Medusa DMT for geotechnical and geophysical offshore testing

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ABSTRACT: The Medusa DMT is a recently developed fully automated version of the Marchetti Flat Plate Dilatometer (DMT), which was first introduced in the late 70s and is commonly employed today in onshore and nearshore site investigation projects. The new enhanced device 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 consulting real time results during test execution. The traditional pneumatic equipment was limited to only onshore and nearshore projects, up to about 30 m water depth. The Medusa DMT may be deployed also in deep offshore surveys, currently down to 1500 m.

Within a project for the design of the new breakwater dam of Genova, in northwest Italy, CPT and DMT were selected for the geotechnical characterization of the upper soil deposits in terms of stratigraphy, compressibility, strength, permeability and possibly providing estimations of stress state and stress history parameters. The water depth ranged between 16 m and 49 m, while the deepest test was a DMT down to 26.4 m below the seabed. The paper describes the equipment, setup and test procedure adopted for this project, employing a seabed penetrometer (Manta), CPTU and Medusa DMT testing equipment.

1 Introduction to DMT and SDMT

1.1 *General introduction*

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 renamed 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).

1.2 *DMT and SDMT testing*

The 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, using 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 center.
- 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 research institutes, introduced in the international standards (ASTM 2015, Eurocode7 2007, ISO 2017) and compared with results of other testing equipment in different soil types.

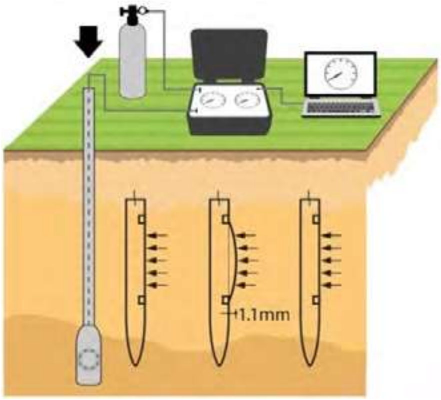

Figure 1. DMT test

In year 2004 the flat dilatometer was enhanced with a true interval seismic module named Seismic Dilatometer (SDMT). Such additional component is an instrumented rod equipped with two receivers spaced 0.5 m (True Interval Measurement) and an electronic board, which amplifies and digitizes the signals of the receivers at depth.

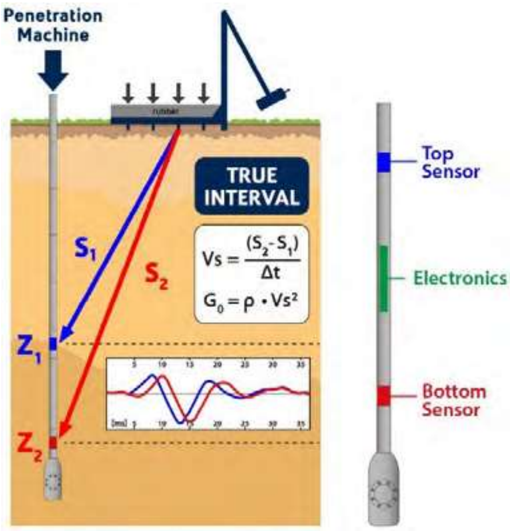

Figure 2. SDMT test

As shown in Figure 2, the shear wave is generated at surface, typically with a hammer horizontally striking a shear beam placed on the ground or on the seabed (with a special setup) and vertically loaded. The recorded seismograms are transmitted to the acquisition system at surface and Vs is evaluated real time. The SDMT may be carried out also in offshore investigations, in combination with specific seabed hammers capable to generate shear waves.

1.3 *Test Results and Geotechnical Applications*

The DMT provides parameters concerning stratigraphy, modulus, stress state, stress history, unit weight and excess pore water pressure. A detailed report of DMT equipment, test procedure, data processing and application to design is published in the TC16 2001 document, referenced in the bibliographic section of this paper. Updates of this document were published in the proceedings of the Third International Conference on the DMT in 2015 (S. Marchetti 2015).

The DMT is employed for a variety of geotechnical design applications such as settlements prediction, ground improvement, P-Y curves for horizontally loaded piles, subgrade reaction modulus for diaphragm walls and pavements, detection of slip surfaces in clayey slopes, liquefaction resistance estimations.

The seismic module expanded the potential of employment also to the geophysical field. In particular, V_s and G_0 are key parameters for seismic response analysis. As indicated by Andrus and Stokoe in 2000, Vs provides and additional independent evaluation of the cyclic resistance ratio (CRR), which may be compared with the estimation from the horizontal stress index K_D (DMT) and the penetration resistance Qc (CPT) for a more detailed data-driven liquefaction risk analysis.

