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Applications and Recent Developments of the Flat Dilatometer (DMT) and Seismic Dilatometer (SDMT)

Applications et développements récents du dilatomètre plat (DMT) et du dilatomètre sismique (SDMT)

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ABSTRACT: The Flat Dilatometer (DMT) is a direct push soil testing device developed in Italy in the late seventies. The in situ measurement of a modulus and the capability of estimating stress history have made it a widely used tool for several geotechnical applications, in particular for settlement prediction, compaction control and liquefaction resistance. Potentiated with the release of its seismic version, the Seismic Dilatometer (SDMT) provides, in addition to the standard DMT parameters, also the shear and compression wave velocities Vs and Vp. The instrument is coded in the international standards (ASTM, ISO), building codes (Eurocode7) and guideline documents (TC16 2001) and is currently used in over 70 countries.
Recent developments of a seabed system (Seafloor DMT) and of a self-contained automated dilatometer probe (Medusa DMT) are presented.

RÉSUMÉ: Le Dilatomètre Plat (DMT) est un appareil d'essai du sol à poussée directe développé en Italie à la fin des années soixante-dix. La mesure in situ de module de sol e la sensibilité au l'histoire du stress l'ont fait largement utilisée pour plusieurs applications géotechniques, notamment pour la prédiction du tassement, le contrôle du compactage et la résistance à la liquéfaction. Le dilatomètre sismique (SDMT) fournit, en plus des paramètres DMT standard, les vitesses de cisaillement et de compression Vs et Vp. L'instrument est codé dans les normes internationales (ASTM, ISO), les codes du bâtiment (Eurocode7) et les documents de référence (TC16 2001) et est actuellement utilisé dans plus de 70 pays.
Les développements récents d'un système de fond marin (Seafloor DMT) et d'une sonde de dilatomètre automatisée autonome (Medusa DMT) sont présentés.

Keywords: DMT, Dilatometer; SDMT; Automated Dilatometer; Medusa

1 INTRODUCTION

The Flat Dilatometer (DMT) is an in situ testing instrument developed in the late seventies by Professor Silvano Marchetti (Marchetti S. 1980). Today it is used in all industrialized countries and the test is coded in international standards (ASTM 2015, ISO 2017) and building codes (Eurocode 7 EN 2007). A dedicated monograph was written by the ISSMGE Technical Committee TC102 (former TC16) (Marchetti S. et al. 2001), describing in detail instrumentation, test procedure and interpretation of the field data to estimate geotechnical parameters. Additional developments and updates of the last 15 years have been recently published (Marchetti S. 2015).

The main key features of the dilatometer are:

- The DMT is a direct push test and therefore has the advantage of not requiring a borehole.
- The insertion of a blade shaped instrument minimizes soil distortions (especially if compared to conical probes), preserving the original characteristics of the soil prior to penetration.
- The DMT is a load-displacement test which performs a direct measurement of soil stiffness, an information unobtainable by other penetration tests that essentially measure "failure" characteristics of the soil.
- The DMT equipment is simple, robust, operator-independent and provides repeatable results.
- DMT measurements are sensitive to stress history, which has a dominant influence on soil behaviour.

2 DILATOMETER TEST

The flat dilatometer consists of a steel blade having a thin, expandable, circular steel membrane mounted on one of its sides. The blade is connected to an electro-pneumatic cable, running through the penetration rods up to the control unit at the surface (Figure 1). The control unit is equipped with pressure gauges, an audio-visual signal and valves for regulating gas pressure supplied by a tank. A USB cable may connect the control unit to a computer for automatic logging of DMT readings. The blade is advanced into the ground using common field machines, i.e. static penetrometers or drill rigs. The DMT may also be driven using a SPT hammer, although statical push is preferable. A heavy penetrometer truck is the most effective way of advancing the blade, because it may apply a 20 ton static push without lateral instability and achieving a productivity up to 100 m of DMT profiling per day. The test procedure consists in advancing the blade into the ground and stopping penetration at each test depth. The membrane is initially flat against the surrounding plane behind it, due to the horizontal pressure of the soil. The operator opens the flow valve on the control unit to inflate the membrane and, in about 30 sec, takes two readings: the P_0 pressure, required to start the expansion of the membrane (lift-off pressure) and the P_1 pressure, required to expand the membrane center 1.1 mm against the soil. A third reading P_2 (closing pressure) may optionally be taken by deflating the membrane with the slow vent valve, just after the second reading P_1 is taken. The blade is then advanced to the next test depth, with a depth increment of typically 0.20 m.

