Deformability parameters in the offshore in situ test survey for the new breakwater project in Genova (Italy)

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ABSTRACT

The harbour of Genova is currently protected by a breakwater barrier that is 4 km long. One of the ongoing PNRR projects in Italy consists in dismissing the current breakwater and rebuilding it farther away from shore. The new breakwater will extend to a length of over 6.2 km and allow large cargo and container ships with over 400 m length to access the harbour. The new breakwater will lie in the currently open and unprotected water of the Genova Bay, with water depths up to 50 m. An extensive in situ test campaign of CPT and DMT tests was carried out for soil characterization, to provide stratigraphy, deformability and strength parameters required for the design of the new breakwater foundations. The Manta seafloor penetrometer designed by Geomil was deployed with a crane, operating from a floating pontoon anchored in turn on each of the test locations. The fully automated version of the flat dilatometer (Medusa DMT) and a CPTU tip were alternatively pushed by the Manta, with penetration depths up to over 27 m from seabed.

This paper presents results of the moduli obtained from DMT tests employing the standard Marchetti’ formulas and compares them with the interpretation from the CPT using different correlation factors. Additionally, the correlations between B_q (obtained from CPTU) and U_d (obtained from DMT) are analysed.

Keywords: medusa DMT, CPT, offshore geotechnics, seabed penetrometer, constrained modulus M, B_q, U_d, friction angle ∅, undrained shear strength S_u

1. Introduction to DMT

For over 70 years, the cone penetration test (CPT) has been the most widespread test for determining the resistance of the soil. The device was then r~~-~~enamed CPTU, with the additional measurement of the excess pore water pressure U caused by the cone penetration. The CPTU essentially measures the force necessary to advance a small diameter conical tip into the subsoil, divided into three main components: cone resistance, sleeve friction resistance and pore water pressure. The correlations between penetration resistance and geotechnical parameters are empirical and may exhibit uncertainties, especially for deformability, stress state and stress history parameters since each site has its own peculiarities in terms of geology and rheological soil characteristics.

In the 70s, Prof. Silvano Marchetti conceived and developed a new device named Marchetti Flat Plate Dilatometer (DMT). The instrument performs direct measurements of horizontal stress and deformability, which provide reliable estimations of soil modulus (Failmezger 2021, Godlewski 2018, Monaco 2015, McNulty 2014, Schmertmann 1986) and stress history parameters (Marchetti 2016 & 2013, Lee 2011, Monaco 2010).

CPTU and DMT tests are in situ tests that may be executed with the same field machines and with rapid interchangeability. Site investigations involving both devices may benefit of direct measurements of both strength (CPT), deformability (DMT) and horizontal stress (DMT).

1.1. DMT testing

The Marchetti Flat Plate Dilatometer is a stainless-steel blade with a flat circular 60 mm diameter steel membrane mounted on one side. In the original pneumatic equipment, a control unit placed at ground surface is connected with a pneumatic-electric cable running through the penetration rods down to the blade at depth. A gas tank supplies the control unit with the source pressure required to expand the membrane. In this configuration the pressure for expanding the membrane is generated and measured at surface, us-ing the automatic acquisition system of the control unit. Figure 1 illustrates the test layout configuration.

The blade is advanced vertically into the ground, stopping at depth intervals of typically 0.20 m. At each test depth the following readings are taken:

- A-reading: pressure at which membrane lifts off from the support behind it.
- B-reading: pressure necessary to expand the membrane of 1.1 mm from its centre.
- C-reading: pressure acting on the membrane when, deflating after B, the membrane returns to the original flat position before the A-reading.

The DMT equipment, the test method and the original correlations are described in the original paper by Prof. Silvano Marchetti (1980) ‘In Situ Tests by Flat Dilatometer’. Since then, the DMT test has been further validated by studies of world-wide re-search institutes, introduced in the international standards (ASTM 2015, Eurocode7 2007, ISO 2017) and compared with results of other testing equipment in different soil types. In year 2004 the flat dilatometer was enhanced with a true interval seismic module named Seismic Dilatometer (SDMT)

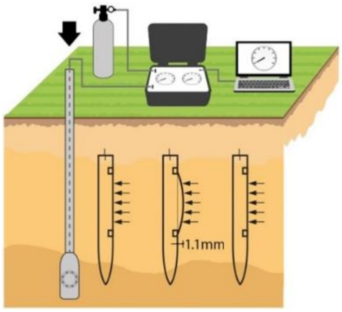


Figure 1. DMT TEST LAYOUT.

1.2. Medusa DMT

The Medusa DMT is a self-contained hydraulic probe able to autonomously perform standard DMT tests, without requiring a gas tank, a pneumatic cable, a control unit and a skilled operator for inflating and deflating the dilatometer membrane. The tool may operate as cableless or employing an electric cable for providing real time results during test execution. Figure 3 shows the main components of the device.

