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WORK PACKAGE 2 "Standardization of Medusa DMT testing"

Medusa dilatometer test

Pre-standard Reference Test Procedure & Guidelines

Report of UnivAQ – DICEAA Working Group
University of L'Aquila, Italy
Coordinator: Paola Monaco

Version 1.1 – 1st March 2021

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in cooperation with Diego Marchetti *(Studio Prof. Marchetti, Rome, Italy)*

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UnivAQ – DICEAA Working Group (Coordinator: Paola Monaco paola.monaco@univaq.it)

Task 1 – Pre-standard report on Medusa DMT

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Task 2 – Field testing at Fucino – Telespazio benchmark test site

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Foreword

This report is issued as part of the cooperation between the University of L'Aquila (UnivAQ), Department of Civil, Architectural and Environmental Engineering (DICEAA), L'Aquila, Italy and Studio Prof. Marchetti, Rome, Italy, within the scope of the "Work Package 2 – Standardization of Medusa DMT testing", part of the Project Agreement No. 19458-CLCS-2 between Studio Prof. Marchetti S.r.l. and EIT RawMaterials CLC South S.r.l. funded by "EIT RawMaterials Booster Call for start-ups, scale-ups and SMEs in response to the COVID-19 crisis".

This report was authored by the geotechnical Working Group at UnivAQ – DICEAA, under the supervision of Studio Prof. Marchetti.

The report presents an overview of the recently developed Medusa dilatometer test technology (Medusa DMT) for in situ soil investigations, including equipment, test procedure, interpretation and applications.

The report is intended to provide a detailed description of the equipment and guidelines for the proper execution of the Medusa dilatometer test (Reference Test Procedure) and to contribute to its standardization.

The report is not a standard in its current form. It may originate a standard in the near future, upon implementation by international standards organizations.

The report was developed based on the revision of existing standards, guidelines and reference documents for the traditional flat dilatometer test (DMT), which were assumed as the starting point for the development of a new specific reference document for the Medusa dilatometer test.

Efforts have been made to preserve similarities in format with the above standards and reference documents, as well as with other representative publications on in situ soil testing.

The content of this report is heavily influenced by the experience of the authors, who are responsible for the facts and the accuracy of the data presented herein. Efforts have been made to keep the content of the report as objective as possible. Occasionally subjective comments, based on the authors experience, have been included when considered potentially helpful to the readers.

1 Scope

This document establishes guidelines for equipment requirements, test procedure and reporting on Medusa dilatometer tests.

The Medusa dilatometer (Medusa DMT) is a self-contained cableless steel probe composed of a Marchetti flat plate dilatometer with standard dimensions and a set of components connected behind it, protected with a watertight steel tube. Such components, that will described in detail in Section 5 of this document, enable to generate and measure within the probe the pressure for performing autonomously dilatometer tests, without the need of a gas pressure source nor of a pneumatic cable. An optional electric cable may be used for obtaining real time results during tests execution.

The basic Medusa dilatometer test consists in inserting the probe vertically into the soil and measuring, at selected depth intervals, two pressures: the *A*-pressure, required to just start the membrane expansion, and the *B*-pressure, required to expand the membrane centre 1.10 mm against the soil. A third pressure, the *C*-pressure, can optionally be measured by slowly deflating the membrane just after the *B*-pressure reading.

The dilatometer test is mostly used in clays, silts and sands.

The main aims of this report include:

- description and technical details of the Medusa DMT equipment;
- description of the standard test procedure for the Medusa DMT;
- description of alternative test procedures for the Medusa DMT and relevant fields of application;
- guidelines for data reduction, interpretation and reporting of Medusa DMT test results.

The report also presents information on the experimental validation of the Medusa DMT and comparisons with traditional DMT results.

As a complement to the above outlined items, the report finally describes the main results of a field testing campaign specifically planned within this project at a benchmark research test site (Fucino – Telespazio, Italy), aimed to validate/correct the Medusa DMT testing procedures to be included in this document.

2 Terms, definitions and symbols

2.1 Components

dilatometer blade
blade-shaped steel probe that is inserted into the soil to performing a flat dilatometer test

Medusa DMT
set of components required to perform automated dilatometer measurements, including the blade, the motorized syringe actuator, the pressure transducer, the data acquisition board and its battery power pack

membrane
thin circular steel membrane mounted on one face of the dilatometer blade which expands against the soil by applying internal pressure

sensing disc
steel disc located inside the blade where the membrane expansion begins and the corresponding pressure is measured

switch mechanism
set of components behind the membrane which commute an electric circuit when, starting from the sensing disc, the membrane centre expands to 0.05 mm (from ON to OFF) and then to 1.10 mm (from OFF to ON)

2.2 Measurements

A-position
position of the membrane when its centre is 0.05 mm distant from the sensing disc

B-position
position of the membrane when its centre is 1.10 mm distant from the sensing disc

A-pressure
pressure applied from the inside of the membrane to expand it against the soil starting from the contact with the sensing disc up to the *A*-position

B-pressure
pressure applied from the inside of the membrane to expand it against the soil up to the *B*-position

C-pressure
pressure applied from the inside of the membrane when the centre of the membrane returns to the *A*-position through a gradual depressurization from the *B*-position

Medusa DMT test cycle
sequence of *A*, *B*, and optionally *C* pressure measurements obtained using the Medusa DMT at a single test depth

Medusa DMT sounding
series of Medusa DMT test cycles performed at spaced depth intervals (typically constant of 0.20 m) starting from a specific location point at ground surface, including below water

2.3 Processing

membrane calibration pressure ΔA
pressure applied from the outside of the membrane to overcome the stiffness of the membrane and deflect it inward to the *A*-position in free air at ambient atmospheric pressure

membrane calibration pressure ΔB
pressure applied from the inside of the membrane to overcome the stiffness of the membrane and expand it outward to the *B*-position in free air at ambient atmospheric pressure

pressure p_0
horizontal pressure against the membrane when it starts to expand, obtained correcting the *A*-pressure with the membrane calibration pressures to deduct the membrane's rigidity

pressure p_1
horizontal pressure against the membrane when it has expanded to the *B*-position, obtained correcting the *B*-pressure with the membrane calibration pressures to deduct the membrane's rigidity

pressure p_2
horizontal pressure against the membrane when it returns to the *A*-position from the *B*-position with gradual depressurization, obtained correcting the *C*-pressure with the membrane calibration pressures to deduct the membrane's rigidity

depth z
depth of a Medusa DMT test cycle considering the centre of the membrane, starting from the ground surface in onshore tests and from the seabed in offshore tests

depth of ground water z_w
depth of the water level measured from the ground surface in onshore tests (positive number) and from the seabed in offshore tests (negative number)

in situ pore water pressure u_0
pore water pressure in situ prior to blade insertion at the depth of the centre of the membrane

in situ effective vertical stress σ'_{v0}
effective vertical stress in situ prior to blade insertion at the depth of the centre of the membrane

material index I_D
parameter used to identify soil type and delineate stratigraphy, calculated as $I_D = (p_1 - p_0) / (p_0 - u_0)$

horizontal stress index K_D
parameter related to in situ horizontal stress and stress history, calculated as $K_D = (p_0 - u_0) / \sigma'_{v0}$

dilatometer modulus E_D
parameter related to soil stiffness, based on linear elastic theory, calculated as $E_D = 34.7\ (p_1 - p_0)$

pore pressure index U_D
parameter related to soil permeability, used to identify soil type and classify soil behaviour in combination with I_D, calculated as $U_D = (p_2 - p_0) / (p_2 - u_0)$

3 Introduction to dilatometer testing, background and references

3.1 Flat dilatometer test (DMT)

The flat dilatometer is an in situ soil testing equipment developed in Italy by Professor Silvano Marchetti in the late 1970s (Marchetti 1980). Initially introduced in North America and Europe, the device is currently used in over 80 countries.

The flat dilatometer consists of a steel blade having a thin, expandable, circular steel membrane mounted on one side (Figure 3.1). When the blade is pushed into the soil, the membrane is flattened against the surrounding plane behind it due to the horizontal pressure of the soil. The blade is connected to a pneumatic-electrical cable running through the insertion rods, up to a control unit at surface. The control unit is equipped with pressure gauges, an audio-visual signal, a flow valve for regulating gas pressure supplied by a gas tank and vent valves for deflation.

The blade is inserted into the ground using common field equipment, such as penetrometers used for the cone penetration test (CPT), or also drill rigs. In the standard DMT test procedure the blade is advanced into the ground and penetration stops at each test depth (typically every 0.20 m). The membrane is inflated with gas to obtain two pressure readings: (1) the *A*-pressure, required at the beginning of the membrane expansion agaist the soil (lift-off pressure, corresponding to an expansion of 0.05 mm at the centre), and (2) the *B*-pressure, required to expand the centre of the membrane 1.10 mm against the soil. A third pressure reading, (3) the *C*-pressure (closing pressure), can optionally be taken by slowly deflating the membrane soon after *B* until it returns to the *A*-position.

The field of application of the DMT spans from extremely soft to very stiff soils that can be penetrated by the blade, preferably using static penetration. The DMT test applies best to clays, silts and sands, where particles are small compared to the size of the membrane. It is not suitable for soils that cannot be penetrated without causing significant damage to the membrane, for example rock and dense gravel. DMT measurements may still be performed in gravel floating in a matrix of finer material. Thin layers of gravels may be crossed for performing tests in finer layers below.

The DMT test results are commonly used to obtain information on soil stratigraphy, in situ stress state and stress history, deformation properties and shear strength, for a variety of geotechnical engineering applications.

The flat dilatometer test is standardized in ASTM D6635-15 (*Standard Test Method for Performing the Flat Plate Dilatometer)*, in EN 1997-2:2007 (*Eurocode 7: Geotechnical Design – Part 2: Ground Investigation and Testing*) and in ISO 22476-11:2017(E) (*Geotechnical investigation and testing – Field testing – Part 11: Flat dilatometer test*).

A basic reference document (Marchetti et al. 2001), including detailed information on the DMT equipment, test procedure, interpretation and applications, was released in 2001 by the ISSMGE Technical Committee TC16 (now TC102) – In-Situ Testing. Further updates were provided by Marchetti (2015) and Marchetti and Monaco (2018).

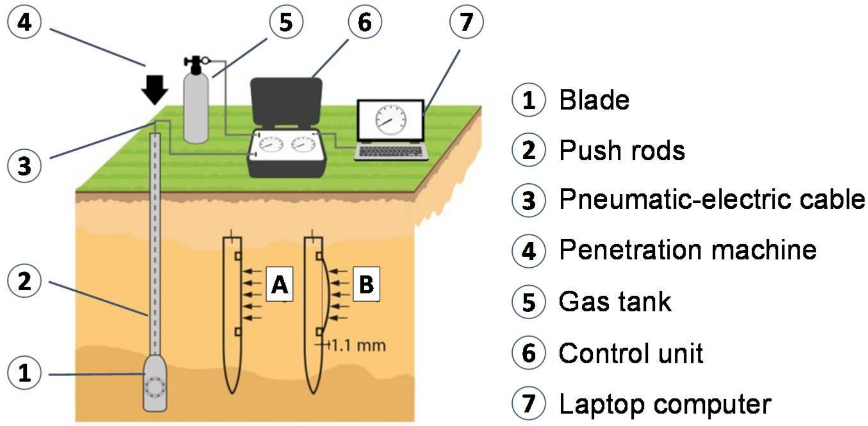


Figure 3.1. Main components of the traditional pneumatic DMT equipment and test layout

3.2 Seismic dilatometer test (SDMT)

The seismic dilatometer (SDMT), described by Marchetti et al. (2008), is the combination of the flat dilatometer with an add-on seismic module for measuring the shear wave velocity V_S, in addition to the standard DMT results.

The seismic module (Figure 3.2a) is a cylindrical element interposed between the bottom of the push rods and the DMT blade, equipped with two receivers fixed at a vertical distance of 0.50 m.

The shear wave source, located at the ground surface, generally consists of a pendulum hammer which strikes horizontally a rectangular steel plate pressed against the soil by the weight of a vertical load and oriented with its impact axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the generated shear wave. When a shear wave is generated at surface, it first reaches the upper receiver, then, after a delay, the lower receiver (Figure 3.2b). The seismograms acquired by the two receivers, amplified and digitized at depth, are transmitted to a computer at the surface for real-time interpretation of the V_S.

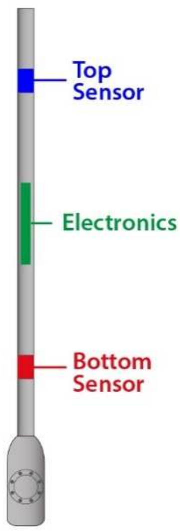
The recorded signals are processed using the true-interval interpretation method (Figure 3.2b). V_S is obtained as the ratio between the difference in distance between the source and the two receivers ($S_2 - S_1$) at the instant of the energization, assuming S_1 and S_2 as the straight shear wave travel paths, and the time delay in the arrival of the wave recorded at the lower and upper receiver (Δt), evaluated numerically using cross-correlation over the two wave traces.

The true-interval configuration using two receivers is very effective for the wave delay evaluation, because it relies on the same wave travelling to both receivers, as opposed to the pseudo-interval configuration in which two distinct waves are generated and recorded by a single receiver at different depths. Furthermore, the true-interval configuration is not affected by possible inaccuracies typical of the pseudo-interval configuration related to the "zero time" (trigger), because in the true-interval configuration the time origin is common to both wave traces independently of the trigger instant. In addition, the cross-correlation delay evaluation relies on the analysis of two waveforms rather than relying only on a single – subjectively selected – first arrival time on each wave trace. The typically observed repeatability of V_S measurements obtained by SDMT is remarkable (≈ 1%, i.e. a few m/s).