The data processing is based on two calculation steps. The first step consists in the evaluation of four intermediate parameters:

I_D: Material index, containing information on the soil type (sand, silt, clay)

K_D: Horizontal stress index, containing information on stress history

E_D: Dilatometer Modulus, corresponding to the modulus measured during membrane expansion

U_D: Pore Pressure Index, containing information on drained/undrained soil behaviour

The intermediate parameters are definitions applied directly on the field pressure readings, without involving correlations.

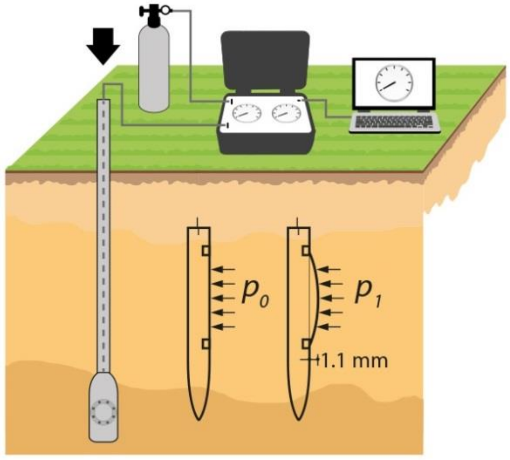

Figure 1. DMT test layout

The intermediate parameters are then converted by means of commonly used correlations (Marchetti S. 1980, Marchetti S. et al. 2001) to the following geotechnical parameters: vertical drained confined tangent modulus M (at geostatic stress), undrained shear strength Cu (clays), lateral earth pressure coefficient K_0 (clays), overconsolidation ratio OCR (clays), friction angle (sands) and bulk unit weight. Consolidation and permeability coefficients may be estimated performing dissipation tests (Totani et al 1998). In sands, the P_2 reading provides a direct measurement of the equilibrium pore pressure U (Schmertmann 1988). A typical example of profiles obtained by DMT is shown in Figure 2, combining intermediate parameters (I_D and K_D) with interpreted geotechnical parameters (M, Cu and ϕ). The profile of K_D has a similar trend of the OCR profile. In clays $K_D \approx 2$ indicates OCR = 1, while $K_D > 2$ identifies over-consolidation. The K_D profile often provides, at a first glance, an understanding of the stress history of the deposit.

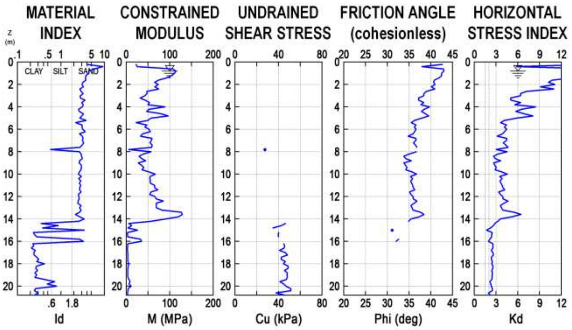

Figure 2. Example of DMT results (Fiumicino 2005)

3 TESTABLE SOILS

The DMT may be used in soils that are extremely soft (nearly liquid) to very dense soils, up to soft rocks. The blade is very robust and may safely withstand a push force up to 25-30 ton. Soils have been tested with undrained shear strength Cu in clays ranging from 2-4 kPa up to 1000 kPa (marls) and contrained modulus M between 0.4 MPa and 400 MPa. The DMT is not adequate in rock and course material such as boulders or dense gravel. However several tests have been succesfully performed in soils with low contents of gravel, floating in a matrix of sand, silt or clay.

4 SEISMIC DILATOMETER (SDMT)

The SDMT is the combination of the Flat Dilatometer with an add-on seismic module for measuring the shear wave velocity (Marchetti S. et al 2008) and optionally also the compression wave velocity (Amoroso et al 2016). The seismic module is an instrumented steel rod placed just above the DMT blade and equipped with two receivers spaced 0.5 m. When a shear or compression wave is generated at surface, it first arrives to the upper receiver, then, after a delay, to the lower receiver. The wave traces of the two receivers are amplified and digitized at depth and transmitted to the computer at surface. The software processes the signals and evaluates the arrival delay, providing a real time interpretation of the wave velocity. For example Figure 3 shows that the shear wave velocity Vs is obtained as the ratio between the difference of the wave travelpath from the source to the receivers (S2 - S1) and the wave arrival delay Δt from the first to the second receiver.