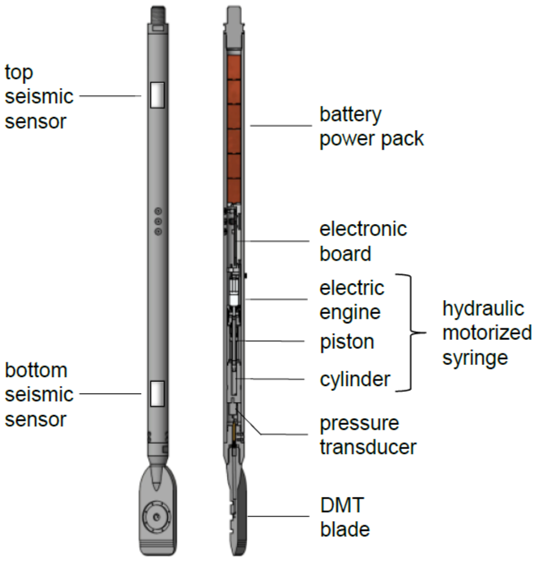


Figure 2. MEDUSA DMT

A rechargeable battery pack powers an electronic board, connected to a pressure transducer and to a custom designed hydraulic motorized syringe. The firmware loaded in the electronic board activates the syringe to generate and measure the pressure required for the DMT readings. The maximum operating pressure is 25 MPa. An electric wire provides the contact status of the membrane to the electronic board. The A, B, C pressure readings are taken by the electronics board implementing the same test procedure used for the traditional pneumatic DMT equipment. The blade of the Medusa DMT has the same exact dimensions of a standard DMT (ASTM 2015), to maintain the same data processing of test data from the standard pneumatic equipment. The probe is 1.10 m long.

A field-testing campaign was specifically planned to validate Medusa DMT test results at Fucino-Telespazio (Italy), a well-documented benchmark test site constituted by a geologically NC, cemented, quite homogeneous soft lacustrine clay of high plasticity. The test results were compared with standard pneumatic DMT tests and with results of other testing tools. The corresponding publication (Monaco 2022) confirmed excellent agreement in the 30 m depth profiles.

As a historical note, the Medusa DMT device was originally conceived only for deep drilling surveys, onshore as well as offshore (Sacchetto et al. 2006). Wireline systems for offshore geotechnical drilling consist in employing alternatively coring, sampling, downhole testing tools inside the drill string, managed by a recovery cable instead of drill rods. Therefore, the key requirements of the design for the new DMT system were that it did not require any cable, it was mechanically adaptable to wireline technology, completely autonomous in performing the measurements and able to store test data in a memory, downloadable after probe retrieval (Marchetti 2019). In the following years, the development of the Medusa DMT took place regardless of the wireline system and parallel to the development of the seismic module, to replace the original electro-pneumatic system, but still maintaining the potential to be used in a wireline system for offshore drilling.

At a later stage and with the contribution of EIT Raw Materials funding, the automated dilatometer probe was redesigned to host seismic S-wave sensors, leading to the enhanced Medusa SDMT probe.

1.3. Applicability to Offshore Investigations

In the last decades the standard pneumatic DMT was adopted in several nearshore projects with water depths up to 30 m (Marchetti 2018). Deeper water testing was limited by pressure equalization on the opposite ends of extensive pneumatic cables. Long cables (say > 50m), necessary to fully cover water depth and total penetration depth, in combination with typical soft layers just below the seafloor, lead to unacceptable uncertainty and scatter in DMT results. The hydraulic motorized syringe of the Medusa DMT eliminates the requirement of a pneumatic cable and generates pressure with oil, a nearly in-compressible fluid, distributing instantly isotropic pressure directly to the pressure transducer integrated in the probe. The gain in accuracy and repeatability of the new device over the pneumatic configuration is surprisingly high, as shown in the comparative results of a soft Brazilian clay (Marchetti, Danziger and Jannuzzi 2021).

An additional benefit of the motorized syringe automation is that it implements the exact membrane inflation rate indicated in the international standards (ASTM 2015, Eurocode7 2007, ISO 2017). In particular, the A reading is taken in 15 s from initial pressurization and the B reading in additional 15 s, without requiring the acceptable error of ±5 sec (not always respected using the pneumatic equipment). The motivation stems once again from the fluid incompressibility, which enables a volume-controlled membrane expansion. Furthermore, the membrane displacement against the soil occurs gradually and at a constant rate, not at a casual rate as with the pneumatic equipment.

As anticipated in the previous section, the Medusa DMT may operate as cableless. However, this feature was not yet employed in practice, because it would impede to access real time test results. The Medusa DMT was designed to also operate using the same electric wire requirements commonly adopted for CPT cables. This compatibility proved to be successful and to increase productivity in site investigations requesting intensive interchangeability between DMT and CPT testing, such as the Genova Breakwater project described in the next section.

In offshore projects, as well as onshore, CPT tests measure cone penetration resistance while penetrating at the nominal speed of 2 cm/s referred to a fixed level, generally represented by the seabed. This reference should not be affected by the heave of the surface waves, as it would strongly affect the standard rate of penetration and, consequently, the penetration resistance measurements.