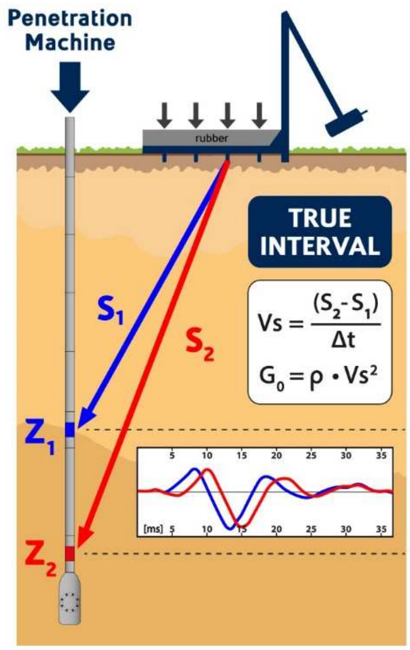
Shear wave velocity measurements are commonly performed at depth intervals of 0.50 m, while DMT readings every 0.20 m.

The SPDMT is an enhanced version of the seismic dilatometer equipment with two additional receivers for measuring the compression wave velocity V_P. Results obtained with this new instrument providing both V_S and V_P measurements, in addition to the standard DMT results, have been reported by Amoroso et al. (2016, 2020).

The SDMT may be used in all penetrable soils as recommended for standard DMT equipment (clays, silts, sands). However, it may also be employed in non-penetrable soils (e.g. dense gravel, very hard soils), where the probe may record waveforms inside boreholes backfilled with clean fine to medium gravel (Totani et al. 2009).



(a)



(b)

Figure 3.2. Seismic dilatometer equipment (a) and test layout (b)

4 Summary description of the Medusa dilatometer test

The Medusa dilatometer (Medusa DMT) is a self-contained, fully automated version of the flat dilatometer, able to autonomously perform dilatometer tests without the pneumatic cable (Marchetti 2014). A motorized syringe, driven by an electronic board powered with rechargeable batteries, hydraulically expands the membrane to obtain the *A*, *B*, *C* pressure readings, which are acquired and stored automatically at each test depth.

The Medusa DMT is advanced into the ground using the same field machines, commonly penetrometers or drill rigs, used for the traditional pneumatic DMT and adopting the same depth intervals for testing (typically every 0.20 m).

The device may operate without any cable. An optional electric cable may be used to obtain real-time test data and for monitoring automation parameters during the execution of the measurements. For deeper investigations, the cable may be omitted and the instrument may work independently, performing measurements at preset time intervals and storing the results in the embedded memory.

Originally conceived for offshore testing (Marchetti 2018), the Medusa DMT is increasingly used in routine onshore investigations, also due to the possibility of additional measurements not feasible with the traditional pneumatic equipment.

The field of soil type application of the Medusa DMT is the same as for the traditional pneumatic DMT (clays, silts, sands).

Sections 5, 6, 7, 8, 9 of this report provide detailed information on the Medusa dilatometer equipment, test procedure, data reduction and interpretation, and reporting of test results. This core information could be incorporated in a future standard for the Medusa DMT, upon implementation by international standards organizations.

The following sections illustrate the main advantages of the Medusa DMT over the traditional pneumatic DMT (Section 10) and experimental results obtained using the Medusa DMT, including validation and comparisons with traditional DMT results, obtained at various well-documented test sites (Sections 11, 12).

5 Medusa DMT testing equipment

5.1 Medusa dilatometer probe

The Medusa dilatometer (Medusa DMT) probe is composed of a dilatometer blade combined with a rod behind it containing all the necessary components for performing DMT measurements, without necessarily requiring a cable to the surface. Figure 5.1 illustrates the main components of the instrument, excluding the required penetration machine and rods for inserting and advancing the probe into the ground.

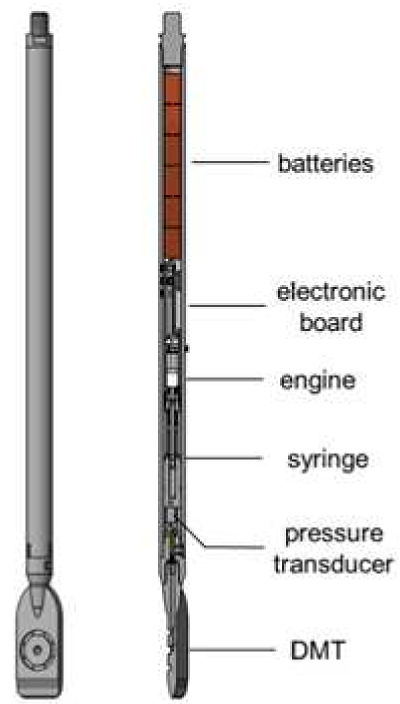


Figure 5.1. Main components of the Medusa dilatometer

The main components inside the rod behind the blade include:

- Oil for pressurization
- Battery pack
- Electronic board
- Motorized syringe
- Pressure transducer
- Steel rod

The equipment requires also the following additional components:

- Medusa DMT control unit
- Computer and software
- Electric cable

The dimensions, tolerances and technical characteristics of the equipment components must comply with the indications included in this document as they may affect the test results.

Medusa dilatometer blade and membrane

The dilatometer blade has the same dimensions of the standard Marchetti flat plate dilatometer (Marchetti 1980) and is employed with the same working principle of the original instrument (ASTM D6635-15, ISO 22476-11:2017(E)). The dimensions of the blade, the membrane and the apex angle of the penetrating edge shall be within the limits of the original instrument as shown in Figure 5.2.

The nominal dimensions of the blade are 95 mm width (± 1.0 mm) and 15 mm thickness (± 1.0 mm). The blade has a lower cutting edge to penetrate the soil, with an apex angle comprised between 12° and 16°. The upper section of the blade is 170-180 mm long. The lower tapered section of the tip is 50 mm long.

The circular steel membrane is 60 mm in diameter. The membrane is mounted flush on the blade and kept in place by a retaining ring. Membrane thickness may vary between 0.20 mm to 0.30 mm, although the standard for the Medusa dilatometer is 0.30 mm.

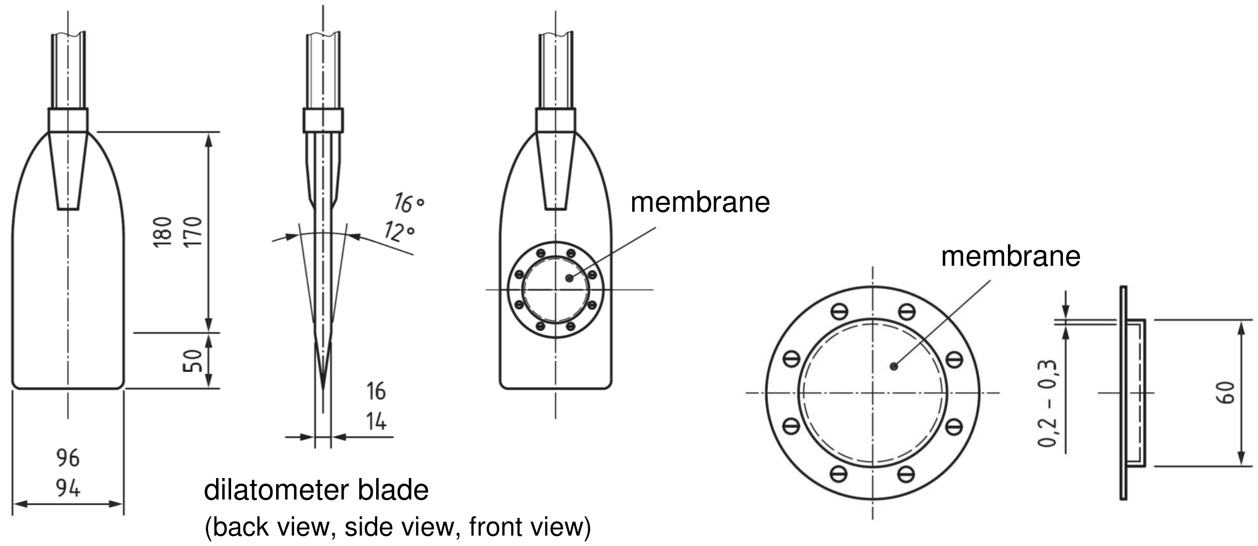


Figure 5.2. Dimensions of the dilatometer blade and membrane (ISO 22476-11:2017(E))

Figure 5.3 illustrates the working principle of the flat plate dilatometer. Behind the membrane there is a sensing disc, which is stationary and kept in place by a plastic seating. A quartz non-conductive cylinder is pushed by a metallic conductive spring-loaded cylinder against the membrane centre. The insulating seat prevents electric contact of the sensing disc with the steel body of the dilatometer. The blade works like an electric switch, which is active (ON) if there is electric contact between the sensing disc and the steel body of the blade or inactive (OFF) if they are electrically isolated. In particular the electric contact is active in each of the following cases:

C1 the membrane is flat against the sensing disc, providing the electric contact;

C2 the centre of the membrane has expanded horizontally against the soil of a fix displacement (typically 1.10 mm). The electric contact to the sensing disc is provided by the steel spring and steel cylinder.

At all intermediate positions of the membrane between C1 and C2 there is no electrical contact.

Once the blade is advanced at the test depth, the horizontal pressure of the soil flattens the membrane against the sensing disc and the contact is active (C1). When the internal pressure to the membrane is increased (Figure 5.3), for some time the membrane does not move and remains in contact with its metal support (C1). When the internal pressure counterbalances the external soil pressure, the membrane starts to expand horizontally, losing electric contact with its support (contact inactive). The contact interruption detects the instant for recording the lift-off pressure, defined as *A*-pressure. The pressure continues to increases and as the membranes expands, the contact remains inactive. When the membrane has expanded to a predefined displacement of its centre (typically 1.10 mm), the spring-loaded cylinder will touch the sensing disc, providing the electric contact between the body of the blade and the sensing disc (C2). The reactivation of the contact detects the instant for recording the full expansion pressure, defined as *B*-pressure.

The top of the sensing disc exhibits a 0.05 mm protruding feeler, for improving the sharpness of the contact interruption at the lift-off of the membrane.

The acceptable tolerances of the blade, the sensing disc, its feeler and the quartz cylinder ensure that the membrane expansion will be ± 0.02 mm compared to the nominal membrane expansion (typically 1.10 mm). For this reason only original and calibrated components shall be used, supplied with a certificate of compliance with the acceptable tolerances.

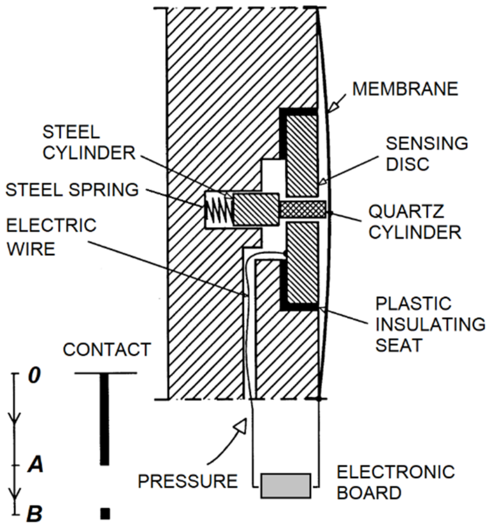


Figure 5.3. Detail of the operation mechanism of the dilatometer blade

Oil for pressurization

The fluid used for pressurizing the Medusa DMT is ENI ITE 600, a mineral oil compliant with the corrosion standards ASTM D1275-15 and CIGRE TF A2.32.01.

Battery pack

The Medusa DMT includes a rechargeable battery pack for powering the electronic board and the motorized syringe for generating the pressure required for DMT readings. The acceptable voltage is between 7.2 and 12.0 V. In the cabled version, the battery capacity is 2400 mAh and it is continuously recharged from the surface during the test. In the cableless version, the battery capacity is 9000 mAh to ensure a full 24 hour work supply on site. In this last case, the batteries must be fully charged before starting the test.

Electronic board

The Medusa DMT electronic board is powered by rechargeable batteries and acquires data from sensors equipped in the probe. This includes a wire connected to the sensing disc of the blade and a wire to the body of the blade, for detecting the membrane contact status. The electronic board acquires data from the high accuracy pressure transducer. The embedded data acquisition system must provide a resolution of 1 kPa, even when the pressure scale range is 25 MPa.

The electronic board sample frequency of the pressure readings and of the membrane contact status must be at least 50 Hz, required for high accuracy detection of the DMT pressure readings.

The board activates the motorized syringe for generating the pressures necessary for test execution. In particular, it inflates and deflates the membrane and records the DMT pressure readings at the corresponding transitions of the contact status. The board also acquires data related to Medusa DMT components (e.g. battery charge status, voltage and current to the engine of the motorized syringe, position of the motorized syringe piston, etc.).

In the cableless version, only the DMT readings are stored in a permanent memory and downloaded once the probe returns at surface using a short communication cable. In the cabled version, all the acquired data is transmitted real time to the surface, providing besides the DMT readings, also other data for full control over the motorized syringe and over other components of the instrument.

Motorized syringe

The motorized syringe is composed of an engine, a transmission block, a piston and a cylinder. The engine is powered by the batteries and activated by the electronic board. The transmission block provides a linear motion to the piston inside a cylinder, to increase and decrease the oil pressure to the DMT membrane. The piston has a seal for compressing the oil in the cylinder, which must be replaced if damaged or excessively worn out. The motorized syringe must be able to generate a negative pressure, necessary for the membrane calibration. It must be able to apply at least 10 MPa, although the current version is designed for 25 MPa.

Pressure transducer

A high accuracy absolute pressure transducer is used to measure the pressure generated by the motorized syringe and operating on the membrane. This sensor must provide pressure measurements with a resolution of 1 kPa, a reproducibility of 2.5 kPa and an accuracy of at least 0.25 % of the scale range. The pressure transducer has a standard scale range of 10 MPa. However for higher pressures (e.g. for deep offshore testing) a 25 MPa scale range may be used. The transducer must be capable of measuring negative pressures, required for membrane calibration. The pressure transducer must be periodically calibrated against a reference instrument, at least every year.