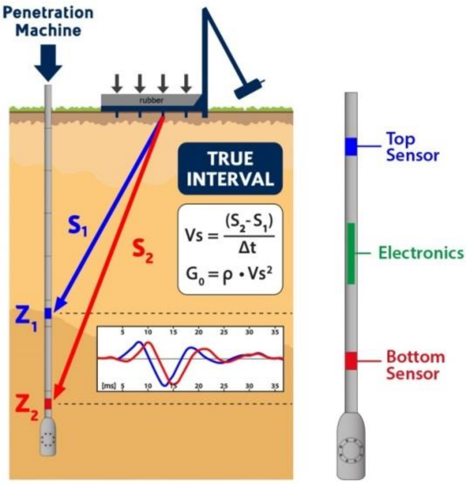

Figure 3. SDMT test layout and instrumentation

The true-interval test configuration based on two receivers has several advantages over the pseudo-interval one receiver configuration, providing higher accuracy delay Δt and, consequently, also of the wave velocity. First of all the true-interval configuration eliminates any possible difference in the zero registration time detected by the trigger. The reason is that the trigger instant is the same time origin for both traces used to identify the arrival delay Δt. In the pseudo-interval configuration, the delay is evaluated on two traces recorded with distinct hammer blows, where triggering differences may introduce errors in the evaluated Δt. Secondly, in the pseudo interval system, any error in the exact depth of the sensor affects the travelpaths S1 and S2 and propagates to the wave velocity calculation. In the true-interval configuration the sensors are placed, for construction of the probe, at a fix distance that may not vary, even in case of a penetration depth error. Any error of this kind would not affect the correctness of the wave velocity evaluation, but only assign Vs at a different test depth. This is an acceptable approximation, considering that the evaluated wave velocity is an average in the layer between the depths of the two sensors (i.e. 0.5 m).

Digital acquisition at depth, combined with the true interval configuration, enables the SDMT to provide high accuracy Vs profiles with a repeatability of typically within 1% (i.e. a few m/s). Several comparisons and case histories have shown very good agreement between SDMT and Crosshole results in different soil types (Amoroso et al. 2015, Décourt et al. 2016, Pein et al. 2019).

The SDMT may be employed in penetrable soils as the DMT, but also in non penetrable soils. In this second case, the tests are performed in a sand backfilled borehole (Totani 2009).

5 SENSITIVITY OF K_D TO STRESS HISTORY

Several researchers have observed, both in large calibration chambers (Jamiolkowski 1998, Lee 2011) and in the field (Schmertmann 1986), that the K_D parameter is considerably more sensitive to stress history than penetration resistance Q_{cn}. As an example, Fig. 4 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 between 1 and 8. Half of the specimens were tested by CPT, the other half by DMT. Figure 4 shows that OCR produces a substantial increase of K_D and almost a negligible increase of the normalized tip resistance Q_{cn}.

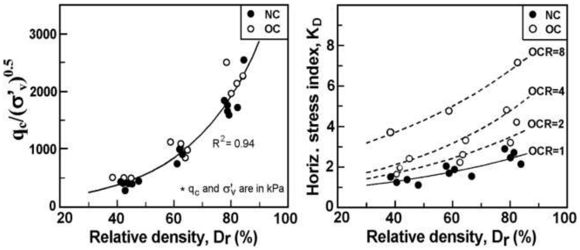

Figure 4. CPT and DMT sensitivity to stress history

stress history of the soil plays a key role for geotechnical design, in particular for settlements prediction, compaction control and liquefaction resistance estimation. If stress history is ignored, its benefits are wasted. Stress history is a substantial economical resource, which often leads to more economical design.

6 APPLICATIONS TO ENGINEERING DESIGN

6.1 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. Specific comments and methodologies are presented below concerning some of the main applications for which the DMT is commonly employed.

6.2 *Settlements of Shallow Foundations*

Predicting settlements of shallow foundations is the No. 1 application of the DMT, especially in sands, where undisturbed samples cannot be retrieved. Settlements may be calculated by means of the one-dimensional formula Eq. (1).

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

The vertical stress increments $\Delta\sigma_v$ are calculated according to Boussinesq and M is the constrained modulus that may be estimated with M_{DMT} from the Flat Dilatometer. The validity of the method has been confirmed by a large number of case histories showing good agreement between measured and DMT-predicted settlements or moduli (Monaco et al. 2006).