Several research groups have studied the combination of the operative constrained modulus M_{DMT} at intermediate strain level with the maximum modulus G_0 at low strain level to estimate G-gamma decay curves from in situ measurements (Amoroso 2014). Advanced software programs implementing finite element methods (FEM) are able to employ such curves, adopting a different modulus at each strain level, in the attempt of a higher detailed analysis of soil deformation (Di Mariano 2019).

There are more than 1000 publications on the DMT and SDMT and today the test is performed in over 80 countries worldwide.

2 **Medusa DMT**

2.1 *Equipment description*

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 consulting real time results during test execution. Figure 3 shows the main components of the device.

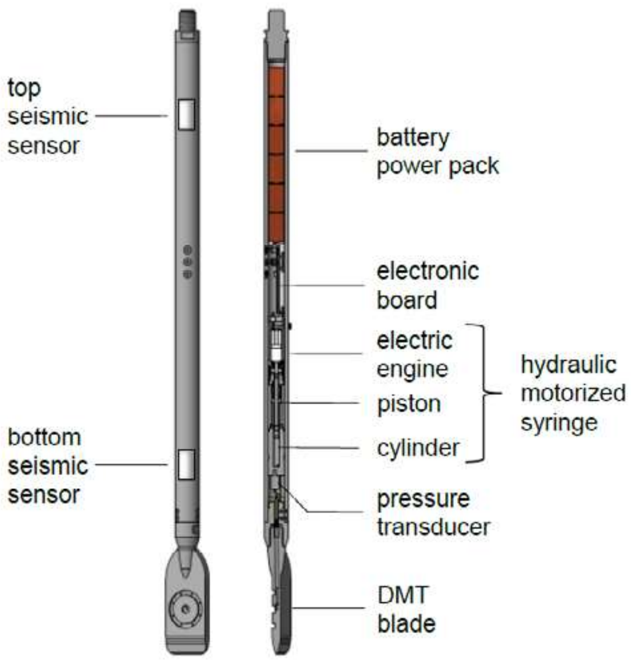

Figure 3. Medusa DMT

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 also 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.

2.2 *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 incompressible 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 penetration resistance measurements and the standard rate of penetration.

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.

Some research groups pointed out that in partially drained geomaterials the penetration rate of both CPT and DMT may alter the excess pore water pressure and soil conditions, to the point that the results may vary significantly (Schnaid 2016). However, it is a very reduced set of soils that are generally classified as silts or related to tailings dams geomaterials (Oberhollenzer 2022). The possibility of expanding the dilatometer membrane imposing a faster pressurization rate, now possible with the Medusa DMT, appears promising for the study of partial drainage (Monaco 2021, Schnaid 2018).

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.

3 Genova breakwater project

3.1 *Project description*

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

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 behavior 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 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;
- CPT and DMT provide results real time during test execution and not in a matter of weeks or months.
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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.

3.2 *Test Execution*

The offshore CPTU and DMT tests were performed using the Seabed Manta penetrometer (Figure 4), designed by Geomil, a Dutch firm specialised in CPT equipment and penetrometers. The machine was loaded on a floating barge equipped with a 30 m height crane, provided by the Client. A 3 m 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 four 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. Stopping penetration every meter was not necessary, because all the column of rods was already preloaded vertically above the machine. A constant-tension winch automatically maintained the rods vertically to avoid their collapse during all operations, including hoisting between the barge and the sea.

Figure 4. setup of the equipment and MANTA Penetrometer

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.

Figure 5. Office Container, Manta control unit and cantilever

The Manta seabed frame allows to employ casing, with outer diameter (OD) 55 mm, for the lateral support of the penetration rods OD 36 mm running inside the casing itself. This option was necessary in the locations with a top soft clay layer, up to 12 m thick, to penetrate the more resistant layers below it. Without casing it was not possible, in the first tests, to apply the available push force of the machine, as the rods buckled in the soft clay layer. In such circumstances, the test had to stop at the lower bound of the clay layer. Using the casing, employed for a length between 5 m and 10 m according to the available information of the soft clay layer thickness, it was possible to increment the push force and penetrate all the layers of interest, including some meters in the over consolidated 'Ortovero' clay.

Originally 17 CPTU and 8 DMT tests were planned in total, with three dissipations in each test location, rigorously in the first 10 m of the top clay layer. Considering the test results were provided to the project designers in real time, additional tests were subsequently requested for a total of 26 CPTU and 16 DMT tests. As of 22 March 2023:

- 24 CPTU tests were completed with a penetration depth ranging from 4.58 m to 24.82 m from the seabed.
- 15 DMT tests to a depth ranging from 5.0 m to 26.4 m.

with a water depth ranging from 16 m to 49 m.