In DMT testing, penetration is required only to advance the blade to the next test depth, since the measurements are performed when the instrument is not penetrating. For this reason, the DMT has no specific constraint on the penetration speed and may be performed also bearing a small vessel heave during penetration, releasing the push rods during measurement execution.

The Medusa DMT may be deployed offshore employing a Jackup, a vessel with dynamic positioning or using a seabed penetrometer, as in the Genova Breakwater project described in the next section.

2. GENOVA BREAKWATER PROJECT

2.1. Project description

Within a project for the design of the new breakwater barrier of Genova, located in the Northwest of Italy, an intensive test campaign comprising CPT and DMT tests was planned for the soil characterization of the upper soil deposits above the bedrock or Ortovero stiff clay, mainly composed of clayey silt, silty sand.

The aim of the soil investigation project was to provide real time results on stratigraphy, thickness of the soil to be treated with Stone Columns (SC), compressibility, consolidation and permeability parameters, resistance and possibly to estimate the stress state and stress history of the tested layers, to simulate the behaviour of the soil after the installation of the Stone Columns and after the structural loads are applied.

Instead of sampling and laboratory testing, the project Designers specifically opted for the execution of DMT and CPT for several reasons:

- the most relevant layers for the project were the shallow ones, namely the first 20 meters (in average) below the seabed, which are well within the standard depth range of both in situ tests.
- CPT and DMT provide continuous soil profiles with depth and not punctual results at large depth intervals as for laboratory tests.
- CPT and DMT results are repeatable and reliable, without depending on sampling activities, which are considerably difficult in sands and in very soft silty soils and most of the times uncertain, due to disturbance during sampling and in the preparation of specimens for laboratory tests.
- CPT and DMT provide results ~~in~~ real time during test execution and not in a matter of weeks or months (as with Laboratory tests)

CPTU and DMT-A dissipation tests were also performed for the estimation of the consolidation and permeability coefficients in the finer materials.

The offshore test site is outside the existing breakwater barrier of Genova, in unprotected water and fully exposed to winds ranging from South-East to South-West. Water depth was indicated as variable between 20~~-~~ m and 50 m, and the target penetration depth was set between 15 m and 30 m from the seabed, according to the estimated bedrock depth in each test location.

2.2. Execution of the Tests

The offshore CPTU and DMT tests were performed using the Seabed Manta penetrometer designed by Geomil, a Dutch firm specialized in CPT equipment and penetrometers and operated by MSH Marine Sampling Holland, a Dutch Company with great experience in offshore testing.

Figure 3. MANTA SEABED PENETROMETER

The machine was loaded on a floating barge equipped with a 30 m height crane, provided by the Client. A 3 m long metallic cantilever was welded on the edge of the barge, where the Manta was hoisted overboard and lowered vertically down to the seabed. The cantilever is necessary to safely handle the rods for their preload before lowering the machine and for unloading rods when necessary. In each test location the barge was anchored with 4 anchors or dead bodies, to minimize its lateral movements. The Manta seabed penetrometer has a maximum thrust of 200 kN and the reaction force is given by its own weight, which is considerably lower. The maximum estimated thrust for the project was set to 160 kN, therefore ballast was added to the machine for a total weight of approximately 180 kN. To avoid excessive sinking below the seabed, two lateral ‘wings’ were installed on the base edges of the machine, increasing the surface on which the weight of penetrometer and ballast was distributed. The 2-meter penetration rods were pushed continuously at constant penetration rate of 2 cm/s. The CPT tests were carried out continuously from the seabed down to the refusal test depth.

Figure 4. OFFICE CONTAINER, MANTA CONTROL UNIT AND CANTILEVER

The tests data was digitized directly in the Medusa DMT probe or in the penetrometer at seabed for the CPTU and transferred to the surface computer via the umbilical cable of the Manta, necessary to control the penetrometer for its push/pull activities. A container on board of the barge was used as an office for operating the Manta control unit, connected to a computer for the data acquisition of the CPTU and Medusa DMT instrumentation. The software of each device allowed to access real-time results of CPTU or DMT test data, including the inclination of the probes.

At the date of February 6th, 2024:

- 28 CPTU tests were completed with a penetration depth ranging from 4.58 m to 29.~~5~~ 4 m from the seabed.
- 19 DMT tests to a depth ranging from 5.0 m to 29.4 m. with a water depth ranging from 16 m to 49 m.

Presently (February 2024), in the same project, additional CPTU and DMT are taking place in other test locations. Furthermore, the seafloor penetrometer has been successfully employed for installing piezometers in the trial field CP1, to monitor the pore water pressure during the consolidation that will be caused by the loading.

2.3. TEST RESULTS

Both in situ tests (DMT and CPT) clearly confirmed the three different layers of clayey silt, silty sand overlaying the rock reported by the preliminary design stratigraphy. However, the depth and thickness of each layer was more accurately determined. Thus, the preliminary stratigraphy was revised and corrected in each CPT and DMT test location.