Figure 5 compares the distortions caused by the penetration of differently shaped probes (Baligh and Scott 1975). The photographs clearly illustrate that, during penetration, wedge shape probes disturb the soil much less than conical shaped probes, preserving the original state of the soil prior to penetration. This difference, in combination with the direct load-displacement measurement of the membrane expansion, may explain why the DMT provides reliable modulus estimates, especially if compared with estimates from conical shaped probes.

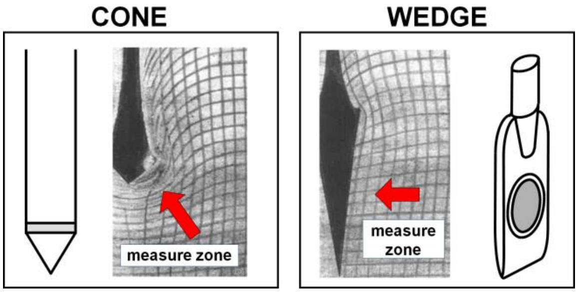

Figure 5. Distortions in clay: cone vs wedge

6.3 *Compaction Control*

Before-after DMT tests are commonly used to measure the increase in modulus and OCR due to various soil improvement techniques. Comparative studies have shown that DMT results are approximately twice more sensitive to compaction effects than CPT results. Schmertmann found that the compaction produced on average an M_{DMT} gain 2.3 times the q_c gain (Schmertmann 1986). A similar trend was observed by Jendeby in a compaction project of a loose sandfill, with an increase of the ratio M_{DMT} / q_c from a pre-compaction value of 5-12 to a post-compaction M_{DMT} / q_c value of 12-24 (Jendeby 1992). 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 several other researchers. For example Balachowski concluded that "The mean increase of M_{DMT} within the compacted sandy layer is about 2.3 times higher than corresponding increase of q_c" (Balachowski 2015), the same ratio published by Schmertmann 30 years before.

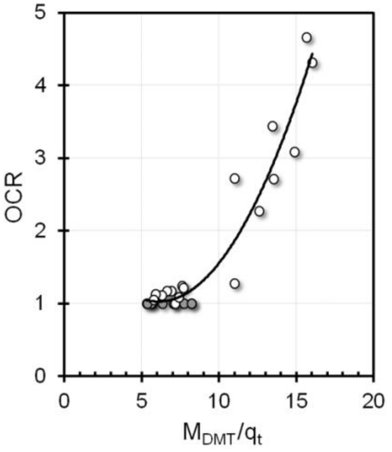

Figure 6. Correlation OCR = f (M_{DMT}/q_c) in sands

In most compaction projects, designers are often interested to assess not only the gain in modulus M, but also the gain in OCR. In granular soils OCR may be estimated, before and after compaction, from the ratio M_{DMT} / q_c using equation Eq. (2) represented graphically in Figure 6 (Monaco et al. 2014):

$$OCR = a\left(\frac{M_{DMT}}{q_c}\right)^2 - b\left(\frac{M_{DMT}}{q_c}\right) + c \qquad (2)$$

$a = 0.0344, b = 0.4174, c = 2.2914$

The OCR formula requires both CPT and DMT tests in the same locations. As shown in Figure (4), already addressed in a previous section of this document, K_D is sensitive to both relative density (D_r) and stress history (OCR), however in a "cumulative" manner. A high K_D may reflect a high D_r and a low OCR or a low D_r and a high OCR. The diagrams of Figure 4 show that normalized Q_c is sensitive only to variations of D_r, regardless of OCR. Thus, the combination of K_D with Q_c enables to separate the two unknowns and to provide estimations of OCR. As a consequence, it is impossible to estimate OCR in granular soils from either CPT or DMT results alone. Profiles of OCR - or of its proxy M_{DMT}/q_c - are often plotted by designers to quantify the gain in OCR due to the compaction process (e.g. Figure 7, Kurek 2013).