Steel rod

A high strength steel rod contains the Medusa DMT components connected behind the blade, to protect them from the soil and from the high pressures used during penetration. The inner diameter is 34.5 mm and the outer diameter is 50 mm. The rods are connected at the lower end to an adaptor screwed to the blade, with an o-ring for water tightness. The top end of the rod is screwed to a top adaptor, using the same o-ring of the lower connection.

The length of the rod of the cableless version is about 1.05 m, due to the longer battery pack. This rod also has an additional sealed opening, for connecting a cable to the probe for battery charge, time synchronization, measurements pre-programming and data download required in the cableless configuration.

Medusa DMT control unit

The Medusa control unit exhibits a pannel connector for the cable connection to the Medusa DMT probe, a socket for a 15 V power supply and a standard USB connector for communication with a computer.

Computer and software

A Windows computer with at least one standard USB port is required to run the software for operating the Medusa DMT.

The cabled version requires a software for starting the measurement cycle at each test depth. The pressure applied to the membrane generated by the motorized syringe and the contact status are displayed real time during the entire test cycle. The *A*, *B* and *C* pressure readings are displayed and stored.

The cableless version requires a completely different software. It is used before starting the test for defining the periodic scheduling of the readings and to synchronize the time, before the probe is disconnected from the computer and pushed into the ground to start the test. During the sounding, the software will display the activity of the instrument, so that the operator will know when to operate the penetration machine to advance the instrument to the next test depth and when to wait for measurement execution. Once the sounding is completed and the probe is retrieved at surface, the Medusa DMT is connected to the computer for membrane calibration and the sounding test data is downloaded.

Electric cable

In the cabled version, an electric cable is used to connect the control unit and computer at ground surface to the Medusa DMT at depth. In this configuration, the operator activates the Medusa DMT test cycle from the computer as soon as the test depth is reached. Since the cables are not extendable, the proper length must be chosen greater than the maximum possible test depth, generally of at least 5 m for easy handling of the cable at surface. The cable connection to the Medusa DMT probe must be waterproof and the cable resistant, as for traditional direct push equipment (CPT and DMT). Figure 5.4a provides a sketch of the cable and its connectors. To avoid improper function, all connectors must always be protected with caps when disconnected.

In the cableless version the cable is used only for rapid connections before and after the test, to pre-program the measurements scheduling before the test and to download the measurement data at the end of the test. There is no waterproof requirement for any connections, as they all occur out of the ground. The cable is short (typically 5-7 m) and flexible for easy handling (Figure 5.4b).

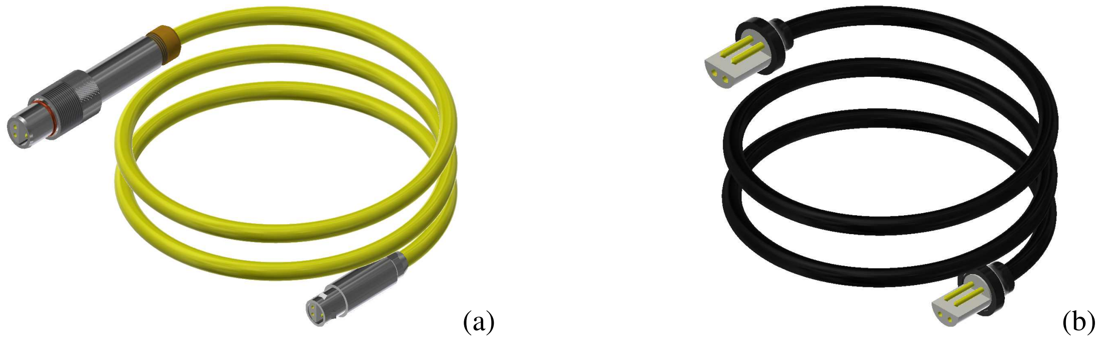


Figure 5.4. Electric cable: (a) cabled version, (b) cableless version

5.2 <u>Working principle</u>

The electronic board, powered by the rechargeable battery pack, is connected to the pressure transducer and to the motorized syringe. The firmware coded in the electronic board activates the motorized syringe for generating the pressure required for expanding hydraulically the membrane to obtain the DMT pressure readings. The high accuracy pressure transducer measures the pressure generated by the syringe and operating on the membrane. An electric wire provides the contact status of the membrane to the electronic board. The *A*, *B*, *C* pressure readings are taken by the electronic board with the same criteria used for the traditional pneumatic DMT equipment.

When the Medusa DMT is operated in cableless mode, a programmable time (Medusa Cycle Period, T_{MCP}) determines when to start each measurement cycle starting from a time origin. A waterproof connector on the rod provides a rapid connection for battery recharge, for time synchronization of the time origin, for defining the Medusa Cycle Period and for downloading the data after the test.

The T_{MCP} period is the sum of the times necessary to perform the following two operations:

1. Perform DMT measurements: the electronic board activates the motorized syringe to acquire the *A*, *B,* and (optionally) *C* pressure readings, which are stored in the EPROM memory (T_M = maximum time allocated for measurements).
2. Wait for penetration to the next test depth, with the system set in an idle state ($T_W = T_{MCP} - T_M$ = time allocated for penetration to the next test depth).

For example, the total period T_{MCP} may be set to 1 minute, with $T_M = T_W = 30$ seconds. In the first 30 seconds (T_M) the DMT pressure readings will be completed, then the probe will stay in the idle state for the remaining 30 seconds (T_W), until the total programmed period (T_{MCP}) of 1 minute has elapsed. During these last 30 seconds (T_W), the instrumentation is advanced to the next test depth.

The Medusa DMT test cycles are repeated sequentially until the probe is retrieved and connected to the computer at surface. During test execution, the computer will display if the Medusa DMT is performing measurements or is in the idle state, so that the operator may correspondingly wait for the test cycle to complete or penetrate the probe to the next test depth. The operator must indicate in the software the test depth for each sequentially numbered test cycle. When the data will be downloaded, the software will associate the correct depth to the DMT readings of the corresponding test cycle.

In the cabled version of the Medusa DMT, an electric cable connects the control unit and computer to the probe at depth. The operator activates each measurement cycle from the computer as soon as the test depth is reached. During the cycle all automation parameters, such as the battery status, voltage and current provided to the engine, position of the piston of the motorized syringe, probe inclination and other additional information and the DMT parameters, such as pressure and membrane contact status, are displayed real time. The DMT pressure readings are also collected and stored in real time, with the possibility of plotting preliminary profiles of the results. The cabled configuration should be used whenever possible. In this case the overall test productivity is higher.

5.3 Medusa SDMT

The Medusa SDMT is a Medusa DMT equipped with seismic sensors for the measurement of the shear wave velocity V_S and, optionally, also of the compression wave velocity V_P. The test procedure for the seismic measurements is compliant with the specifications for downhole testing and seismic cone testing included in ASTM D7400/D7400M-19.

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. The Medusa SDMT test layout, as well as the interpretation, is the same as for the traditional SDMT (Figure 3.2b). The shear wave velocity V_S is obtained as the ratio between the difference of the wave travelpath from the source to the receivers ($S_2 - S_1$) and the wave arrival delay Δt from the first to the second receiver.

The main components required by the Medusa SDMT in addition to the Medusa DMT are:

- Seismic sensors
- Modified steel rod
- Medusa SDMT control unit
- Shear wave source (hammer)
- Trigger
- Software

Seismic sensors

The seismic sensors are monoaxial geophones, placed with their sensitive axis in a radial direction with respect to the longitudinal axis of the probe. Information on correct shear wave source placement and sensor orientation is provided in § 7.2.

Steel rod

The high strength steel rod enclosing the Medusa SDMT is 0.80 m long with an inner diameter of 34.5 mm, exactly as the Medusa DMT rod. The main difference consists in the openings necessary to host the seismic sensors, with o-rings for water-tightness. The outer rod diameter is enlarged to 58 mm in proximity of the sensor openings and is tapered to 50 mm in the centre of the probe.

Medusa SDMT control unit

The Medusa SDMT control unit is required for the data acquistion of seismic measurements. It also replaces the Medusa DMT control unit for handling Medusa DMT testing. The unit includes a socket for connecting the external trigger, besides additional leds and an acoustic buzzer.

Shear wave source

The shear wave source is composed of a specific shear beam and a hammer that must hit the beam in the horizontal direction, parallel to the ground, as shown in Figure 3.2b. The hammer requires a head having a weight of at least 2 kg if the maximum test depth is 10 m, adding 1 kg for each additional 10 m of test depth. With reasonable limits and proportion to the shear beam, the heavier the hammer head, the higher the energy of the generated shear wave for deep seismic testing.

Trigger

The trigger is composed of a shock sensor, a cable and a connection to the Medusa SDMT control unit. It is used to detect the impact of the hammer when it hits the shear beam. The electronic board uses this information to determine when to start the registration from the seismic sensors.

Computer and software

A Windows computer with at least one standard USB port is required to run the software for operating the Medusa SDMT. The software commonly used for recording and processing S-waves is SDMT Pro, first released in November 2020.

5.4 Field machines, rods and adaptors

A field machine and rods are required to insert the Medusa DMT/SDMT into the ground and to advance it sequentially at the test depths of interest. An adaptor is necessary to connect the probe to the rods pushed by the field machine.

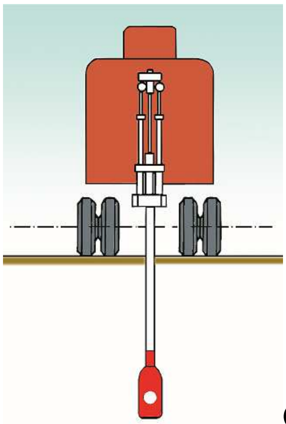
5.4.1 Thrust machine

The Medusa DMT is advanced into the ground using any thrust machine, most commonly a cone penetrometer rig or a drill rig (Figure 5.5). The machine must be capable of advancing the probe vertically, with no significant horizontal or torsional forces, and preferably applying a thrust force up to 200 kN or more. To increase the capacity of penetration, suitable dead loads and/or anchors may be used.

The thrust machine shall be capable to apply a penetration rate of 20 mm/s (± 10.0 mm/s, ISO 22476-11:2017(E)), as for the cone penetration test.

Alternatively, when static push is not feasible, the Medusa DMT may be driven, e.g. using a reduced free-fall height of the Standard Penetration Test (SPT) hammer and rods or the dynamic penetration test setup. The full stroke of a standard SPT hammer may damage the seismic sensors and the electronic boards inside the probe.

In general static push is by far preferable and driving should be avoided (ASTM D6635-15, Marchetti et al. 2001), except when advancing the probe through stiff or strongly cemented layers which cannot be penetrated by static push.


(a)

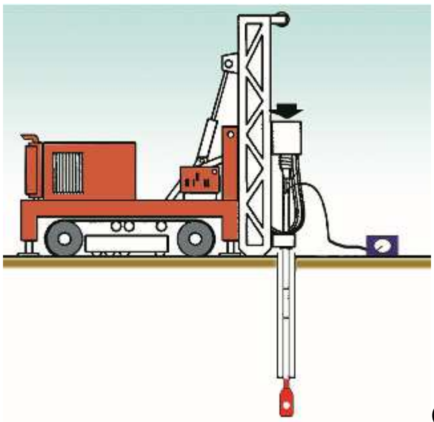

(b)

Figure 5.5. Thrust machines for advancing the Medusa DMT/SDMT: (a) truck penetrometer, (b) drill rig

NOTE: Possible problems using light rigs (ISSMGE TC16 Report, Marchetti et al. 2001)

Heavy truck-mounted penetrometers are incomparably more efficient than drill rigs. Moreover the soil provides lateral support to the rods (which is not the case in a borehole). Pushing the Medusa DMT with a 20 ton penetrometer truck is most effective and yields the highest productivity (up to 100 m of sounding per day).

Drill rigs or light rigs may be used only in medium to soft soils or to shallow test depths. Drill rigs may also be necessary in soils containing occasional boulders or hard layers, where the obstacle-destroying capability will permit to continue the test past the obstacle.

NOTE: Preboring used to advance Medusa DMT soundings

Drill rig support may be required to bore through impenetrable soil or rock layers above the target test depth.

When the Medusa dilatometer sounding is resumed after preboring, the initial test results obtained in the zone of disturbance at the hole bottom, typically 3 to 5 borehole diameters, should be disregarded.

When the Medusa dilatometer test is performed inside a borehole, the diameter of the borehole (and casing, if required) should be as small as possible to minimize the risk of buckling, but large enough to permit the insertion of the probe (preferably 100-120 mm). In all cases the blade penetration must occur in "fresh" (i.e. not previously penetrated) soil.

NOTE: Distance from nearby soundings and borings

Medusa DMT soundings should not be performed within the zone of soil affected by another sounding or boring. Good test practice requires a minimum clear distance of 1 m from nearby existing DMT (or CPT) soundings, and 25 borehole diameters from an existing unbackfilled or uncased boring (ASTM D6635-15).

5.4.2 Push rods

Push rods are required to transfer the thrust from the penetration machine to the Medusa DMT probe. The push rods shall be straight and resistant against buckling. Most commonly, CPT rods or drill rig rods are employed, having an external diameter of 36 mm, 44 mm or 50 mm and a length of 1 m. Longer rods (e.g. 3 m) may cause excessive rigidity and increment the risk of rod rupture.

Above the ground level, the rods should be guided with a larger diameter pipe to avoid buckling in free air.

In the cabled version of the Medusa DMT, the electric cable runs inside the rods from the ground surface down to the probe at depth. For this reason the inner diameter of the rods should be of at least 16 mm.