According to the Designers, the combination of DMT and CPT tests provided an exhaustive soil characterization in terms of stratigraphy, strength, compressibility, and stress history, complemented with information on permeability. The 2023 survey (phase 1) lasted two months in total (27 January – 26 March 2023), including considerable delays caused by weather. The 2024 survey (phase 2) started late January 2024 and still in progress at present date (February 6th, 2024)

3. INTERPRETATION of DATA

3.1. Interpretation of CPT tests

The CPT tests have been processed and interpreted by using the CPeT-IT software version 3.9.2.17 developed by GEOLOGISMIKI in collaboration with Prof. Peter Robertson, directly inputting the data of CPT tests in GEF format provided by the Contractor.

It was very important to determine the soil behaviour after installation of SC Stone Columns, therefore compressibility and permeability parameters have been calculated from CPT and DMT data; these data have been used by Designers for the geotechnical model of the subsoil and will be carefully verified with back-analysis after installation of monitoring equipment (piezometers and inclinometers) under two large submarine embankments (trial field CP1 and CP2).

The classification of the type of soil is conducted according to Robertson's theory (1990), which is based on normalized parameters. In particular, the measurement of neutral pressure, tip resistance and lateral friction is normalized as shown below:

$$Q = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \qquad B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}}$$

$$F = \frac{f_s}{q_t - \sigma_{v0}} \cdot 100$$

With these normalized parameters it is possible to calculate the I_c index, whose value is given by:

$$I_c = \sqrt{\{3 - log[Q \cdot (1 - B_q)]\}^2 + [1.5 + 1.3 \cdot (log\,F)]^2}$$

Depending on the I_c value it is possible to classify the behaviour of the soil and hence distinguish the various types.

To determine the confined elastic modulus of the cohesive layers (the most important for calculation of the settlements), reference was made to the Robertson correlation (2009):

$$M = \alpha_M (q_t - \sigma_{v0})$$

Where:

$$\alpha_M = \begin{cases} Q_{tn}, if\ Q_{tn} \leq 14 \\ 14, if\ \ Q_{tn} > 14 \end{cases}$$

With:

$$Q_{tn} = [\frac{q_t - \sigma_{v0}}{p_a}] \left(\frac{p_a}{\sigma'_{v0}}\right)^n$$

$$n = 0.381(I_c) + 0.05\left(\frac{\sigma'_{v0}}{p_a}\right) - 0.15 \ \le 1.0$$

p_a=atmospheric pressure ≅ 0.1 MPa

To determine the undrained shear strength of the cohesive layers (zones 1,2,3 of Table 1) reference was made to the following formula:

$$S_U = \frac{(q_t - \sigma_v)}{N_{kt}}$$

With:

$$N_{kt} = 10.50 + 7\log(F_R) \ or \ user \ defined$$

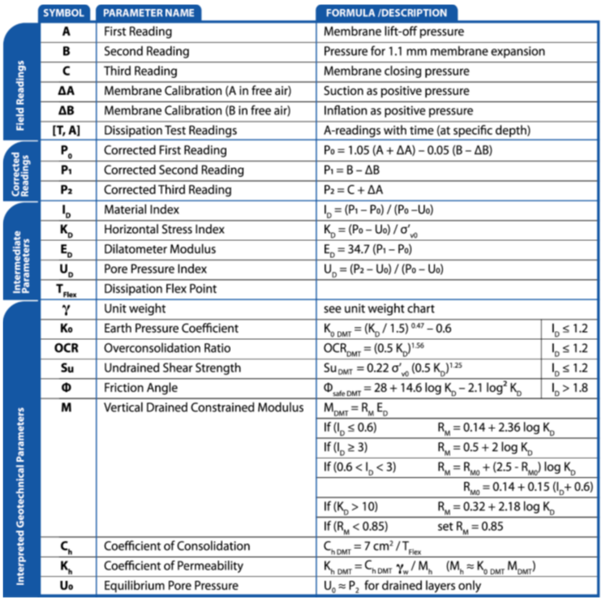
To determine the drained friction angle ∅ of the granular soils (zone 4, 5, 6 with reference to Table 1)

$$\emptyset = 17.60 + 11\log(Q_t)$$

All the calculations have been made using CPeT-IT software and verified with Microsoft Excel™ spreadsheets.