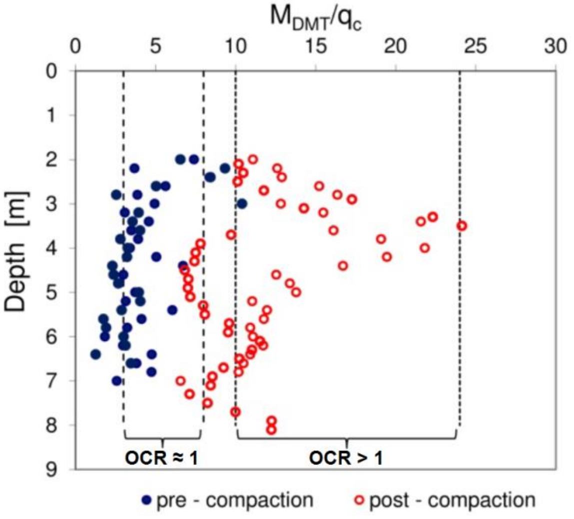

Figure 7. M_{DMT}/q_c before and after compaction

Since the primary aim of ground improvement is to limit settlements, it appears more rational to establish an acceptance criterion in terms of minimum modulus rather than of minimum D_r, as modulus relates more closely to the motivation of ground improvement (Schmertmann 1986). In the job described in Schmertmann's paper, the designers replaced the q_c to D_r criterion to a minimum M_{DMT} acceptance profile. Similarly Balachowski (2015) 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 to avoid the in situ D_r estimation, often problematic, because there is no unique mapping q_c to D_r applicable to all sands (e.g. Robertson and Campanella 1983).

6.4 Estimating liquefaction resistance CRR from K_D

The first CRR-K_D correlation was proposed just a few years after the first developments of the DMT instrument (Marchetti S. 1982). Subsequent research studies and case histories proposed modifications of the curve, which progressively converged to a narrow central band.

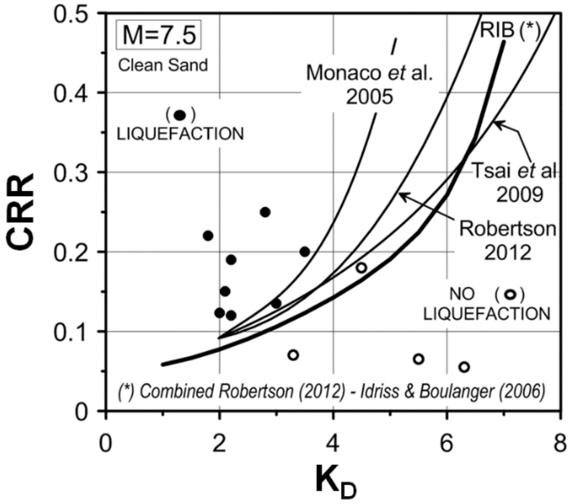

Figure 8. Recent CRR-KD correlations in clean sand

Most of the interest in the CRR-K_D correlation is motivated by the the fact that stress history increases significantly both CRR and K_D, but only slightly the normalized tip resistance Q_{cn} (Fig. 4). Hence it is reasonable to expect that a correlation K_D-CRR will exhibit less dispersion than Q_{cn} - CRR. A collection of recent CRR-K_D curves is shown in Fig. 8.

As suggested by Marchetti S. (2015), the recommended CRR-K_D correlation may be derived by the combination of the most updated CRR-Q_{cn} curve, combined with the average interrelationship $Q_{cn} = 25\ K_D$ proposed by Robertson (2012). Figure 8 shows with label 'RIB*' the curve obtained using 2006 CRR-Q_{cn} curve (Idriss and Boulanger 2006).

When both DMT and CPT test results are available, two independent estimates of CRR may be obtained: one from Q_C and the other from K_D. The two CRR estimates are independent, because the first one is obtained only from DMT results and the second one only from CPT results.

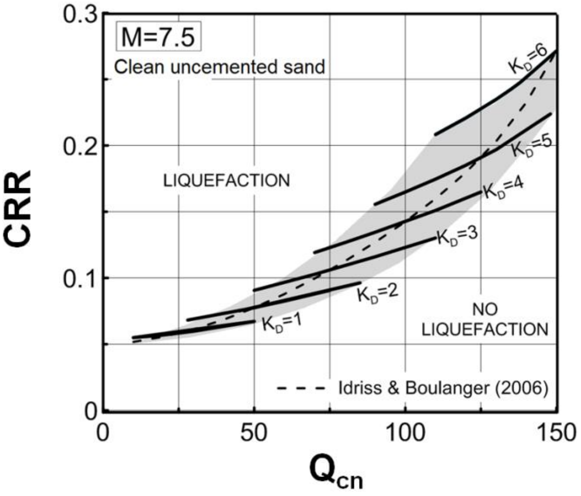

Figure 9. Chart for CRR = f (Q_{cn}, K_D) estimation in clean sand (Marchetti S. 2015)

The chart shown in Fig. 9 (Marchetti S. 2015) presents a correlation of CRR based at the same time on Q_{cn} and K_D, in the form CRR=f(Q_{cn},K_D), rather than providing two independent CRR estimates from two distinct one-to-one CRR correlation. As a numerical example: for Q_{cn}=100 and K_D=4, Fig. 9 provides CRR=0.14. However, for the same Q_{cn}=100, if K_D=5, CRR=0.17. In other words, for the same Q_{cn}, CRR estimates are higher if K_D is more than average (i.e. > Q_{cn}/25) and are lower if K_D is less than average. K_D acts like a pivot, enhancing the CRR-Q_{cn} correlation with its contribution of stress history.