Friction reducers, consisting of local enlargement in rod diameter, may be used to reduce the friction against the rods during penetration. When employed, usually only one friction reducer is placed between the first rod and the Medusa DMT probe. A suitable load cell may be optionally placed between the push rods and the Medusa dilatometer, to measure the thrust applied during penetration. (This measurement however is not strictly necessary for the standard interpretation of the test results).

NOTE: Use of stronger rods

Many heavy truck penetrometers are equipped also with rods much stronger than the common 36 mm CPT rods, typically with diameter between 44 mm and 50 mm, 1 m length, same steel as CPT rods (yield strength > 1000 MPa). A very suitable and convenient type of rod is the commercially available 44 mm rod, used for pushing 15 cm^2 cones.

Stronger rods have been introduced because the rods are ‘the weakest element in the chain’, when working with heavy duty trucks and the high strength DMT blades, able to withstand a working load of approximately 250 kN.

Stronger rods have several advantages:

- capability of penetrating through cemented layers/obstacles;
- increased lateral stability against buckling in the first few meters in soft soils, or when the rods are pushed inside an empty borehole;
- possibility of using the full push capacity of the penetrometer;
- reduced risk of deviation from the verticality in deep soundings;
- drastically reduced risk of loosing the rods.

Obvious drawbacks are the initial cost and the heavier weight. Also, their use may not be convenient in overconsolidated clay, because of the increased lateral friction.

5.4.3 Rod adaptors

The Medusa DMT is connected to the push rods using an adaptor. The lower thread of the adaptor must exhibit a thread M33/3.5, as shown in Figure 5.6. The top thread of the adaptor must be able to connect to the employed rods. Today there are several constructors of CPT rods manufactured with different threads, without a world-wide standard. For this reason the adaptor may be supplied threaded only on the M33 end and not threaded at the opposite end, so that it may be threaded according to the employed rods or welded to a rod.

In the cabled version of the Medusa DMT, a slotted adaptor may be necessary to allow for the lateral exit of cable, otherwise pinched by the pushing head of the field machine. Some new generation penetrometers grip the rods laterally to applying thrust, instead of using a top pushing head. In this case there is no need of the slotted adaptor.

In the cabled version of the Medusa DMT, when testing starts from the bottom of a borehole, the electric cable may either run all the way to the surface inside the rods, or it may exit laterally from the rods at a suitable distance above the blade. In this case an additional intermediate slotted adaptor is needed to enable the exit of the cable out of the rods. Above this point the cable is taped to the outside of the rods typically at 1-1.5 m intervals up to the surface.

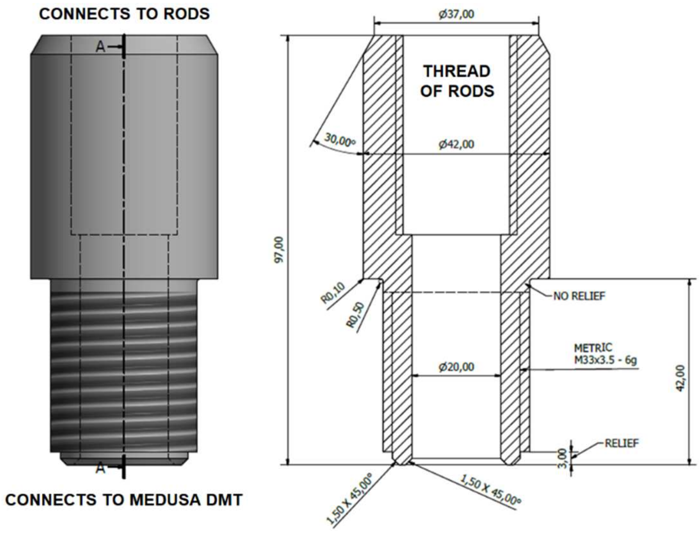


Figure 5.6. Adaptor for Medusa DMT

5.4.4 Torpedo

The Torpedo assembly is commonly adopted when using a drill rig and is composed of the following parts (Figure 5.7):

- The Medusa DMT probe
- Series of rods, typically 3-5 m
- An adaptor between the rods and the Medusa DMT probe
- The Torpedo slotted adaptor, connecting the drill rods (typically 76 mm diameter) to the employed rods (typically 50 mm rods). It exhibits a hole for the lateral exit of the cable and a vertical channel to protect it. An enlarged diameter collar ensures a free space for the cable between the drill rods and the casing.

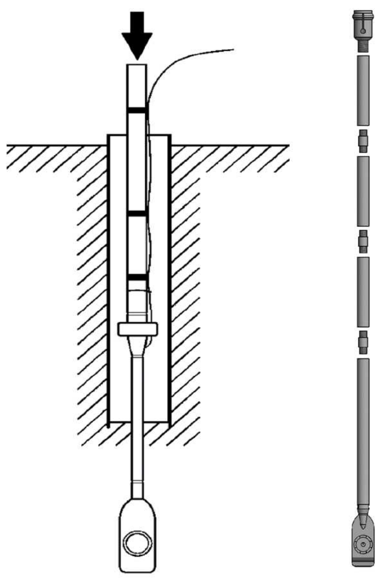


Figure 5.7. Torpedo assembly

The Torpedo is pre-assembled at the beginning of the sounding. After each drilling sequence, the casing is advanced to the last drilled depth. The preassembled Torpedo is connected to the drill rods and lowered to the bottom borehole, taping the cable above its exit every 1-1.5 m up to the surface.

The operator should not allow the slotted adaptor with the exposed cable to penetrate the soil, as it will probably break. Therefore, after each drill sequence, the maximum test depth starting from the bottom of the borehole is limited to the length of rods of the Torpedo.

The Torpedo configuration is less productive than a penetrometer, because of the required alternations between drilling and measurements. However the main advantage is that, if there is an impenetrable layer causing refusal, it is possible to drill through and continue the test below it, with virtually no depth limitation.

6 Medusa DMT test procedure

6.1 Equipment maintenance and checks

All the Medusa DMT components, including the connectors, the control unit and the measuring devices, must be periodically checked, at least once per year. In addition, the measuring unit (pressure transducer) must be periodically calibrated against a suitable reference instrument to ensure that it provides reliable and accurate pressure measurements.

The inner parts of the instrument behind the membrane must be kept perfectly clean to ensure proper electrical contacts. In particular, these components must be completely free from dirt, grains, tissue or rust. The dilatometer blade and membrane shall be visually inspected before starting a new sounding.

The blade must be planar and have a sharp penetration edge. The maximum out of plane deviation of the blade, defined as the maximum clearance under a 150 mm long straight edge placed along the blade parallel to its axis, shall not exceed 0.5 mm. The blade shall be mounted axially with the Medusa rod. The maximum coaxiality error of the blade, defined as the deviation of the penetration edge from the axis of the Medusa rod to which the blade is attached and the push rods, must not exceed 1.5 mm.

The membrane surface must be regular, clean of soil particles, free of any deep scratches, wrinkles or dimples. Sample calibration cycles (described in § 6.2) shall be performed to check if the calibration constants are in tolerance and if the membrane expands smoothly in air without popping or snapping sounds.

The supplied soil simulator shall be used to apply pressure to the membrane to perform sample DMT test cycles.

Before starting a sounding, the linearity of the push rods should be checked by one of the following methods (ISO 22476-11:2017(E)):

- hold the rod vertically and rotate it, if the rod appears to wobble, its straightness is not acceptable;
- roll the rods on a plane surface, if the rod appears to wobble, its straightness is not acceptable;
- slide a straight hollow tube slightly longer than the rod over the rod, if the rod can pass through the tube without jamming, its straightness is acceptable.

If any indications of bending appear, the use of the rods should be suspended.

Other methods of checking rod straightness may be used if they provide consistent indications with those suggested above.

In the cabled version of the Medusa DMT, pre-thread the electrical cable through a suitable number of push rods and the adaptors. During this operation keep the cable terminals protected from dirt using the supplied caps. Connect the cable to the Medusa DMT and tighten the corresponding threaded ring manually. Connect the Medusa dilatometer to the bottom push rod with the adaptor. Avoid excessive twists in the cable while making the connections.

6.2 Membrane calibration

As in a traditional dilatometer test, the A, B, C pressure readings must be corrected with the calibration offsets ΔA and ΔB to obtain p_0, p_1, p_2, respectively, to account for membrane stiffness (see ISSMGE TC16 Report, Marchetti et al. 2001 for details). The calibration correction eliminates also any zero offset error of the pressure transducer, since all the measurements are performed with the same pressure sensor.

The membrane calibration procedure consists of measuring the ΔA and ΔB pressures, necessary to displace the membrane to the A and B positions starting from an intermediate position in free air and in absence of soil (Figure 6.1).

ΔA is defined as the external pressure which must be applied to the membrane, in free air, to obtain electric contact of the membrane with the sensing disc feeler (i.e. A-position, corresponding to a membrane centre expansion of 0.05 mm). This calibration constant is measured applying suction to the inner side of the membrane, thus measuring a negative pressure which is then converted to positive for input in the data processing calculation.

ΔB is defined as the internal pressure necessary, in free air, to expand the membrane centre of 1.10 mm from the sensing disc (i.e. *B*-position).

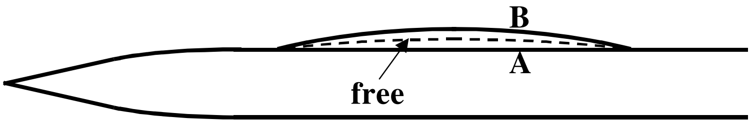


Figure 6.1. Positions of the membrane

During membrane calibration the Medusa DMT must be in the vertical position, to include also the pressure effects of the weight of the hydraulic liquid in the system.

The calibration procedure provides a preliminary check of the equipment's functionality, strongly recommended prior to field testing (possibly the day before). If the equipment is disassembled and reassembled for any reason, the operator should verify the calibration constants before proceeding.

The membrane calibration shall be performed before starting a new sounding (initial calibration values), after instrument retrieval at ground surface at the end of a sounding (final calibration values) and, in general, whenever the probe is removed from the ground, even after one single measurement during a sounding.

The membrane corrections ΔA, ΔB shall be measured and stored with the Medusa DMT equipment ready for starting soil penetration in onshore investigations or, just before lowering the probe in water, in offshore investigations.

ΔA, ΔB are usually measured, as a preliminary check of the equipment, in the office before going to the field. However the initial ΔA, ΔB values to use are the ones taken in the field just before the sounding.

The calibration constants are acceptable if all of the following conditions are respected:

- $\Delta A \in$ [5 – 50 kPa]
- $\Delta B \in$ [20 – 100 kPa]
- $(\Delta B - \Delta A) \in$ [40 – 110 kPa]

If the initial values of ΔA, ΔB do not comply with the above mentioned conditions, the Medusa DMT membrane must be replaced before use in the field.

The calibration values of a membrane remain relatively constant during a sounding, therefore the comparison of initial vs. final values provides a useful indication on the membrane condition. The change of ΔA and/or ΔB between the initial and final values of the sounding shall not exceed 25 kPa, otherwise the test results shall be discarded.

All calibration values of ΔA and ΔB shall be stored in the Medusa DMT software. This includes necessarily the initial and final values, but also additional values if a membrane required replacement before the end of the sounding. The new released software SDMT Pro (2020), employable to process DMT and SDMT data, enables to assign ΔA and ΔB for specific depth intervals of DMT measurements, instead of constant values for all the DMT readings of a same sounding.

The calibration correction using ΔA and ΔB is the first step of the data processing. Any error related to their measurement will propagate to all subsequent steps of the processing and involve all the DMT tests results, with no exception. For this reason, calibration must rigorously be performed as indicated in this document.

NOTE: When to replace a membrane (ISSMGE TC16 Report, Marchetti et al. 2001)

If the ΔA and ΔB values do not comply with the acceptance conditions indicated above, membrane change is mandatory. It is not recommended to change an old membrane if the calibration constants ΔA and ΔB are in tolerance. Indeed an old membrane is preferable, in principle, to a new one, having more stable values of the calibration constants. If however, with a visual inspection, wrinkles, scratches, excessive wear are observed, membrane replacement is strongly recommended even if ΔA, ΔB are in tolerance, to avoid sudden rupture during testing.

After a membrane has been replaced, the new one shall be "exercised", before calibration, in order to stabilize the ΔA, ΔB values (i.e. obtain ΔA, ΔB values which will remain constant during the sounding).

The exercising operation may be performed using the software supplied with the equipment. It consists in applying sequential cycles of pressurization and depressurization. The recommended maximum exercising pressure depends on membrane thickness, as indicated in Table 6.1.

Table 6.1. Membrane exercise parameters

Membrane thickness	Number of cycles	Exercising pressure
0.20 mm	3	500 kPa
0.25 mm	3	600 kPa
0.30 mm	5	700 kPa

After exercising a new membrane, or to check if a membrane requires to be exercised, the calibration procedure shall be performed verifying that ΔA and ΔB are within the above tolerance indications. If the values are negligibly outside the range of tolerance (± 5 kPa), it is possible to repeat the membrane exercise procedure and check if the values have improved to comply with the membrane calibration requirements. In this case it is possible to increase of maximum 100 kPa the value of the exercising pressure.

6.3 Operations before testing

Before starting a new sounding the operator shall:

- verify the equipment maintenance and checks described in § 6.1.
- Run and save at least 3 membrane calibration cycles with the Medusa DMT, immediately before starting soil penetration onshore or prior to lowering the instrument into water in offshore investigations.
- Check the following conditions for two specific parameters, related to the syringe piston position, saved with the calibration test cycles:
  XA ∈ [2 – 10 mm]
  ΔX ∈ [8 – 16 mm]
- In the Medusa DMT cabled version, pre-thread the electric cable through the push rods, connect its lower end to the probe and its upper end to the acquisition unit at surface. Additional rods may be threaded later on during the test, temporarily disconnecting the cable from the acquisition unit when the probe is idle and not performing measurements.
- Run the diagnostic test to check that the indicated voltage of the battery pack of the Medusa DMT is at least 7.2 V for the cabled configuration and at least 8.8 V for the cableless configuration.
- In the cableless version, before lowering the probe, the Medusa DMT must be connected to the software to configure the scheduling of the measurements (in particular T_{MCP}, T_M, T_W).