3.3 *Test results*

A previous preliminary site characterization (PFTE – 'Progetto di Fattibilità Tecnica ed Economica') provided a 3d map with approximate indications on the stratigraphy of the test site subsoil. Figure 7 shows a stratigraphic excerpt of the PFTE, limited to test locations CPT 6 and DMT 10. Figures 7 to 9 show the results of test CPT 6, including a CPTU dissipation test. Figures 10 to 13 show the results of test DMT 10, including a DMT-A dissipation test.

Both in situ tests clearly distinguished the three different layers of clayey silt, silty sand and Ortovero clay reported by the PFTE stratigraphy. However, the depth and thickness of each layer was more accurately determined. Thus, the PTFE stratigraphy was revised and corrected in each CPT and DMT test location.

The DMT estimated overconsolidation ratio (OCR) parameter displayed in Figure 11 identifies the top soft clayey layer as normally consolidated and highlights the overconsolidated nature of the lower Ortovero clay.

The designers selected the DMT Constrained Modulus profile of Figure 12 as the reference for the soil deformation properties. The Undrained Shear Strength provided by the CPT results (not available for publication) was taken as a reference, as the Su profile from the DMT was considered slightly over-conservative.

The dissipation tests of both DMT and CPT provided similar results for permeability in the top soft layer, relevant for the analysis of the Stone Columns installation and for the structural loads.

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 survey lasted two months in total (27 January – 26 March 2023), including considerable delays caused by weather. Preliminary results were delivered at the end of each test. Itwas not possible to carry out SDMT (seismic) Vs measurements because the seabed hammer was not available for combination with the Manta unit.

4 Summary and conclusions

The Flat Dilatometer is an in-situ test commonly employed onshore and nearshore since the early 1970s, providing continuous depth profiles of 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. Standard offshore vessels and CPT penetration machines may be used for deploying the Medusa DMT as well. The two probes may operate with the same electric cable, so that their interchangeability is simple and rapid.

The paper presents an offshore project outside Genova harbour in northwest Italy, for the construction of a new breakwater barrier. The Manta seabed penetrometer deployed with a crane from a floating barge was employed for CPT and Medusa DMT tests. Sample profiles of CPT and DMT results are shown and compared with the available stratigraphy of a previous preliminary survey (PFTE).

The combination of the two in situ tests based on the direct measurement of penetration resistance and pore pressure (CPTU) and the direct measurement of soil deformation and horizontal stress (DMT), provided in the Genova breakwater project a substantial matching of soil stratigraphy and key parameters for compressibility, strength, and permeability.