7 THE SEAFLOOR DILATOMETER

The Seafloor Dilatometer (Seafloor DMT) was developed to perform DMT tests operating directly from the seabed (Fig. 10). The machine is composed of an upper pushing unit, having an approximate weight of 60-80 kg and thus easily transportable. The lower part is a low-tech heavy "ballast", generally constructed near the test site. The pushing system is securely fixed to the top of the ballast using 4 bolts.

Figure 10. Seafloor DMT (Marchetti D. 2018)

The Seafloor DMT was designed to operate up to a waterdepth of about 100 m and is able to apply up to 5 ton push. Usually six or seven penetration rods are pre-charged vertically on top of the pushing system, before lowering the machine to the seabed. Additional rods may be added as long as verticality in the rodstring is ensured, for example sustaining it with a buoy, with a trestle fixed to the top of the ballast or maintaining the rods vertical from the surface deck level.

Considering that penetration speed does not influence DMT readings, which are taken when penetration is stopped, the Seafloor DMT was designed to push with multiple short length strokes (ex. 0.10 m). This mechanism makes the Seafloor DMT a very cost-effective solution, especially if compared to CPT seabed units, which have to ensure and record a constant penetration speed of 2 cm/s.

8 THE MEDUSA DMT

The Medusa DMT is an automated dilatometer probe able to autonomously perform dilatometer tests (Marchetti D. 2018, Marchetti D. 2019). An electronic board, powered with rechargeable batteries, activates a motorized syringe for hydraulically expanding the DMT membrane (Figure 11). The blade has the same dimensions of the original standard flat plate dilatometer. The device may operate cableless (MEMO mode), a valid option especially in offshore projects at medium to large depths (> 100 m). Whenever possible the Medusa is operated with an electric cable, to obtain real time results during test execution.

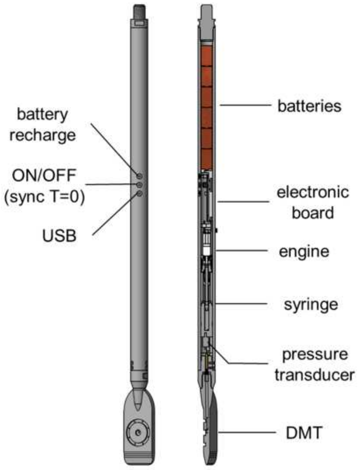

Figure 11. Medusa DMT layout

Comparisons between results of the traditional pneumatic DMT equipment and of the Medusa DMT have shown very good agreeement. The automation of both the inflation and deflation of the membrane has further increased the repeatability of DMT measurements. The Medusa DMT is capable of measuring the total horizontal pressure of the soil with time, suggesting some potentiality for improving K_0 and OCR interpretation in sand, for characterizing partially draining soils (Schnaid 2018) and for extending the range of soils to perform dissipation tests for estimations of consolidation and permeability coefficients.

9 CONCLUSIONS

The Flat Dilatometer is a relatively recent in situ testing tool, providing estimates of several key parameters for geotechnical design. The instrument is fast and simple to operate, the measurements are accurate, repeatable and operator independent. Compared to other testing probes, the DMT minimizes distortions and soil disturbance during penetration.

The results of the tests are very sensitive to stress history, a key property determining soil behaviour. For this reason the DMT results are employed in numerous applications, among which settlements prediction, compaction control and liquefaction resistance described in this paper.

The addition of a seismic module (SDMT) enables to obtain measurements of the shear and compression wave velocities, in addition to standard dilatometer parameters. The true interval configuration provides highly accurate and repeatable results, because it records traces with the same time origin for both receivers which correspond to the same wave generated by a single hammer blow.

The Seafloor DMT is an innovative cost-effective penetrometer for advancing the DMT directly from the seabed. The Medusa DMT is an automated dilatometer probe which simplifies test execution and maximises the quality of dilatometer measurements.

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