6.4 Test procedure

The Medusa DMT may perform dilatometer measurements using distinct test procedures described herein. The 'standard' DMT procedure is the same procedure of the traditional pneumatic flat plate dilatometer test. All the alternative procedures differ from the standard procedure mainly in the technique used for taking the *A*-pressure reading(s). Section 12 contains test results obtained with the test procedures discussed in this section, performed in the Italian research test site of Fucino – Telespazio in September 2020.

6.4.1 Standard DMT procedure (STD)

The Medusa DMT shall be inserted vertically into the soil, from the ground surface or from the bottom of a borehole and then advanced to the selected test depths, typically with depth intervals of 0.20 m, as for the traditional pneumatic DMT. Smaller depth intervals (of at least 0.10 m) may be occasionally prescribed to obtain a more detailed soil profile, generally limited to a single portion of the sounding.

The 'standard' DMT procedure consists in the sequence of operations illustrated in Figure 6.2.

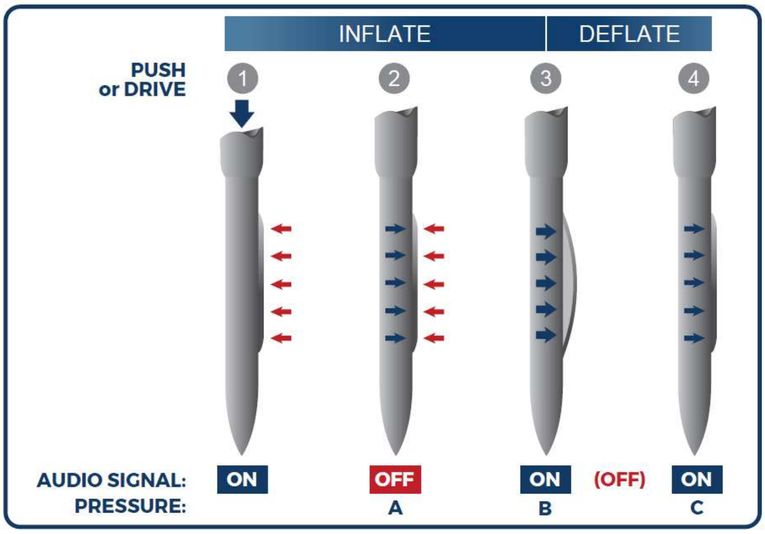


Figure 6.2. Sequence of the standard DMT procedure

The standard DMT procedure consists of the following step-by-step operations.

Step 1. Advancement of the probe, stop of penetration and start of pressurization

During the insertion of the probe, the membrane is not pressurized. As the blade penetrates, the electrical signal shall be activated, because the soil flattens the membrane against the sensing disc. If the soil pressure is not sufficient for this purpose, the Medusa DMT will apply the minimum suction necessary for activating the membrane contact.

As soon as the next test depth is reached, the penetration is stopped and the DMT test cycle shall start. In the cabled Medusa DMT configuration, the operator will activate the DMT test cycle through a command button of the software. In the cableless version, where the start time of the test cycles is periodic and pre-programmed, the probe penetration will be tuned to ensure that the probe will arrive at the test depth when the start time of the cycle will start. More details are available in a dedicated note at the end of this paragraph.

Step 2. A-pressure reading

The activated motorized syringe gradually increases the hydraulic pressure to the membrane. When the internal oil pressure equals the external soil pressure, the membrane lifts-off from its seat and starts to expand laterally. When the membrane has expanded of 0.05 mm at its centre, the electric contact between the membrane and the sensing disc is deactivated and the pressure is recorded and assigned to the *A*-pressure reading. The pressurization rate is regulated so that the *A*-pressure reading is obtained in approximately 15 s after reaching the test depth (i.e. start of pressurization), with ± 5 s tolerance, according to the standards of the traditional pneumatic dilatometer (ASTM D6635-15, ISO 22476-11:2017(E)). Different timings may be set, although not compliant with the current standards of DMT test.

Step 3. B-pressure reading

After the *A*-reading, the motorized syringe continues to increase the pressure. During the consequent membrane expansion the electric contact between the membrane and the blade body remains deactivated, until the membrane displacement at the centre equals 1.10 mm. At this instant the electric contact reactivates and the second pressure reading *B* is recorded. The pressurization rate is tuned by the motorized syringe to obtain the *B*-pressure reading in approximately 15 s after the *A*-pressure reading, with ± 5 s tolerance. Different timings may be set, although not compliant with the current standards of DMT tests.

Step 4. Depressurization and optional C-pressure reading

As soon as the *B*-reading is obtained, the motorized syringe will start decreasing the oil pressure until the membrane will return to its initial position.

If only the A and B pressure readings are of interest, the basic dilatometer test procedure is completed. In this case the depressurization will be fast, to minimize the time to be ready to start the next test cycle.

If the C-pressure reading is requested, the motorized syringe will apply a gradual and controlled depressurization after the B-reading. The membrane will slowly return to its initial position against the sensing disc. At the instant in which the contact reactivates, the corresponding pressure is assigned to the C-pressure reading. The C-reading is typically obtained in approximately 30-40 s after start of depressurization following the B-reading.

The probe is then ready to advance to the next test depth or to be retrieved if the target depth has been tested.

The test sequence (Steps 1 to 4) is repeated at each test depth, down to the maximum depth of the sounding.

The test depth of each set or subset of DMT readings (A, B, C) shall be recorded with reference to the centre of the membrane below ground level or below the seabed in offshore test sites.

NOTE: Additional details for the Medusa DMT cableless configuration

- The penetration machine operator must advance the Medusa DMT probe so that it will arrive to the next test depth (approximately) when the motorized syringe is pre-programmed to start the next DMT test cycle. The software, previously synchronized with the instrument and using the pre-programmed periods (T_{MCP}, T_M, T_W), visualizes the Medusa DMT activities and their time intervals, supporting the operator in such penetration timing.
- The above specified time limits for the A and B pressure readings, besides an estimate for the timing of the C-pressure reading or for the rapid return of the membrane if the C-pressure reading is not of interest, shall be accounted for when programming the Medusa Cycle Period (T_{MCP}), by setting an adequate value for the maximum time allocated for the entire sequence of measurements (T_M).

Figure 6.3 shows a set of graphs of a sample full Medusa DMT test cycle carried out according to the standard DMT procedure. Time starts (t = 0 sec) when the operator activates the cycle from the software when using the cabled version of the Medusa DMT, or at every multiple of T_{MCP} in the cableless version. The graphs show the registration during the test cycle of the following parameters:

- pressure to the membrane generated by the motorized syringe (blue)
- membrane contact status (red)
- position of the piston in the motorized syringe (green)
- current provided to the engine of the motorized syringe (purple)

Initially, the membrane contact status will be activated (ON) and the pressure will be at an initial (irrelevant) value, lower than the A-pressure. The electronic board starts to supply current to the engine which advances the piston in the motorized syringe, gradually increasing the pressure to the membrane. When such generated pressure is equal to the total horizontal pressure of the soil against the membrane, it will start to expand and, after the 0.05 mm displacement imposed by the feeler, the contact status will deactivate (OFF) and the A-pressure reading will be recorded and stored. The motorized syringe will continue to increase the inner pressure and the membrane will expand further. When the membrane will have expanded 1.10 mm at its centre, the B-pressure reading will be stored. The motorized syringe will immediately invert the direction of the piston movement and the pressure will start to decrease. If the C-pressure reading is requested, the depressurization of the membrane will be gradual and the reading will be recorded when the signal will reactivate. If the C-pressure reading is not requested, the motorized syringe will depressurize as fast as possible, returning the membrane in its initial position ready for the next test cycle.

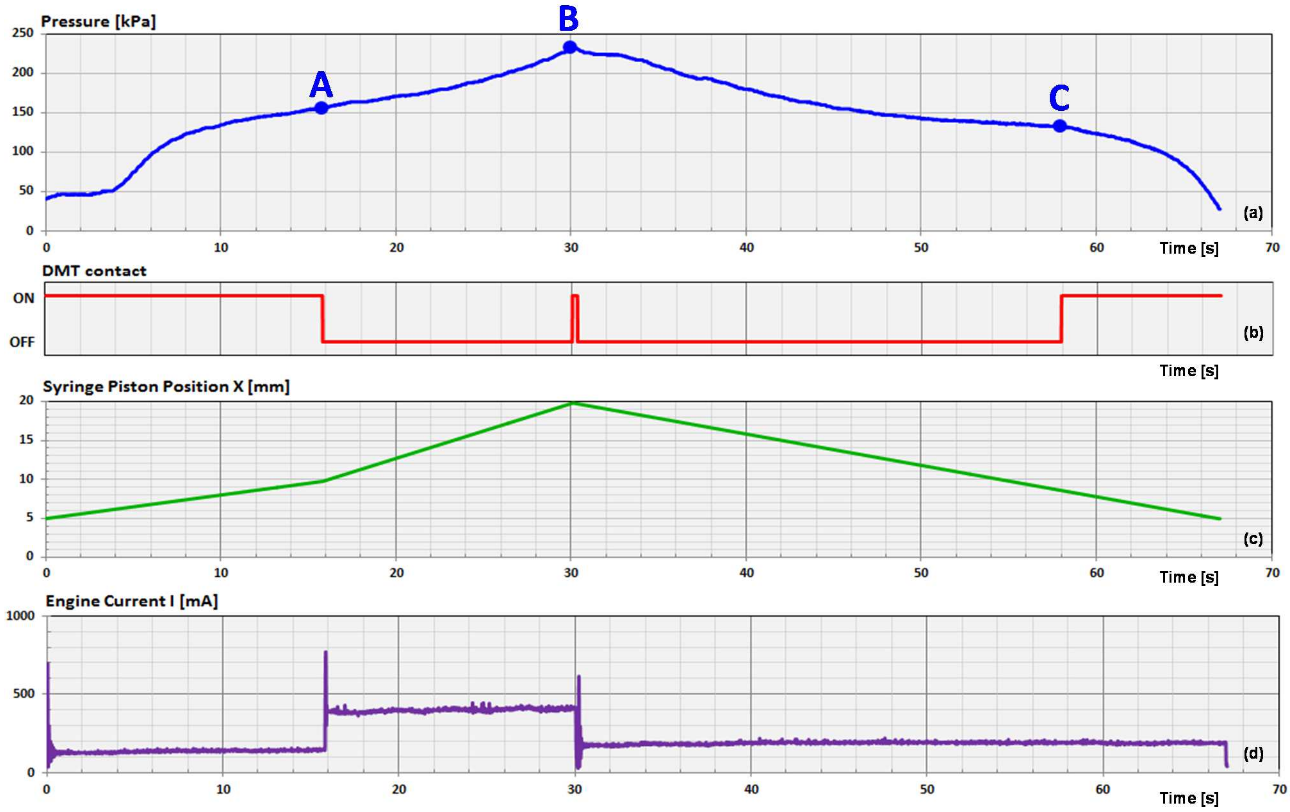


Figure 6.3. Example of data recorded in a full Medusa DMT test cycle adopting the standard DMT procedure: (a) pressure and *A*, *B*, *C* readings, (b) membrane contact status, (c) syringe piston position, (d) engine current. All data are plotted versus time, where $t = 0$ corresponds to the instant when penetration stops and the test cycle begins.

6.4.2 DMT Repeated *A*-readings procedure (DMT-RA)

The DMT Repeated *A*-readings procedure differs from the standard DMT procedure only in the first part of the measurement sequence, before membrane expansion, while the *B*-pressure and the optional *C*-pressure readings are taken exactly in the same way.

The previous section describes in detail that, in the standard DMT procedure, the *A*-reading is taken when the membrane centre has expanded horizontally 0.05 mm against the soil, replicating exactly the same procedure implemented in the traditional pneumatic DMT test.

The motorized syringe of the Medusa DMT, driven by the electronic board, is also able to maintain the membrane in equilibrium with negligible horizontal displacement of the membrane. This new test procedure makes use of this capability.

The initial stage of the DMT test cycle with this new test procedure, before penetrating to the next test depth, consists in maintaining the membrane in equilibrium with the soil pressure. This state is obtained with very rapid pressure corrections operated by the motorized syringe in equilibrium on the contact transitions (ON-OFF-ON-OFF etc.), with negligible membrane displacement. In this situation the membrane is in equilibrium at 0.05 mm distance from the sensing disc. When the new test depth is reached, the test cycle starts ($t = 0$ s) and repeated sequential *A*-readings are taken with time during the rapid pressure corrections of the motorized syringe, monitoring the total horizontal soil pressure against the membrane with time. All the sequential *A*-readings are obtained without any displacement of the soil, because the blade is advanced to the test depth with the membrane already at 0.05 mm displacement from the sensing disc.

Such DMT Repeated *A*-readings test procedure is characterized by the duration (T_{diss}) of the sequential *A*-readings taken with time (dissipation), before concluding the DMT test cycle with the standard *B* and optional *C* readings. The parameter T_{diss} may be selected and pre-programmed before starting the test cycle, so that the membrane expansion will be activated after time T_{diss} has elapsed. Alternatively, the sequence of dissipation readings may be interrupted by the operator through a command-button of the software, which starts membrane expansion to *B*. Typically T_{diss} is set between 10-20 seconds, commonly equal to 15 seconds to comply with the timing suggested by the pneumatic DMT standards (ASTM D6635-15, ISO 22476-

11:2017(E)). The procedure and timing for taking the *B* and *C* pressure readings are the same as in the standard test procedure.