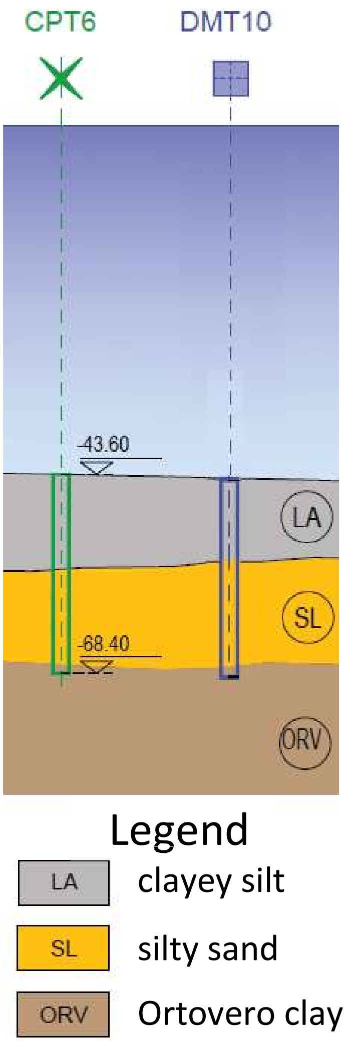

Figure 6. Stratigraphy excerpt from preliminary survey PFTE

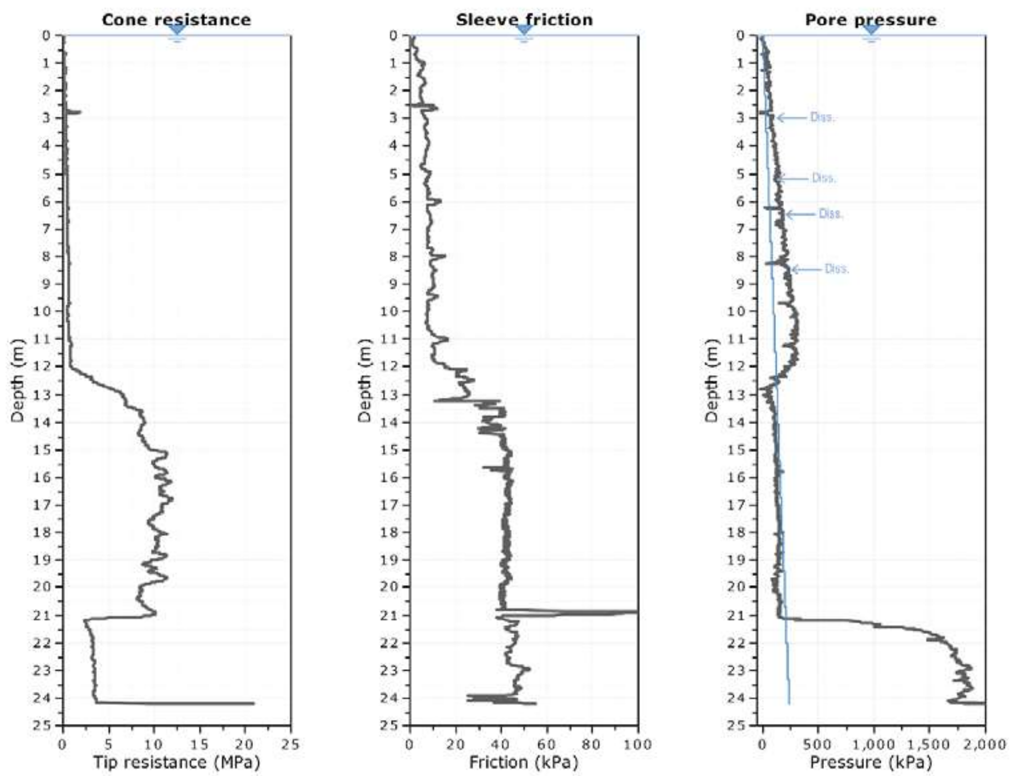