3.2. Interpretation of DMT tests

The basic formulas for processing DMT measurements and the main correlations are summarized in the following Tables:



	SYMBOL	PARAMETER NAME	FORMULA /DESCRIPTION	
Field Readings	A	First Reading	Membrane lift-off pressure	
	B	Second Reading	Pressure for 1.1 mm membrane expansion	
	C	Third Reading	Membrane closing pressure	
	ΔA	Membrane Calibration (A in free air)	Suction as positive pressure	
	ΔB	Membrane Calibration (B in free air)	Inflation as positive pressure	
	[T, A]	Dissipation Test Readings	A-readings with time (at specific depth)	
Corrected Readings	P_0	Corrected First Reading	$P_0 = 1.05\,(A + \Delta A) - 0.05\,(B - \Delta B)$	
	P_1	Corrected Second Reading	$P_1 = B - \Delta B$	
	P_2	Corrected Third Reading	$P_2 = C + \Delta A$	
Intermediate Parameters	I_D	Material Index	$I_D = (P_1 - P_0) / (P_0 - U_0)$	
	K_D	Horizontal Stress Index	$K_D = (P_0 - U_0) / \sigma'_{v0}$	
	E_D	Dilatometer Modulus	$E_D = 34.7\,(P_1 - P_0)$	
	U_D	Pore Pressure Index	$U_D = (P_2 - U_0) / (P_0 - U_0)$	
	T_{Flex}	Dissipation Flex Point		
Interpreted Geotechnical Parameters	γ	Unit weight	see unit weight chart	
	K_0	Earth Pressure Coefficient	$K_{0\,DMT} = (K_D / 1.5)^{0.47} - 0.6$	$I_D \le 1.2$
	OCR	Overconsolidation Ratio	$OCR_{DMT} = (0.5\,K_D)^{1.56}$	$I_D \le 1.2$
	Su	Undrained Shear Strength	$Su_{DMT} = 0.22\,\sigma'_{v0}\,(0.5\,K_D)^{1.25}$	$I_D \le 1.2$
	Φ	Friction Angle	$\Phi_{safe\,DMT} = 28 + 14.6 \log K_D - 2.1 \log^2 K_D$	$I_D > 1.8$
	M	Vertical Drained Constrained Modulus	$M_{DMT} = R_M\,E_D$	
			If $(I_D \le 0.6)$	$R_M = 0.14 + 2.36 \log K_D$
			If $(I_D \ge 3)$	$R_M = 0.5 + 2 \log K_D$
			If $(0.6 < I_D < 3)$	$R_M = R_{M0} + (2.5 - R_{M0}) \log K_D$
				$R_{M0} = 0.14 + 0.15\,(I_D + 0.6)$
			If $(K_D > 10)$	$R_M = 0.32 + 2.18 \log K_D$
			If $(R_M < 0.85)$	set $R_M = 0.85$
	C_h	Coefficient of Consolidation	$C_{h\,DMT} = 7\ cm^2 / T_{Flex}$	
	K_h	Coefficient of Permeability	$K_{h\,DMT} = C_{h\,DMT}\,\gamma_w / M_h \quad (M_h \approx K_{0\,DMT}\,M_{DMT})$	
	U_0	Equilibrium Pore Pressure	$U_0 \approx P_2$ for drained layers only	

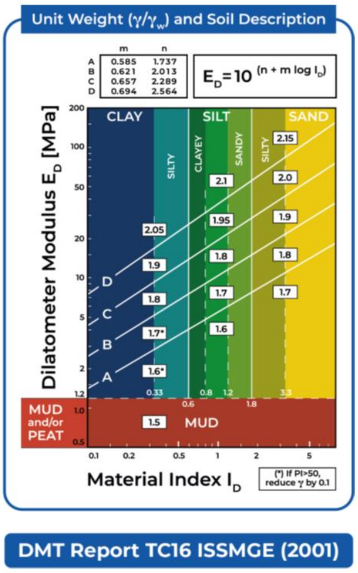
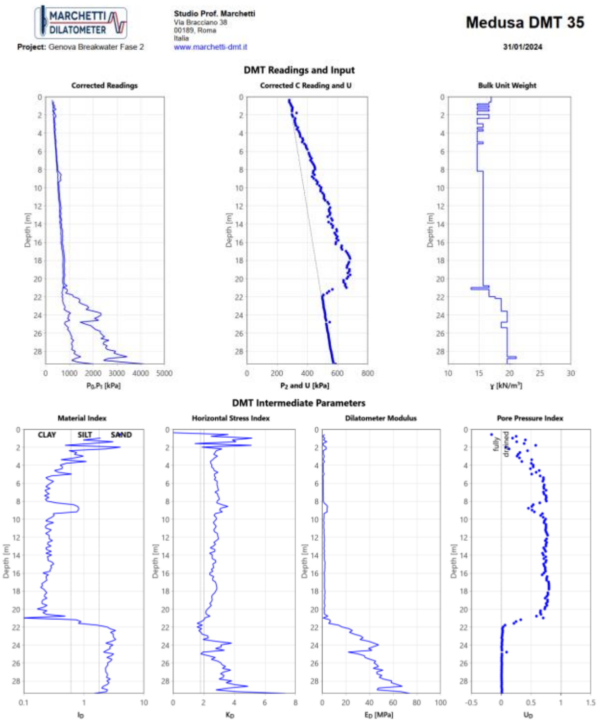


Figure 5. Summary of measurements and equations for calculating corrected values, estimating intermediate parameters and geotechnical parameters from DMT tests (ISSMGE, 2001)

All the calculations have been made using SDMT Pro ver. 2.1.8 software and processed with Microsoft Excel spreadsheets for comparison with CPT data.