Figure 6.4 illustrates a sample of results obtained by the DMT Repeated *A*-readings procedure at the research test site of Fucino – Telespazio (see Section 12). The decrease of the horizontal soil pressure observed during the *A*-pressure readings in 15 seconds is of 6.2%, as expectable for a clay.

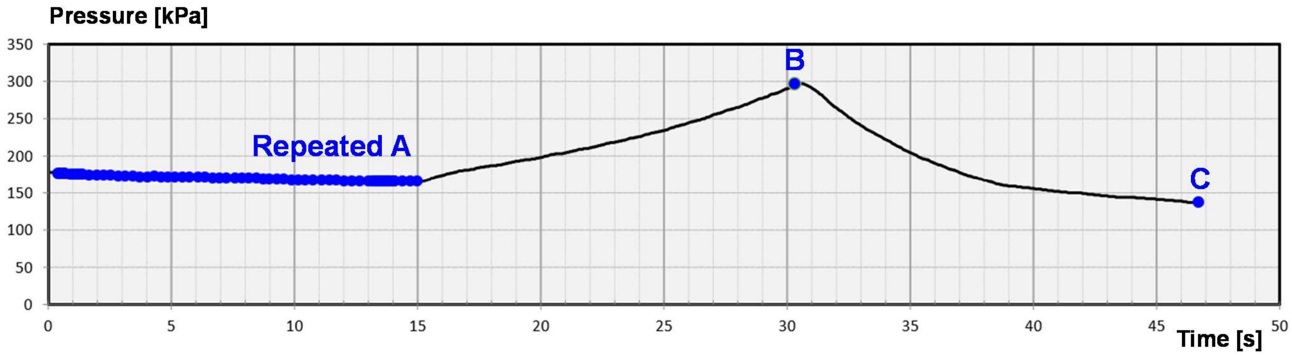


Figure 6.4. Full test cycle obtained by DMT Repeated *A*-readings procedure (DMT-RA) at the research test site of Fucino – Telespazio (September 2020), sounding Medusa 2, depth 8.0 m

6.4.3 DMT *A*-reading while penetrating procedure (DMTA-WP)

The capability of the Medusa DMT to maintain the membrane in equilibrium with negligible horizontal displacement enables to obtain continuous measurements of the total horizontal pressure of the soil against the membrane during penetration of the probe.

The DMTA-WP procedure consists in performing repeated *A*-pressure measurements (equivalent to *A*-pressure reading at t = 0 s instead of the standard DMT time of t = 15 s) recorded during penetration of the Medusa DMT at a constant rate. The sequence of *A*-readings is generally taken over depth intervals of 1 m, corresponding to the typical length of push rods. Almost all penetrometers require to stop penetration every meter to add a push rod, during which *B* and *C* pressure readings may be taken without employing additional time.

A constant penetration rate of 20 mm/s (± 10.0 mm/s), as in the standard test procedure, is generally adopted.

The current Medusa DMT equipment does not include instrumentation to measure the penetration depth during the readings. Most penetrometers include an encoder (for CPT measurements) and may output a time vs. depth file, helpful for accurately associating the *A*-readings to the corresponding depth at which they were taken. When such information is missing, the time-depth relation may be estimated assuming an average speed of penetration, estimated by measuring the time for penetrating a 1-meter rod. The average speed and the time from the start of penetration enables to estimate the depth of each *A*-reading. Although not as accurate as with an encoder, the error is reasonably limited in terms of % error, since each measuring interval is maximum 1 m long. An example of application of the DMTA-WP procedure at the research test site of Fucino – Telespazio (September 2020), with continuous *A*-pressure measurements over 1 m depth intervals and *B* and *C* pressure readings taken every 1 m, is described in Section 12.

6.4.4 Notes for all test procedures

NOTE: Frequency of C-readings

C-readings are time consuming and their execution at each test depth may slow down the overall sounding productivity. Section 8 describes in detail the information provided by this specific DMT measurement. In particular, the corrected *C*-reading p_2 estimates the in situ pore water pressure u_0 in fully drained layers, identified by the condition:

C1 *B-reading* ≥ 2.5 *A-reading*

If the u_0 profile may be estimated with confidence, sporadic *C*-readings may be performed only in fully drained layers (detected by the above C1 condition), to check that the assumed profile is correct.

If unknown, it is extremely helpful for the estimation of the u_0 profile to perform *C*-readings in all fully drained layers, eventually spacing say 1 m in thick layers to save time.

In deposits composed of interbedded coarse and fine-grained layers, besides estimating the u_0 profile in the fully drained layers, the *C*-pressure readings and the derived pore pressure index U_D may help discern free-draining layers from non free-draining layers and may be taken regularly at each test depth.

NOTE: Medusa DMT test cycle start time

The start time of the Medusa DMT test cycle for any of the test procedures described in § 6.4 must occur when penetration stops, with an acceptable error of say ± 3 seconds.
In the cabled version of the Medusa DMT, the operator should start the test cycle with a command button on the software as soon as the instruments has arrived at the next test depth.
In the cableless version of the Medusa DMT, this condition should be enforced indirectly, regulating the speed of penetration. The operator will look at the computer screen, on which the software will indicate the remaining time before the next Medusa test cycle will start, and operate the machine to have the probe at the next test depth approximately when the cycle will start. In case of a large error (≥ 5 seconds), it is recommended to wait for the full test cycle to conclude, and try to meet the requirement for the next test cycle.

NOTE: Deviation from verticality

The Medusa DMT blade may drift out of the initial verticality when inserted, especially at surface, due to initial horizontal forces acting or, also at depth, when penetrating soils with inclusions or when encountering obstructions. The deeper the sounding, the more likely an appreciable deflection may occur. This problem is generally not relevant in ordinary sands and clays for sounding depths within 15 m. However, the operator should be alert for indications of possible inclination drifts, such as unusual "crunching" sounds, inclination of the rods pushed at surface, suspicious data, or specific soil layers encountered deeper than expected. Experience indicates no significant effect on the test results for soundings performed within 15 degrees of the vertical axis (ASTM D6635-15). Inclinometer data acquired with the Medusa DMT may be helpful to monitor inclination.

NOTE: Data checks during testing

During DMT data acquisition some of the following checks may help to recognize if there is some problem with the measurements or not:

- the difference between the *B* and *A* pressure readings ($B - A$) should always be greater than the sum of the ΔA and ΔB calibrations ($\Delta A + \Delta B$).
- The *A*-pressure and *C*-pressure readings may be negative and as low as the first calibration pressure ($- \Delta A$), which happens if there is a void in the soil, but not lower. Lower values are probably due to a defective pressure transducer.
- If the piston position X goes beyond 35 mm with a corresponding pressure below 5 MPa, probably the Medusa DMT requires maintenance, for example change of the piston seal.

NOTE: Oil conduit

The oil pressure is generated by the motorized syringe with a piston advancing in a metallic cylinder. The oil then flows to the handlebar component, which distributes the oil to the pressure transducer and down to the blade running through the axial channel inside the splitter. If the instrument has been assembled incorrectly or after long inactivity (≥ 6 months), some of the washers and gaskets may loose tightness and cause oil leakage. Before starting a test, the user must ensure that the entire oil conduit, from the piston head to the inner side of the blade's membrane, is fully saturated and pressure tight. These checks consist in performing and saving sample DMT calibration cycles and verifying the conditions on XA and ΔX indicated in § 6.3, followed by a visual inspection to exclude oil leaks.

NOTE: Accuracy of Medusa DMT measurements

The DMT is a displacement-controlled test, where pressures are recorded at predetermined displacements of the membrane centre in the horizontal direction. The working principle for the displacement measurements is based on balance of zero method (or null method). The membrane is not the measuring unit, but simply a passive separator between the soil and the internal pressure generated by the motorized syringe. The predetermined displacements are detected through electric contacts activated by the components behind the membrane (quartz cylinder, sensing disc, steel cylinder, steel spring, etc.). All such inner components are machined with extremely low tolerances and their dimensions must not be altered. When occasionally a membrane breaks, the user must check for visible scratches on the exposed sensing disc, quartz cylinder and feeler, while the other components are protected behind the sensing disc. All DMT components must be replaced only with original components supplied by the constructor, responsible of the quality checks that are necessary for the high accuracy of the measurements.

NOTE: Reproducibility of Medusa DMT results

The high reproducibility of the test results is a characteristic of the pneumatic DMT equipment observed by many users in the past forty years. Peaks and other relevant discontinuities in test profiles superimpose systematically in adjacent soundings, thus reflecting soil variability instead of random instrumental deviations. Even in sand, which is usually considered inherently variable, the DMT has been found to give repeatable profiles.

The automation of the Medusa DMT has further increased the repeatability of dilatometer readings, mainly because pressurization occurs with an incompressible fluid (oil instead of gas) and because the pressure is generated and measured locally at depth, without capacity effects along the pneumatic cable of the traditional equipment.

6.5 Dissipation tests

6.5.1 Standard dissipation test

This test is generally employed in fine-grained soils, with an upper limit of silts or sandy silts, to obtain an estimation of the coefficient of consolidation and the coefficient of permeability (see Section 8).

The test consists in following the DMT Repeated *A*-readings procedure, but the dissipation duration time T_{diss} is generally unknown. The dissipation test starts activating the repeated sequence of *A*-readings with time, without a pre-programmed T_{diss} time for expansion to *B*. The software displays a real-time plot of the dissipation curve of the *A*-readings with time using a semi-logarithmic graph, where the logarithmic scale applies for time on the x-axis. After an initial transient, in which the pressure may have any trend, the values will generally start to decrease. Typically, the graph will exhibit an S-shape curve with an inflection point named t_{flex}. The dissipation test should not be stopped before the A – log t curve has flattened sufficiently to clearly identify t_{flex}. Figure 6.5 shows an example of a dissipation curve obtained with the Medusa DMT in the research test site of Szeged (Hungary) in November 2020, where the *A*-pressure readings have been corrected to p_0 using the calibration data.

Any *B*-pressure reading obtained at the end of the standard dissipation test, named *B-final*, may not be used as a *B*-pressure reading of the standard DMT procedure.

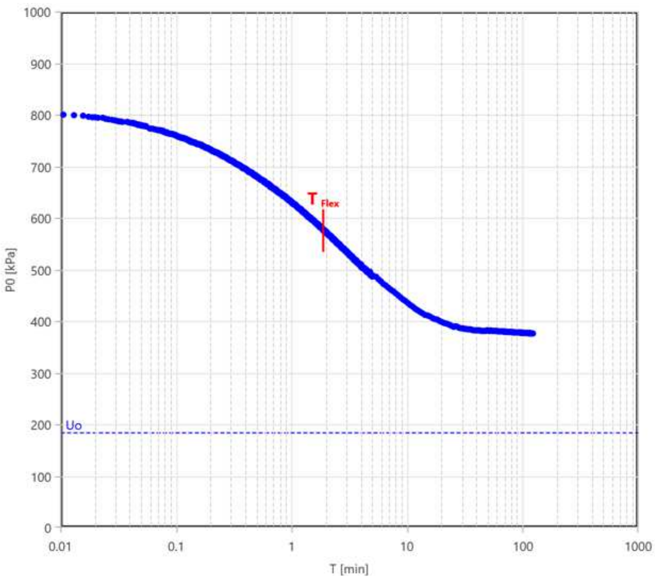


Figure 6.5. Sample dissipation curve obtained with the Medusa DMT (ELI ALPS – Szeged, Hungary, November 2020)

6.5.2 Short dissipation test

This test is generally employed in silts or other intermediate materials (including wastes of tailings dam) to detect partially drained behaviour.

The test consists in following the DMT Repeated *A*-readings procedure employing a T_{diss} of the order of 15 seconds to 2 minutes. In such a short time, no appreciable pore pressure dissipation occurs in clays, so the *A*-pressure remains nearly constant, confirming fully undrained conditions. For opposite reasons, the *A*-pressure readings remain nearly constant also in clean sand, where no excess pore pressure may build up, indicating fully drained behaviour. However in intermediate materials, generally including silty soil or in presence of waste materials related to the mining industry, the excess pore water pressure generated by the blade insertion dissipates in a relatively short time. The detection of this behaviour is important for processing the test results.

Any B-pressure reading obtained at the end of the short dissipation test may be used as a B-pressure reading of the standard DMT procedure only if the dissipation duration T_{diss} is between 10-20 s. Any C-pressure reading may be adopted and processed as if taken with the standard DMT procedure.

6.6 Operations after testing

Once the probe has been retrieved to the ground surface, it must be visually inspected to detect any significant damage to the membrane, such as deep scratches, wrinkles, dimples, cuts along the edge, etc. It is recommended to immediately stick a piece of red tape to any component that requires maintenance before next use in the field.

With the probe out of the ground, the membrane calibration must be repeated and the corresponding values stored in the computer. The procedure, described in detail in § 6.2, includes checks and acceptable tolerances on the comparison between the initial and final values of ΔA and ΔB.

7 Medusa SDMT test procedure

7.1 Preliminary checks

The connection and assembly of the seismic sensors on the Medusa SDMT rod is very critical and must be carried out with maximum attention and care. The frame of each sensor hosts an o-ring that must be placed correctly before tightening the screws that hold them in place. Also the rod requires two o-rings for a watertight connection to the blade adaptor and to the top adaptor. Any o-ring of the instrument may be replaced only with a new one, cleaned and with grease. If the o-ring is pinched, cut or damaged in any way, water will enter the instrument, with catastrophic damages for all the Medusa SDMT components, including Medusa DMT components inside the rod. The user manual supplied with the instrument must contain detailed specifications of these components and detailed instructions for their correct replacement.

