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THE SEISMIC DILATOMETER FOR IN SITU SOIL INVESTIGATIONS

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ABSTRACT
In the last decades we have assisted at a massive migration from laboratory testing to in situ testing, to the point that, today, in situ testing is often the major part of a geotechnical investigation. The State of the Art at the last Geotechnical World Conference in 2009 indicates that direct-push in situ tests, such as the Cone Penetration Test (CPT) and the Flat Dilatometer Test (DMT), are fast and convenient in situ tests for routine site investigation. Scope of this paper is to describe the DMT, the obtained information and engineering applications. The paper also describes the recently developed Seismic Dilatometer (SDMT), which is a DMT with 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.

Keywords: dilatometer test, seismic dilatometer test, geotechnical applications, settlements, liquefaction.

INTRODUCTION

The Flat Dilatometer (DMT) is an in situ testing tool developed about 35 years ago (Marchetti 1980). The DMT is currently used in practically all industrialized countries. It is standardized in the ASTM (2001 & 2007) and the Eurocode 7 (1997 & 2007). The DMT has been object of a detailed monograph by the ISSMGE Technical Committee TC16 (2001).
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, whose knowledge is of primary interest, because Stress History has a dominant influence on soil behavior. In particular stress history is necessary for estimating operative moduli and 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 the seismic zones.

(a) (b) (c)

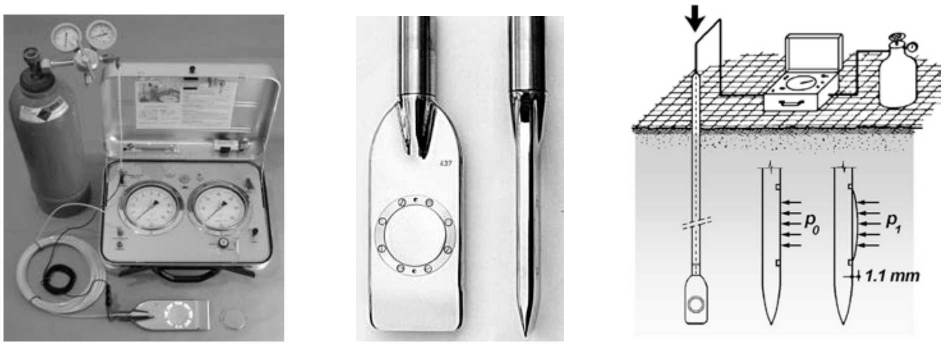


Fig. 1 Flat Dilatometer: (a) Equipment (b) Dilatometer Blade (c) Schematic layout of the seismic dilatometer test.

- SDMT provides both the *Go* stiffness at small strains (the 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 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 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 advanced to the desired test depth, the penetration is stopped. 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 of 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, to: constrained modulus *M*, undrained shear strength *Cu*, *Ko*(clays), *OCR* (clays), friction angle *Ø'* (sands), bulk unit weight. Consolidation and permeability coefficients may be estimated by performing dissipation tests (TC16 2001). The C-reading, in sand, approximately equals the equilibrium pore pressure. An example of the profiles obtained by DMT is shown 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

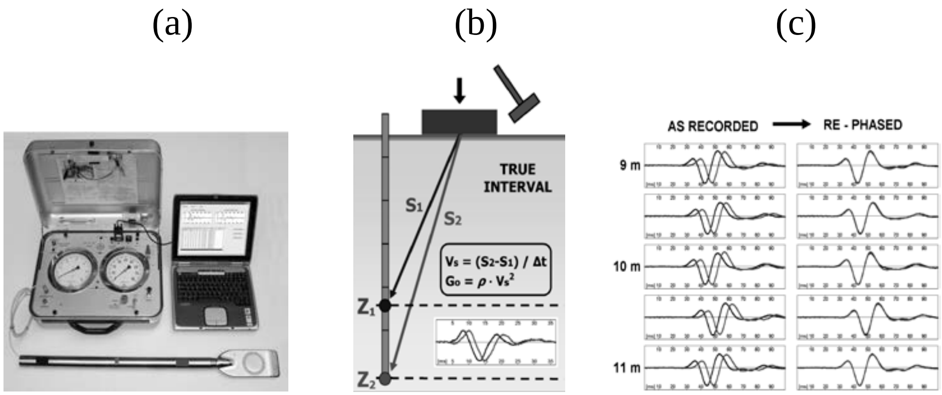


Fig. 2 Seismic Dilatometer: (a) DMT blade and seismic module (b) Schematic layout of the seismic dilatometer test. (c) Example of seismograms as recorded and rephased.

overconsolidation ratio *OCR*. $K_D \approx 2$ indicates in clays *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 all the interpretation formulae may be found in the comprehensive report by the ISSMGE Technical Committee TC16 2001.