Figure 7 CPT 6 raw data profiles

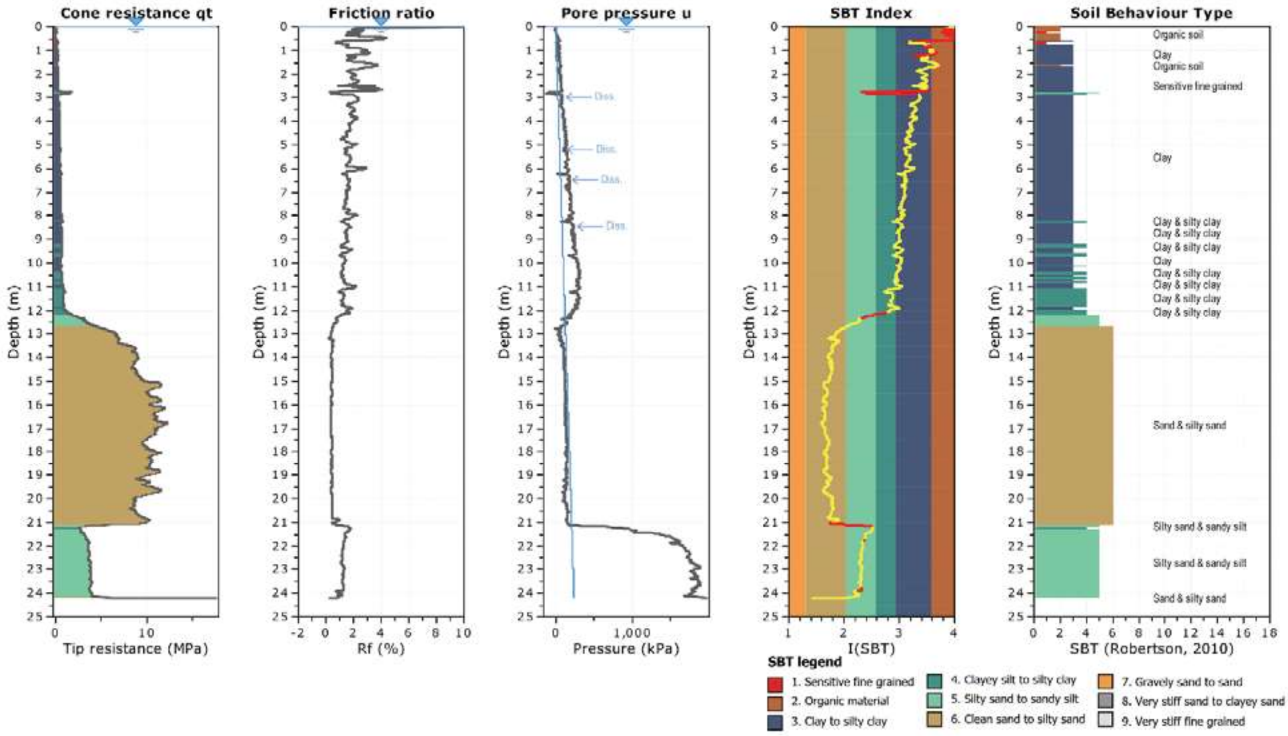

Figure 8 Interpretation of CPT 6 profiles

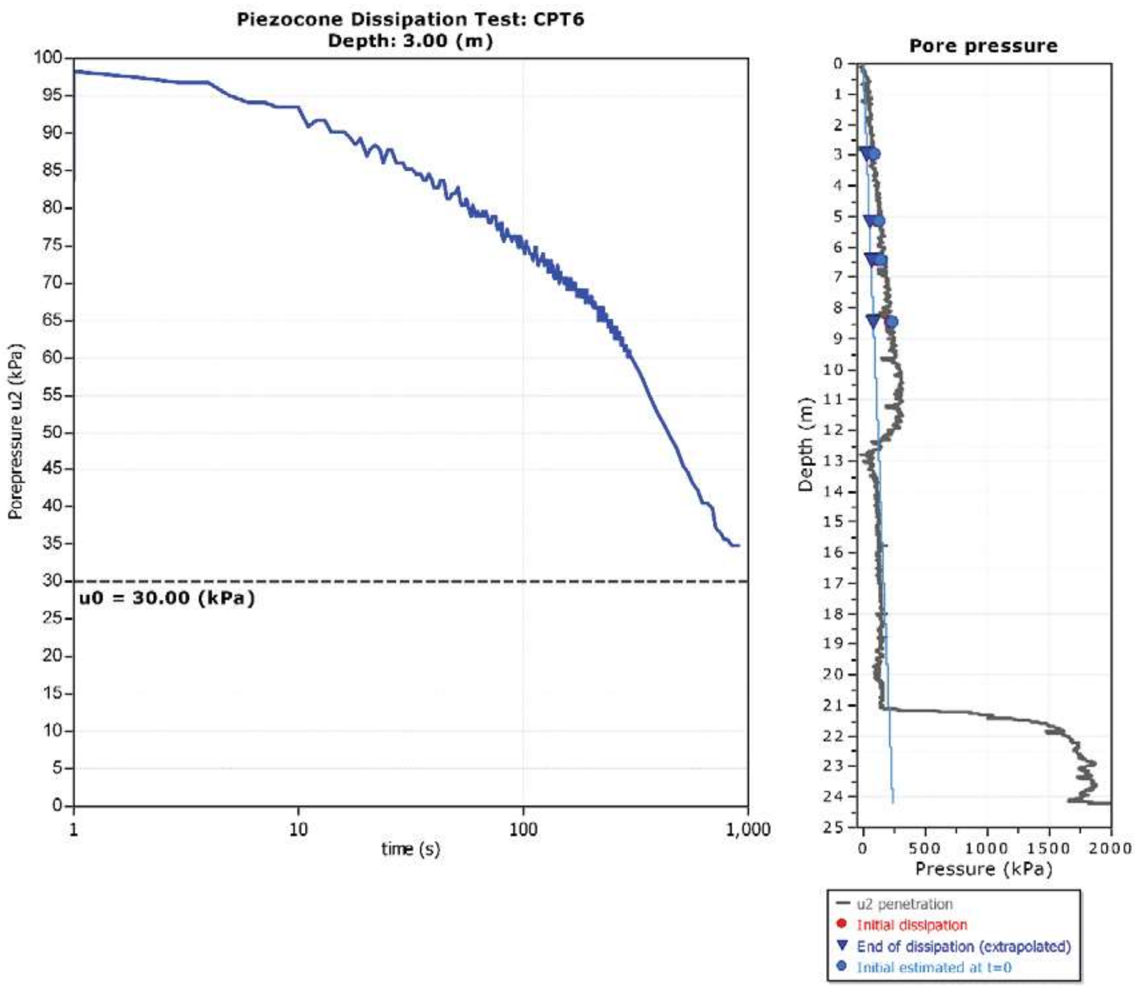