Preliminary checks in the office are strongly recommended before going to the field for seismic testing. The Medusa SDMT components must be connected as follows:

- the probe must be connected to the acquisition unit using the supplied electric cable;
- the acquisition unit must be connected to the computer using the supplied USB cable;
- the acquisition unit must be connected to the supplied power supply only if DMT measurements will also be performed.

Using the software, sample seismograms should be recorded selecting the ‘immediate’ trigger, to check if the waveforms are acquired and displayed on the screen and to check that the recorded seismograms are nearly flat.

Seismograms should also be recorded selecting the ‘automatic’ trigger and tapping the probe to start the registration. The acquired waves are meaningless when performed out of the ground. The test is only to check that this trigger modality is working properly.

Finally, the external trigger must be tested by connecting it to the acquisition unit and selecting ‘external’ in the trigger modality. Tapping the shock sensor of the trigger must lighten the corresponding led on the acquisition unit and activate seismogram registration.

One of the above seismogram acquisition may be performed with the probe inside a tub full of water, to check also for the watertightness of the probe.

7.2 Field setup

Correct layout and test procedure is crucial to generate and record clear shear waves and to obtain accurate profiles of the shear wave velocity V_S. If the recorded waves are not clear, automatic interpretation may be unsuccessful and V_S evaluation may be inaccurate or impossible.

The shear wave source is composed of a metallic shear beam and a hammer. A sample shear beam is shown in Figure 7.1, adequate for test depth of the order of 20 m.

The shear beam must be placed on natural ground. Any pavement must be removed down to the natural soil depth. Sand and/or gravel may be used to replace the removed material up to the ground level, required if the removed thickness is relevant.

Before placing the shear beam, ensure that the material below it is flat, to avoid ‘bridging’ of the beam.

The shear beam should be vertically loaded to ensure coupling with the soil below it. For shallow test depth (i.e. up to 20 m) the full weight of a person on the shear beam is generally sufficient, although the wheel of a car or van is a better choice. For deep seismic testing (≥ 50 m), each size of the shear beam in Figure 7.1 should be approximately doubled, including the thickness of the rubber, and the vertical load should be of at least 1 ton.

Rubber is useful to decouple the vertical load from the beam. In particular, when the hammer hits the shear beam, the impact energy will be transferred (mostly) to the soil rather than to the load.

As a rule of thumb, the hammer head hitting the beam should have a weight of at least 2 kg if the maximum test depth is 10 m, adding 1 kg for each additional 10 m of test depth.

A pendulum structure for activating the hammer with a rope enables rapid hammer blows, which increases test productivity.

The distance between the centre of the shear beam and the centre of the rods (D_{SBR}) must be minimized, provided that no mechanical contact occurs. Typically such distance is between 0.30 m and 1.50 m. Experience has shown the seismic probe may require to be advanced to a depth of about $2 \times D_{SBR}$ for recording clear shear waves.

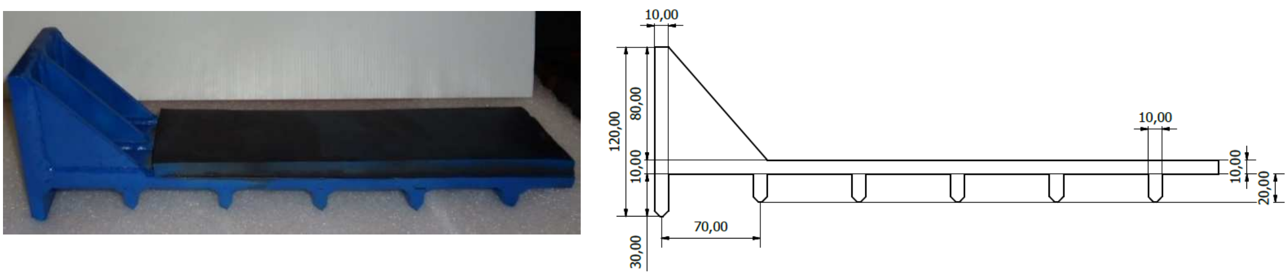


Figure 7.1. Example of shear beam for generating a shear wave

Figure 7.2 displays the correct placement of the hammer and of the sensor axis orientation, pointing out the two following independent recommendations:

1) the hitting direction of the hammer should be perpendicular to the line from the centre of the rods to the centre of shear beam;
2) the hitting direction of the hammer must be parallel to the sensor axis.

Experience has shown that a tolerance of the order of ± 10-15° on the above angular conditions is acceptable.

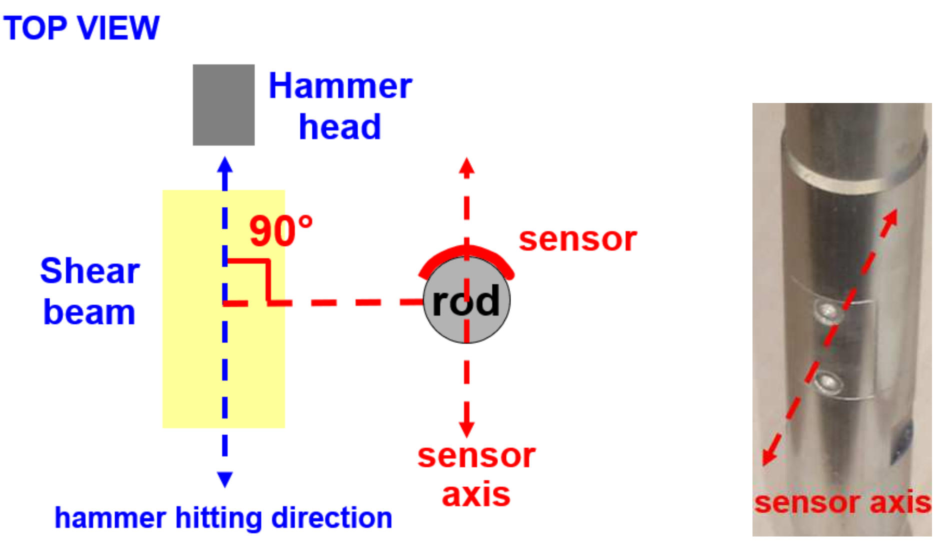


Figure 7.2. Correct orientation of shear beam and sensor axis

Once the shear wave source is placed, the Medusa SDMT components must be connected according to the indications of the previous § 7.1.

The shock sensor of the external trigger should be in stiff mechanical contact with the shear beam for the entire duration of the sounding. For this purpose insulating tape may be used (well tight) or the sensor may be combined with a magnet for a rapid and stable connection to the metallic shear beam.

The computer, with a pre-installation of the software for Medusa SDMT, is generally a laptop constantly powered to avoid shut down during test execution.

7.3 Medusa SDMT test procedure for shear wave velocity

During seismic measurements the reference test depth is the same depth of the DMT blade (i.e. membrane centre), to avoid dealing with different depths when performing both DMT and seismic tests. However the seismic sensors are placed behind the blade, so the software will apply depth corrections according to the geometrical construction offsets of the probe.

The parameters required for the data acquisition of seismic waves are listed in Table 7.1.

Table 7.1. Parameters that characterize the data acquisition of a seismic wave

Parameter	Default	Description
Gain	20	Amplification applied to the sensors signal before acquisition
T sample	200 μs	Data acquisition sample rate (F sample = 1 / T sample)
N sample	700	Number of samples for each waveform
Hammer dist (D_{SBR})	0.50 m	Distance between the centre of the shear beam and the centre of the rods
Trigger	External	Determines when to start the wave registration: • External: selects the external trigger for detecting the wave generation. Registration starts when the trigger sensor detects wave generation and after the time in μs indicated by the Time shift parameter. • Automatic: indicates to use a built in algorithm for detecting the shear wave inside the Medusa SDMT probe. Registration starts when the seismic sensors record a signal higher than a threshold set by the Sensitivity parameter and Loop Samples determines how many previous samples are retrieved before the detection of the wave. • Immediate: registration starts immediately, without waiting for the generation of a wave.

The above parameters are initialized with the indicated default values. Past experience has shown that the default values are the most appropriate to be used when starting from the ground surface, typically at 1-2 m depth. However if the test starts at large depths (≥ 10 m) or the bottom-up depth sequence occurs, the parameters should be tuned accordingly. For example, if the first test depth is at 50 m, the gain and the time shift of the external trigger must be set to higher values than when starting at shallow depths.

The autogain feature, activated by default in the software, is particularly useful during test execution to progressively adjust signal amplification based on depth and on the last generated wave.

Once the probe test depth and the above acquisition parameters are set, the acquisition of the waveforms may start. If the recommended external trigger is selected (or also the automatic trigger), the system will wait for the shear wave generation. The acquired waveforms (seismograms) will be visualized on the computer screen in a matter of seconds. The software will evaluate the wave delay using a built in algorithm based on cross-correlation and the shear wave velocity will be displayed real time.

It is strongly recommended to perform and save at least two seismograms per depth. If the shear wave is clearly detectable in all the traces and if the two repeated V_S values provide a variation coefficient within 5% (or, only for velocities lower than 100 m/s, with a difference of max 10 m/s), then the measurement is acceptable. The finally assigned V_S value is the average of the repeated saved V_S values.

Generally all seismograms and the corresponding V_S are saved. Sometimes the operator may need to discard a seismogram, for example due to accidental triggering and with a meaningless V_S. In this case a saved seismogram may be discarded, so that the V_S evaluation from the repeated V_S values and its variation coefficient are not affected.

Seismic measurements may be performed also in non penetrable soils, using the top-down or bottom-up procedures, inside a backfilled borehole. This methodology was first published by Totani et al. (2009).

8 Medusa DMT test results, data reduction and interpretation

8.1 General information

The primary use of Medusa dilatometer test results is their interpretation to derive common soil parameters that can be used in a variety of geotechnical engineering applications, as illustrated in detail in the ISSMGE TC16 Report (Marchetti et al. 2001) and subsequent updates (Marchetti 2015, Marchetti and Monaco 2018).

In this respect, the Medusa DMT interpretation takes advantage of the wide experience available for the traditional pneumatic DMT test, and essentially shares the same database of established soil property correlations available in literature.

Field test results shall comprise the A, B, C pressures measured at each test depth and the corrections ΔA, ΔB determined by membrane calibration. The sequence of paired values of A, t obtained from dissipation tests at selected depths, when performed, shall also be included.

As in the standard pneumatic DMT test, the Medusa DMT pressure readings A, B, C must be corrected with the calibration offsets ΔA and ΔB and reported as p_0, p_1, p_2 respectively. All subsequent steps of data processing and interpretation of soil parameters, derived from the corrected pressures p_0, p_1, p_2, are the same as for the traditional pneumatic DMT equipment.

The original correlations for estimating soil parameters, introduced by Marchetti (1980), were obtained by calibrating DMT results versus high quality parameters obtained by traditional methods. Many of these correlations form the basis of today interpretation, having been generally confirmed by subsequent research.

The interpretation evolved by first identifying three "intermediate" DMT parameters (Marchetti 1980), namely the material index I_D, the horizontal stress index K_D and the dilatometer modulus E_D, calculated based on p_0 and p_1, then relating these intermediate parameters (not directly p_0 and p_1) to common soil parameters. An additional intermediate parameter, the pore pressure index U_D, based also on p_2, was later introduced by Lutenegger and Kabir (1988).

The intermediate parameters I_D, K_D, E_D, U_D are "objective" parameters – not experimental correlations – calculated from p_0, p_1, p_2 using the formulae reported in § 8.3. These parameters have been introduced because each one of them has some recognizable physical meaning and some engineering usefulness.

The values of the in situ equilibrium pore pressure u_0 and of the vertical effective stress σ'_{v0} prior to blade insertion must also be introduced into the formulae and have to be known, at least approximately. These values of u_0 and σ'_{v0} shall correspond consistently to the same depth and sounding location of p_0, p_1, p_2.

The value of u_0 at any test depth may be estimated from available information on local groundwater conditions and is normally taken as hydrostatic below the groundwater table, with a value of zero assumed above. If better information is available, preferably determined from reliable pore water pressure measurements, it may be used for a higher quality data processing. In sands, u_0 may also be estimated from the depth profile of p_2 (corrected C-pressure), when available.

The value of σ'_{v0} at any test depth shall be estimated from the unit weight of the soil layers above that depth and the in situ pore pressure u_0 at the test depth. An estimate of the unit weight may be obtained from DMT according to available correlations. Commonly in data processing an approximate profile of the total vertical stress σ_{v0} is calculated from the unit weight of the soil γ (in relation to the unit weight of water γ_w) estimated using the chart by Marchetti and Crapps (1981) shown in Figure 8.1 (right), which is also used to obtain a description of the soil type. If a better determination of soil unit weight is available, then it should be used in place of the above estimated values.

The interpreted parameters are common soil parameters, derived from the intermediate parameters using well-established correlations.

Figure 8.1 summarizes the basic DMT data reduction and interpretation formulae, used through various steps in the process starting from field test results and ending with the final interpreted parameters:

(1) correct the field pressure readings A, B, C to obtain the corrected pressures p_0, p_1, p_2;
(2) calculate the intermediate parameters I_D, K_D, E_D, U_D;
(3) obtain interpreted soil parameters of common use in geotechnical engineering by means well-established correlations.

Details are provided in the next paragraphs.

8.2 Corrected pressure readings

Field DMT pressure readings A, B, C shall be corrected for membrane stiffness in order to determine the pressures p_0, p_1, p_2 using the following formulae:

$$p_0 = 1.05\,(A + \Delta A) - 0.05\,(B - \Delta B) \quad (1)$$

$$p_1 = B - \Delta B \quad (2)$$

$$p_2 = C + \Delta A \quad (3)$$

where ΔA, ΔB are the corrections determined by membrane calibration.

NOTE: Correction formulae for p_0 and p_1

The corrected pressure p_0 is intended as the back-extrapolated contact pressure at zero displacement of the membrane centre. The calculation for p_0 in Eq. (1) derives from the assumption of a linear pressure-displacement relationship between the 0.05 mm displacement (elevation of the feeler pin above the sensing disc) at the A-pressure position and the 1.10 mm displacement at the B-pressure position (Marchetti and Crapps 1981).