4. Data Processing

All the CPT and DMT tests have been processed and presented in standard format. Figures 6-7 are examples of the delivered graphs, and all the corresponding data was delivered in numerical format.



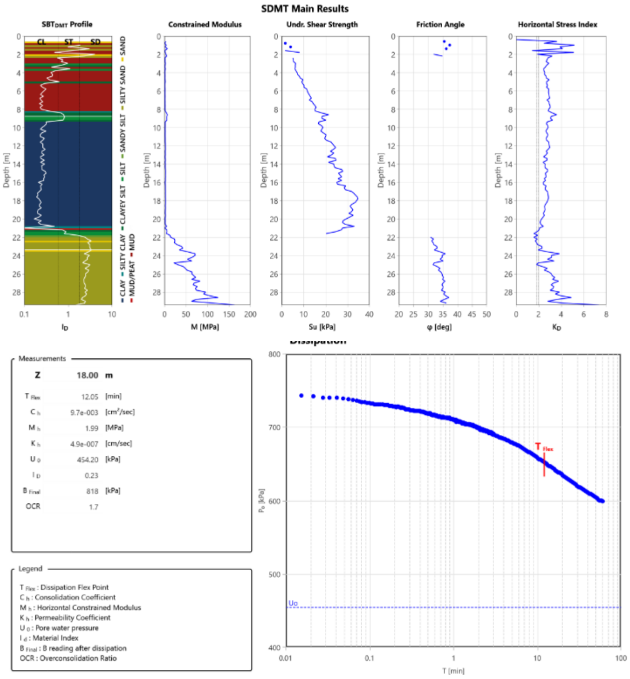
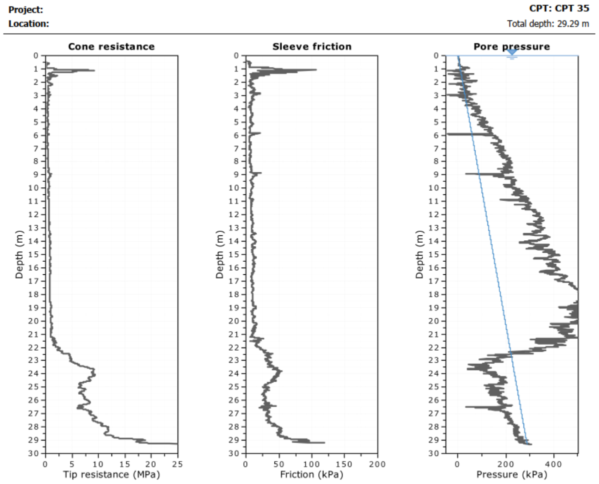
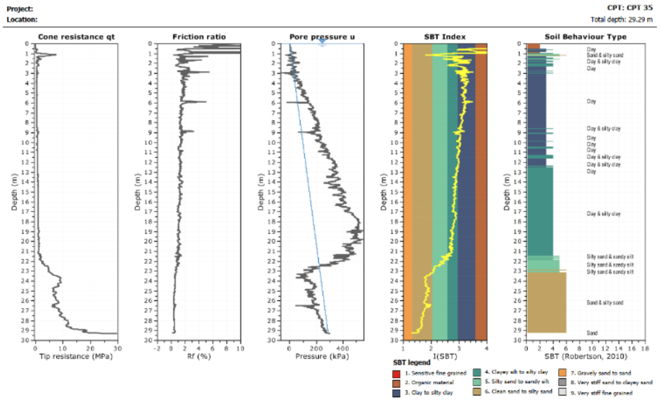


Figure 6. Example of DMT test





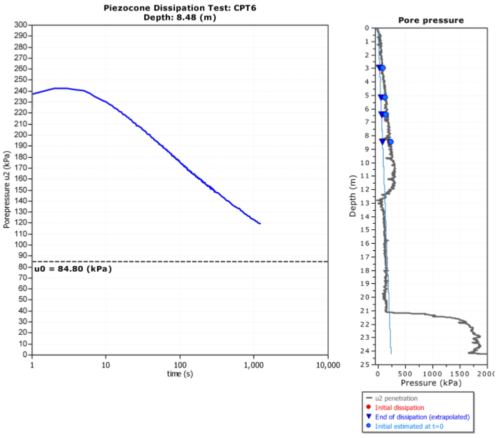


Figure 7. Example of CPT test

Comparative plots were done for each couple or triplet of CPT and DMT test, when executed at a relatively short distance and showing the same stratigraphy.

For greater processing coherence, two significant stratigraphic situations were identified, the first with predominantly cohesive soils (CPT35 and DMT35) and the second with a prevalence of granular soils (CPT33 and DMT32), as shown in Figures 6-7.