Figure 9 CPTU Dissipation Test at 3.0 m in CPT 6

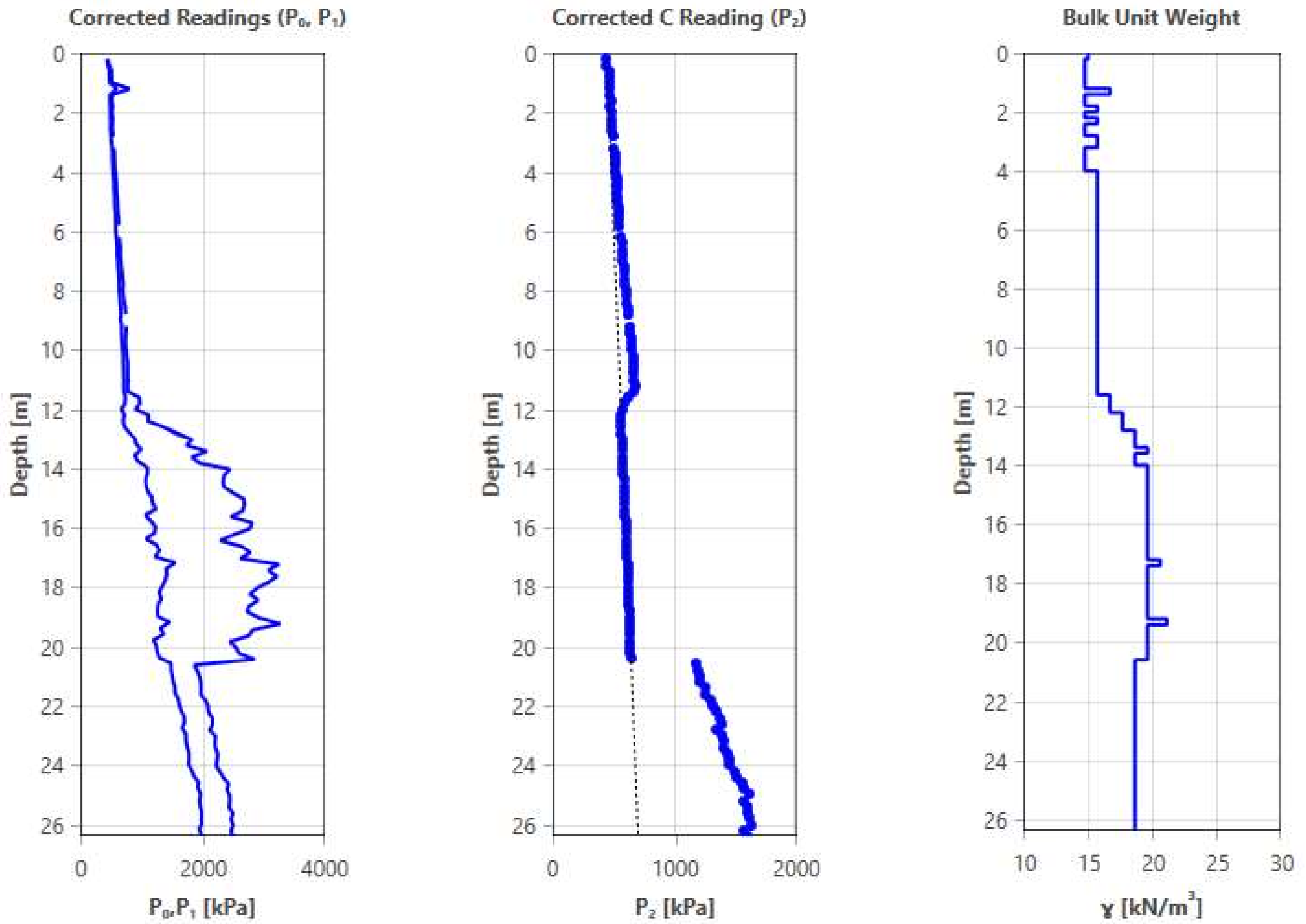

Figure 10 DMT 10 field readings and Bulk Unit Weight