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 (Monaco et al. 2005, Marchetti 2010). The seismic module (Fig. 2a) is a cylindrical 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. *Vs* is obtained (Fig. 2b) as the ratio between the difference in distance between the source and the two receivers (S2 - S1) and the delay from the first to the second receiver (Δt). The true-interval test configuration with two receivers avoids possible inaccuracy in the determination 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 *Vs* measurements is remarkable (observed *Vs* 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 *Vs* profile obtained by the seismic module.

TESTABLE SOILS

The soils that can be investigated by DMT range from extremely soft soils to hard soils like soft rock. 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.

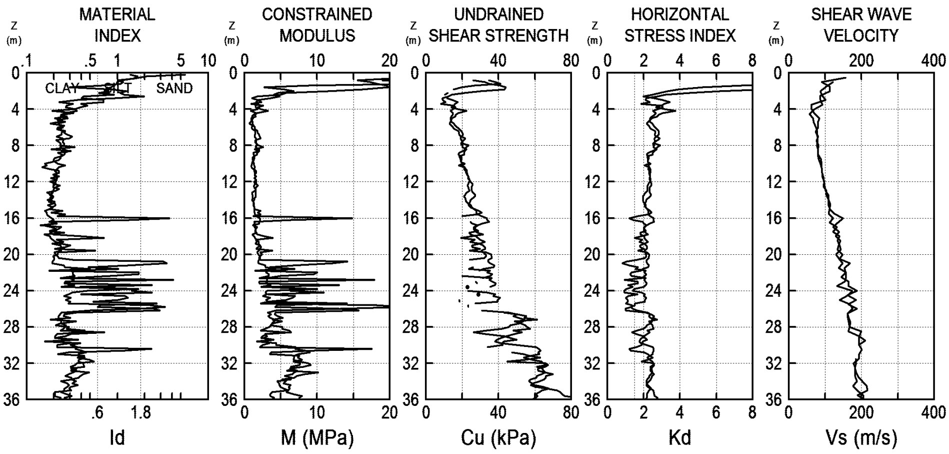


Fig. 3 Example of SDMT results (from two nearby SDMTs)

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 (TC16 2001), though at a lower productivity. Penetration by percussion, e.g. using the SPT hammer, is also possible, although not recommended in soft soils.

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. 4a):

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

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. 4b compares the insertion distortions caused by probes of different shape.

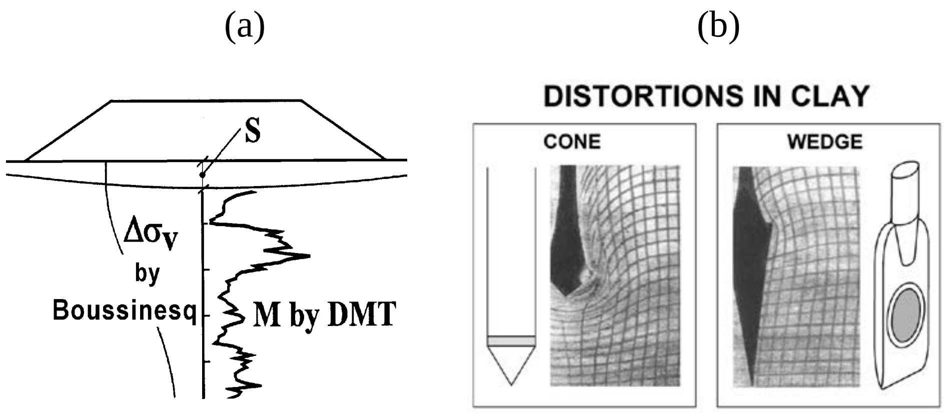


Fig. 4 (a) Settlement prediction by DMT (b) Soil distortions caused by tips of different shape (Baligh & Scott 1975).