The DMT deformability parameters were considered more reliable than those of CPT tests, since the DMT is intrinsically a deformability test.

For cohesive soils, the automated evaluation of Nkt to obtain Su from CPT was highly scattered, varying between 14-22, whereas the constant value of Nkt=22 proved to be the best constant fit for matching Su_{DMT}, obtained using the standard formulae of Marchetti (1980) stemming directly from the DMT field measurements.

The comparison graphs of tests carried out in predominantly cohesive soils are shown in the following figures:

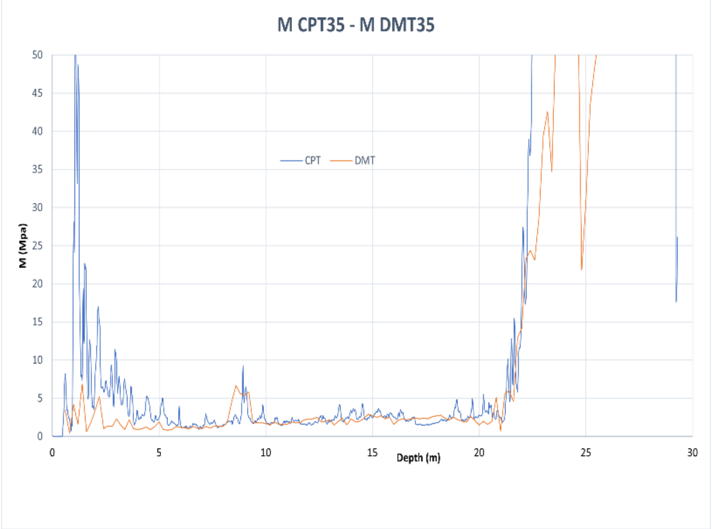


Figure 8a comparison between M_{CPT} and M_{DMT}

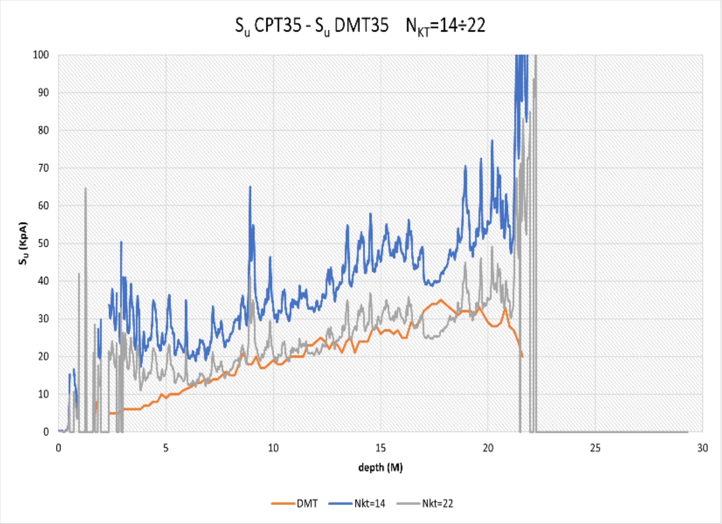


Figure 8b comparison between S_{UCPT} and S_{UDMT} with N_{kt} ranging from 14 to 22.

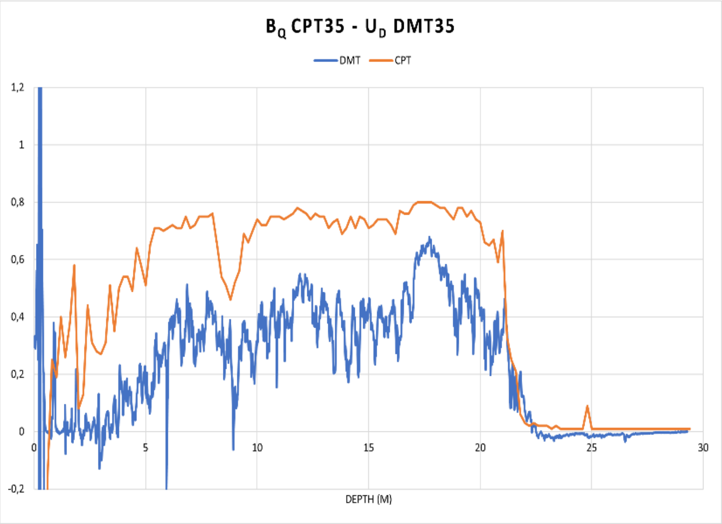


Figure 8c comparison between B_q (CPT) and U_D (DMT) in predominantly cohesive soils

Figure 8. Results of comparisons between M, Su, B_q-U_d in predominantly cohesive soils

The comparison graphs of tests carried out in predominantly granular (sandy) soils are shown in the following figures:

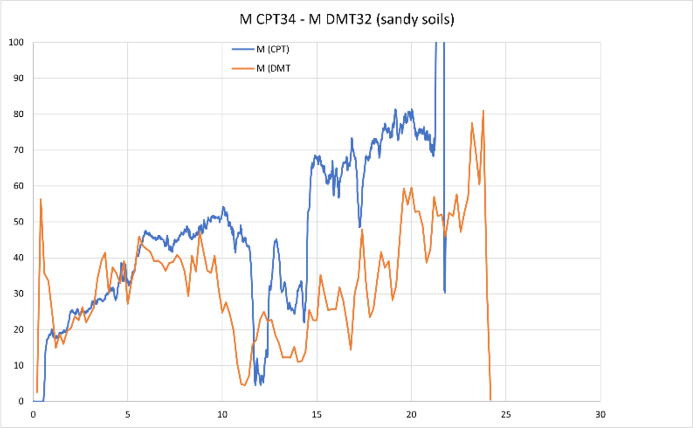


Figure 9a: comparison between M_{CPT} and M_{DMT}

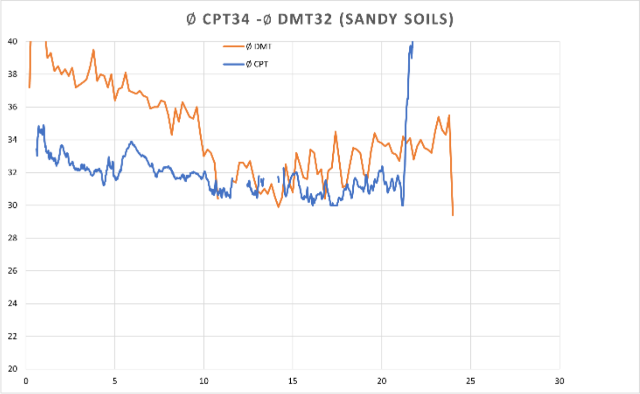


Figure 9b: comparison between $Ø_{CPT}$ and $Ø_{DMT}$

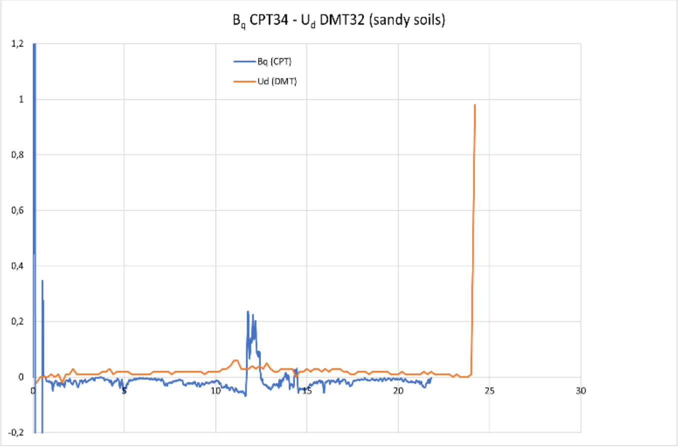


Figure 9c: comparison between B_q (CPT) and U_D (DMT) in predominantly sandy soils

Figure 9. Results of comparisons between M, Ø, B_q-U_d in predominantly sandy soils

5. Conclusions

The Flat Dilatometer is an in-situ test commonly employed onshore and nearshore since the late 70s, providing continuous and accurate soil parameters for geotechnical design.

The fully automated version of the flat dilatometer (Medusa DMT) enables to extend this test also to offshore site investigations. Thes probe may work with the same electric cable of the CPT, so that the interchangeability between the two in situ tests is rapid and simple.

The paper presents an offshore project outside the harbour of Genova in the Northwest of Italy. The Manta seabed penetrometer was employed for CPT and Medusa DMT tests. Profiles of CPT and DMT tests, compared with the available stratigraphy of a previous preliminary survey, exhibit an excellent matching of geotechnical characterization. A comparison between the processed data of CPT and DMT shows that:

- Matching of M (constrained modulus) in cohesive soft soils is excellent, as well as in loose silty sands; in stiff clay or dense sands M_{CPT} seems to be overestimated compared to $M_{DMT.}$
- In soft cohesive soils, at least in offshore environment, the undrained strength $S_{U\ CPT}$ matches very well with $S_{U\ DMT}$, with high values of N_{kt} coefficient.
- $B_{q\ CPT}$ is constantly lower (around 20-30 %) than $U_{d\ DMT}$. However, parameter B_{q_CPT} depends considerably on the saturation of the piezocone. Both parameters B_q and U_d depend also on the evaluation of the unit weight of the soil (that may be inaccurate with non-direct tests like DMT and CPT, especially offshore)
- Friction angle $\emptyset$ in loose silty sands with DMT seems to be overestimated, while $\emptyset_{CPT}$ and $\emptyset_{DMT}$ in denser sand agree reasonably.

The present work indicates that Medusa DMT and CPT are a powerful combination for carrying out a highly reliable and rapid geotechnical characterization of offshore penetrable soils, especially compared to boreholes, sampling and laboratory testing.

Further research could be useful for better calibrating the coefficients of correlation between data calculated with CPT and with DMT, especially in offshore environment.

Acknowledgements

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