DMT data for piles driven in clay, *Proc.* 4th *Int. Conf. on Piling and Deep Foundations*, *DFI*, *Stresa*, Vol. 1 : 263-272.
18. Idriss, I.M. and Boulanger, R.W. (2006), Semi-empirical procedures for evaluating liquefaction potential during earthquakes, *Soil Dynamics and Earthquake Engineering*, 26, 115-130.
19. Robertson, P.K. (2012), Mitchell Lecture. Interpretation of in-situ tests - some insight, *Proc.4th Int. Conf. on Site Characterization ISC-4*, Porto de Galinhas - Brazil, 1, 3-24.
20. Marchetti, S. (1994), An example of use of DMT as an help for evaluating compaction of subgrade and underlying embankment, *Internal Technical Note*, 4pp.

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