Laterally Loaded Piles

Methods have been developed for deriving *P-y* curves from DMT results (Robertson et al. 1987, Marchetti et al. 1991). 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 (TC16 2001) 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 shear bands, remoulded by the sliding, then reconsolidated under the weight of the overlying soil, hence nearly NC, 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 indicate that the percentage increase in M_{DMT} is approximately *twice* the increase in q_t. In other words densification increases both q_t 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 minimum M rather than of minimum D_r - 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.

Liquefiability Evaluation.

Fig. 5 and Fig. 6 show two diagrams for estimating the Cyclic Resistance Ratio (*CRR*) of a *clean* sand (FC<5%) by DMT/ SDMT, using K_D and *Vs* respectively. Note that DMT provides one estimate of *CRR* (based on K_D), while the seismic module of SDMT provides a second independent estimate of *CRR* (based on *Vs*). The curve for estimating *CRR* from *Vs* is by Andrus & Stokoe (2000). Details on the derivation and use of the K_D -CRR curves may be found in Monaco et al. 2005 & 2007. Recent research suggests that the most likely location of the K_D -CRR correlation is in the band comprised between the Monaco (2005) curve and the Robertson (2012) curve. The equation of the curve intermediate between the just mentioned two curves is :

$$CRR = 0.0038\, K_D^{\,3} - 0.0176\, K_D^{\,2} + 0.0532\, K_D + 0.0264 \qquad (2)$$

Eq. 2 is the preferred correlation, as today 2014, for estimating CRR from K_D. The use of K_D to evaluate CRR is increasing, due to the recognized sensitivity of K_D to a number of factors which are known to increase liquefaction resistance – such as stress history (Marchetti 2010), prestraining/aging (Monaco & Marchetti 2007), cementation, structure – but are difficult to sense by other tests, and to the K_D's relationship with the state parameter (Marchetti 2010).

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 (Marchetti 1994). DMT has been used as an economical production tool for quality control of the compaction, with only occasional verifications by the originally specified methods.

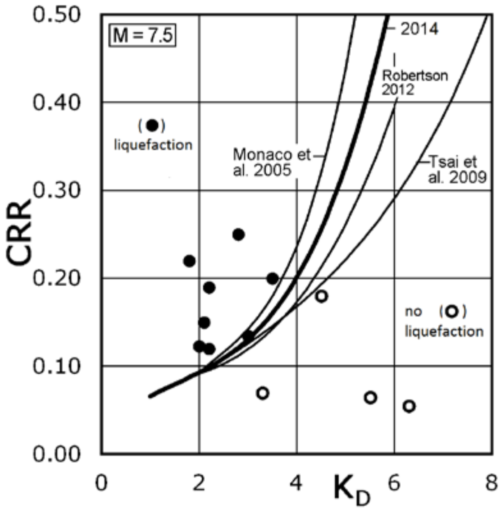
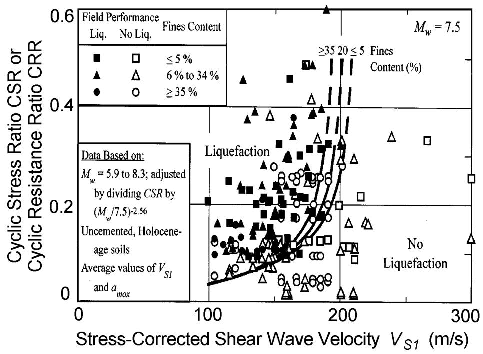


Fig. 5 Curves for evaluating CRR for *clean* sand from K_D



$$\mathrm{CRR} = \left[0.022\left(\frac{K_{a1}V_{S1}}{100}\right)^2 + 2.8\left(\frac{1}{V_{S1}^{*} - K_{a1}V_{s1}} - \frac{1}{V_{S1}^{*}}\right)\right]K_{a2}$$

Fig. 6 Curves for evaluating CRR from Vs (Andrus & Stokoe 2000)

CONCLUSIONS

The Flat Dilatometer is a relatively recent in situ test. It provides estimates of a variety of design parameters. It is 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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