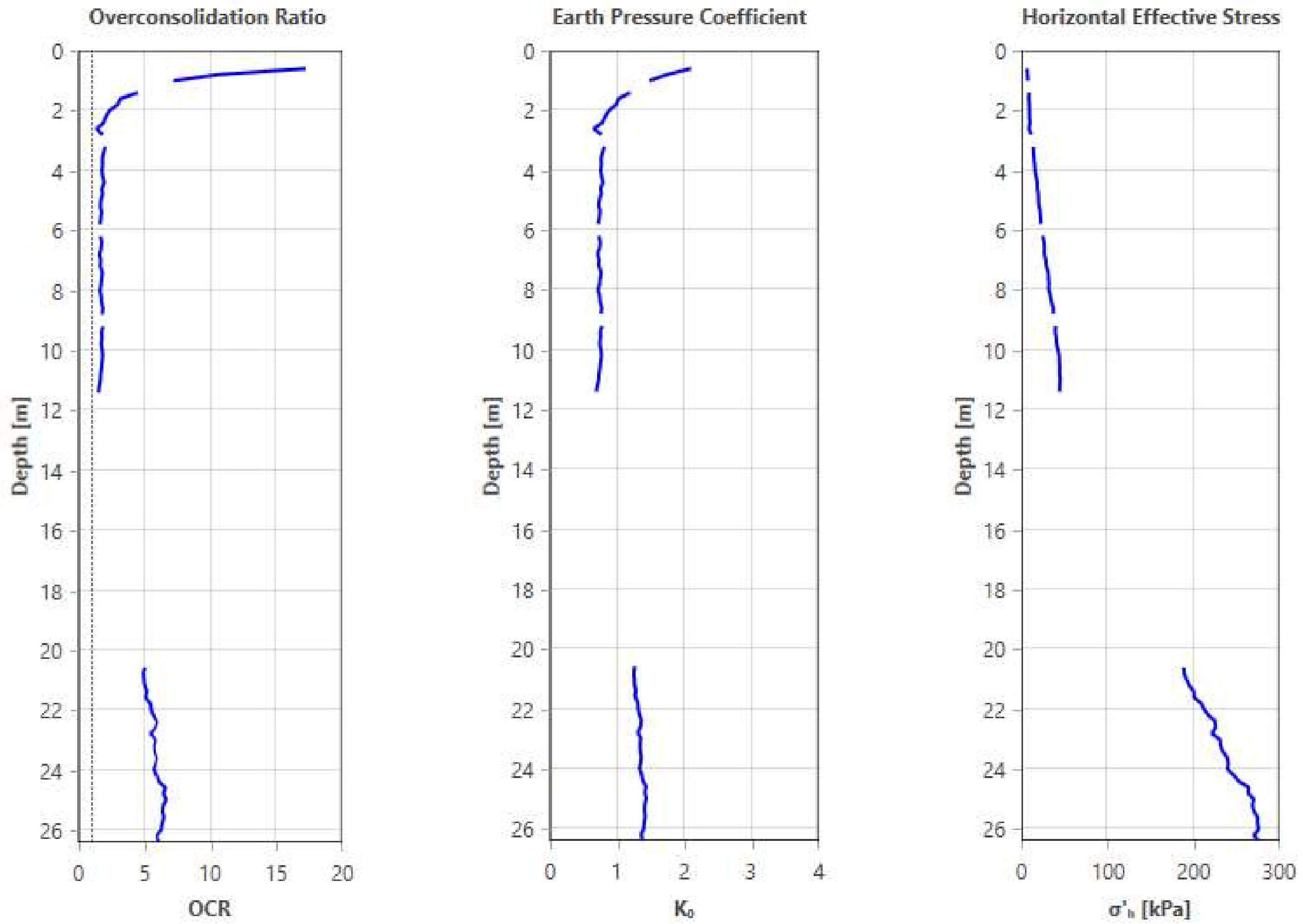

Figure 11 DMT interpretation of Overconsolidation Ratio, Earth Pressure Coefficient, Horizontal Effective Stress

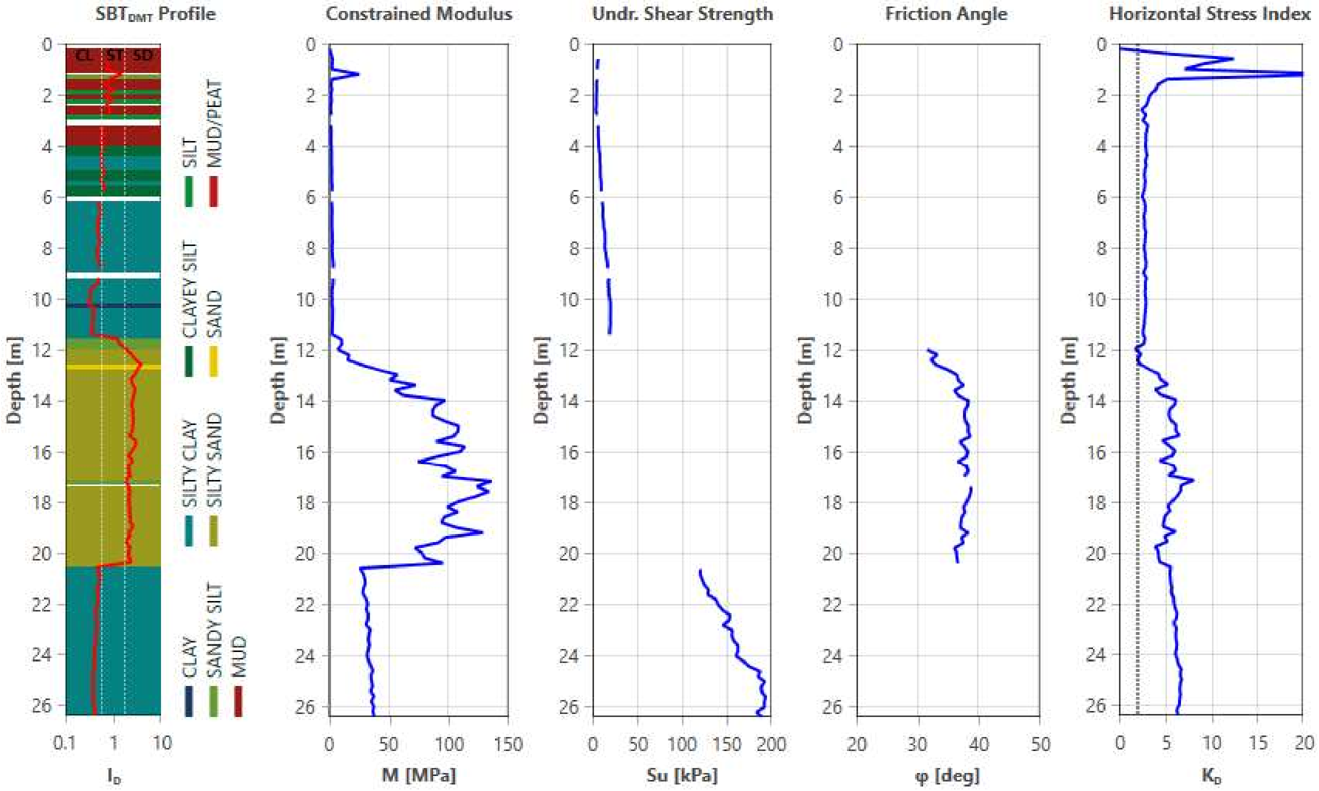

Figure 12 DMT test interpretation: SBT: Soil Behavior Type, Constrained Modulus, Shear Strength (clay), Friction Angle (sand), Horizontal Stress Index

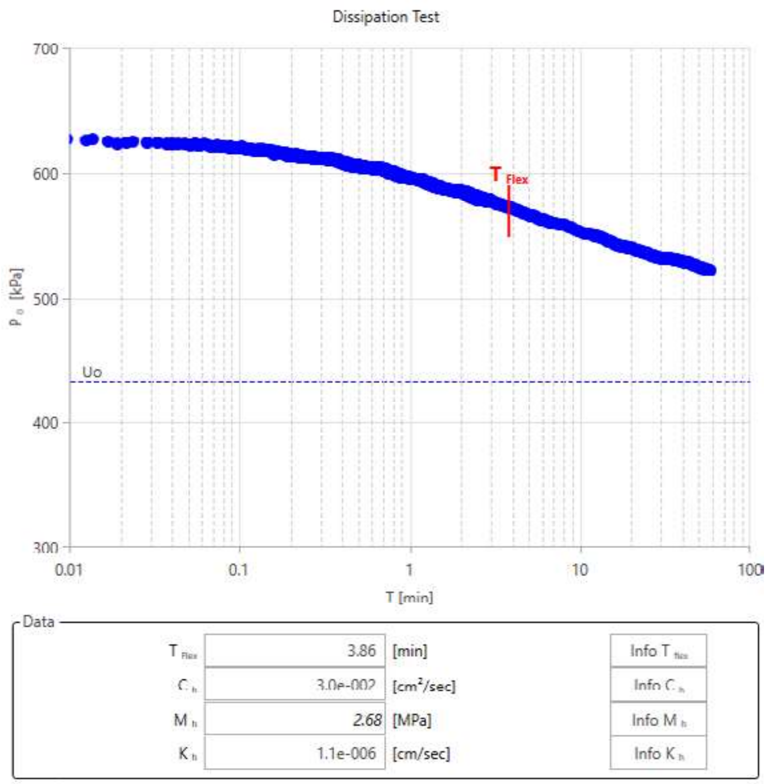

Figure 13 DMT-A dissipation test in DMT 10 at depth 6.0 m

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