For the Medusa DMT, strictly the determination of p_0 by Eq. (1) holds when the A-pressure is obtained using the standard test procedure (STD). When the DMT Repeated A-readings procedure (DMT-RA) or the DMT A-reading while penetrating procedure (DMTA-WP) are applied, the A-pressure is obtained by maintaining the membrane in equilibrium with negligible (virtually zero) horizontal displacement. In that case, the measured A-pressure, corrected for membrane stiffness, could be assumed itself as the contact pressure at zero displacement of the membrane centre, calculated as:

$$p_{0,\mathrm{mod}} = (A + \Delta A) \quad (4)$$

The B-pressure in the DMT Repeated A-readings procedure is obtained in the same way as in the standard test procedure, but the displacement of the membrane centre to reach the B-pressure position is 0.05 mm less than in the standard procedure, because the expansion starts from the 0.05 mm elevation of the feeler pin. Therefore also the formula for calculating the corrected pressure p_1 should be modified accordingly.

However, at present, the issue on which correction formulae for p_0 and p_1 shall apply to field data obtained using test procedures different from the standard procedure requires further insight.

8.3 Intermediate parameters

8.3.1 Material index I_D

The material index I_D, related to soil type, is defined as follows:

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \quad (5)$$

where u_0 is the pre-insertion in situ pore pressure.

The above definition of I_D was introduced by Marchetti (1980) based on the observation that the p_0 and p_1 profiles are systematically "close" to each other in clay and "distant" in sand. Hence the soil type can be broadly identified as follows:

clay $0.1 < I_D < 0.6$

silt $0.6 < I_D < 1.8$

sand $1.8 < I_D < (10)$

In general, I_D provides an expressive profile of soil type, and, in "normal" soils, a reasonable soil description. Note that I_D sometimes misdescribes silt as clay and vice versa, and of course a mixture clay-sand would generally be described by I_D as silt.

When using I_D, it should be intended that I_D is not, of course, the result of a grain size analysis, but a parameter reflecting mechanical behaviour (some kind of "soil behaviour type index"). For example, if a clay for some reasons behaves "more rigidly" than most clays, such clay will be probably interpreted by I_D as silt.

Indeed, a description based on mechanical response rather than on real grain size distribution could be more useful in many applications. If, on the other hand, the interest is on permeability, then I_D should be helpfully supplemented by the pore pressure index U_D.

8.3.2 Horizontal stress index K_D

The horizontal stress index K_D, related to stress history, is defined as follows:

$$K_D = \frac{p_0 - u_0}{\sigma'_{v0}} \tag{6}$$

where σ'_{v0} is the pre-insertion in situ overburden stress.

K_D provides the basis for several soil parameter correlations and is a key result of the dilatometer test.

The horizontal stress index K_D can be regarded as the in situ coefficient of lateral earth pressure K_0 amplified by probe penetration. In genuinely normally consolidated clays (no aging, structure, cementation) the value of K_D is ≈ 2. The K_D profile is similar in shape to the profile of the overconsolidation ratio *OCR*, hence generally helpful for "understanding" the soil deposit and its stress history (Marchetti 1980).

8.3.3 Dilatometer modulus E_D

The dilatometer modulus E_D, related to soil stiffness, is defined as follows:

$$E_D = 34.7\ (p_1 - p_0) \tag{7}$$

The above definition of E_D was obtained based on linear elasticity theory (Gravesen 1960), considering a membrane diameter of 60 mm and a displacement of 1.10 mm at the membrane centre.

E_D is the primary index used in the correlation for determining the constrained modulus *M*, in combination with K_D and I_D. In general, E_D should not be used as such, primarily because it lacks information on stress history.

The dilatometer modulus E_D should not be confused with the Young's modulus *E'*, which can be derived from the constrained modulus *M* using the theory of elasticity.

8.3.4 Pore pressure index U_D

The pore pressure index U_D (Lutenegger and Kabir 1988), related to soil permeability, is defined as follows:

$$U_D = \frac{p_2 - u_0}{p_0 - u_0} \tag{8}$$

where u_0 is the pre-insertion in situ equilibrium pore pressure.

In free-draining soils the corrected *C*-pressure closely approximates the in situ equilibrium pore pressure ($u_0 \approx p_2$). Therefore in sands the *C*-pressure readings provide an estimate of the u_0 profile. Since single *C*-pressure readings may contain some experimental scatter, it is preferable to rely on a p_2 depth profile, rather than on individual measurements, to provide a pore water pressure trend.

In free-draining soils, where p_2 closely approximates u_0, $U_D \approx 0$. In non free-draining soils $p_2 > u_0$, due to excess pore pressures induced by the blade penetration, hence $U_D > 0$. Therefore a depth profile of U_D may be used to distinguish free-draining from non free-draining layers, and also to identify stratigraphy in combination with I_D.

Note that U_D, while useful for the above scope, cannot be expected to offer a scale over the full range of permeabilities. In fact beyond a certain value of the coefficient of permeability *k* the test will be drained anyway, below a certain *k* the test will be undrained anyway.

8.4 Interpretation in terms of soil parameters

The interpretation of Medusa DMT test results in terms of soil parameters is essentially based on the same set of soil property correlations established for the traditional DMT. Numerous correlations, mostly based on a mixture of empirical and theoretical analysis, are available in the literature for obtaining information on soil stratigraphy and geotechnical parameters in various soil types. An exhaustive collection of most widely used DMT correlations can be found in the ISSMGE TC16 Report (Marchetti et al. 2001) and subsequent updates (Marchetti 2015, Marchetti and Monaco 2018).

Figure 8.1 contains a summary of published, widely accepted soil property correlations obtained from DMT. The nature of the soils being tested is the major factor affecting the interpretation. Correlations for clay apply for $I_D < 1.2$. Correlations for sand apply for $I_D > 1.8$.

	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	

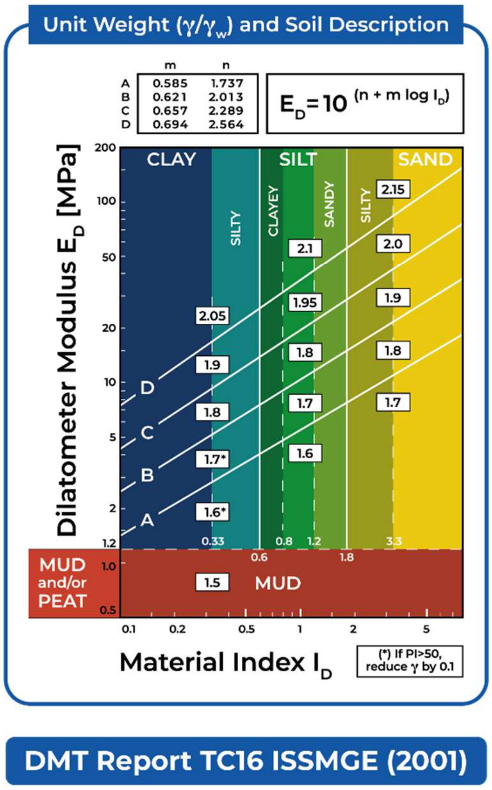


Figure 8.1. Summary of DMT data processing and interpretation formulae, adapted from ISSMGE TC16 Report (Marchetti et al. 2001). On the right: chart for estimating soil type and unit weight γ (normalized to unit weight of water γ_w) from I_D and E_D, graphically modified version of the chart developed by Marchetti and Crapps (1981)

In particular, the correlations in Figure 8.1 provide an interpretation for:

- soil type and unit weight γ (all soils, Marchetti and Crapps 1981)
- in situ stress state and stress history: overconsolidation ratio *OCR* and in situ coefficient of lateral earth pressure K_0 in clay (Marchetti 1980)
- shear strength: undrained shear strength s_u in clay (Marchetti 1980), friction angle φ' in sand (Marchetti 1997)
- stiffness: constrained modulus *M* (all soils, Marchetti 1980)
- consolidation/permeability: horizontal coefficient of consolidation c_h (Marchetti and Totani 1989) and horizontal coefficient of permeability k_h (Schmertmann 1988) in clay
- pore pressure: in situ equilibrium pore pressure u_0 in sand (Schmertmann 1988)

The average accuracy and variability with which the DMT correlations summarized in Figure 8.1 predict engineering soil properties have been investigated by many researchers. These correlations have been generally found to provide reasonable accuracy, except in "non textbook" soils (e.g. very sensitive clays, cemented soils, etc.).

In general, the DMT provides a reliable identification of soil stratigraphy based on the material index I_D, possibly in combination with the pore pressure index U_D. As for CPT/CPTU interpretation, soil types are identified based on mechanical response (soil behaviour type), rather than real grain size distribution.

The constrained modulus *M* and the undrained shear strength s_u in clay are believed to be the most reliable and useful parameters obtained by DMT (Marchetti et al. 2001). In particular, experience has shown that the constrained modulus *M* estimated from DMT generally provides sufficiently accurate predictions of settlements of shallow foundations under working loads. The estimates of the overconsolidation ratio *OCR* and the in situ coefficient of lateral earth pressure K_0 in clay are also generally reliable.

In sand, if data from adjacent DMT and CPT soundings are available, existing correlations (not shown in Figure 8.1) based on combined DMT and CPT test results permit to estimate the overconsolidation ratio *OCR* (Monaco et al. 2014), the in situ coefficient of lateral earth pressure K_0 (Baldi et al. 1986, Hossain and Andrus 2016) and the state parameter ψ (Yu 2004).

When the seismic version of the equipment (Medusa SDMT) is employed, the measurement of the shear wave velocity V_S is also provided, in addition to the DMT field readings. The small strain shear modulus G_0 can be obtained from the relation $G_0 = \rho V_S^2$, where ρ is the soil density that is obtained directly from the unit weight γ.

9 Report of Medusa DMT test results

9.1 General information

Medusa dilatometer test results shall be presented to enable a third party to independently understand and check the results. Data and all test information must be made available also in digital format for easier data exchange.

Preliminary plots and tabular printouts of the test results recorded by the automatic data acquisition system shall be inspected in the field.

Any relevant additional information shall be noted as each sounding is undertaken at the test site before the personnel and equipment are demobilized. During testing, any detail or deviation from the indications contained in this document, or in a published standard, should be recorded.

At the end of the investigation campaign, a final self-explanatory report shall be prepared.

The report shall include an overview of the site work, a plan layout of the investigation with location of all soundings, a description of the test procedures with indication of the reference standard, and the test results from all soundings, comprising the measured test data and their processing in form of graphical plots. The report shall also include the references of the correlations used in the interpretation.

For each Medusa dilatometer test sounding the report shall include the following information.

General information

- Name and location of the job
- Company
- Name of field manager responsible for the project
- Name(s) of Medusa dilatometer operator(s)
- Name(s) of penetrometer or drill rig operator(s)
- Identification number/designation and date of sounding
- Location and GPS coordinates of sounding (specify reference system)
- Ground surface elevation at sounding
- Depth reference elevation (if different from ground surface)
- Groundwater table depth below ground level (negative only in offshore sites) and method used for its determination, or other information used to estimate in situ pore pressures
- Start depth of sounding from ground surface
- Depth and possible causes of interruption of sounding (equipment breakdown, etc.), if any
- Motivation of end of sounding (target depth, maximum thrust force/hard layer, etc.)
- Depth of pre-drilling (include method of drilling and type of drilling fluid used), casing or trenching, if applicable, and information on soil types or materials encountered
- Method of backfilling the borehole, if applicable
- Photographic documentation
- Any other information noted during sounding (e.g. difficulties, abnormalities or damage of Medusa DMT equipment, thrust machine or push rods, etc.)
- Any other notable feature that may influence the test results or their interpretation (e.g. proximity to embankments or cuts, which may affect horizontal soil stresses, etc.)

Equipment

- Serial number of the Medusa dilatometer
- Equipment type (Medusa DMT, Medusa SDMT)
- Measuring range and accuracy of the pressure transducer, documented by a calibration certificate released not earlier than 6 months from the date of sounding
- ΔA, ΔB membrane calibration values before and after each sounding, or whenever the probe is removed from the ground during a sounding

- Type of thrust machine (penetrometer rig, drill rig), maximum thrust capacity, anchoring system etc.
- Type and diameter of push rods
- Rod friction reducer diameter, if used
- For seismic tests: any information on field test setup (shear wave source characteristics, distance from centre of rods, orientation, etc.)

Test procedure

- Description of the applied test procedure with reference to this document (or to a published standard)
- Any deviation from this document (or from a published standard)

Test results

- Field pressure readings *A*, *B* and (optional) *C* and corresponding test depth below ground surface (or below a different specified depth reference elevation), referred to membrane centre
- Corrected pressures p_0, p_1 and (optional) p_2 and applied (average) ΔA, ΔB values
- Estimated unit weight of soil γ
- Soil type description
- Estimated total vertical stress σ_{v0}, in situ pore pressure u_0, and effective vertical stress σ'_{v0}
- Methods used to estimate total vertical stress and pore pressure
- Intermediate parameters I_D, K_D, E_D and (optional) U_D
- Soil parameters obtained from interpretation of test results (constrained modulus *M*, undrained shear strength s_u in clay, friction angle φ' in sand, in situ coefficient of lateral earth pressure K_0 overconsolidation ratio *OCR* in clay, etc.) and reference to the correlations used

For dissipation tests:

- *A*-pressure readings versus log time *t* (in minutes)
- Inflection time t_{flex}, as identified from interpretation
- Horizontal coefficients of consolidation c_h and permeability k_h estimated from the *A* – log *t* curve

For seismic tests:

- Measured V_S values and corresponding test depth below ground surface (or below a different specified depth reference elevation), referred to membrane centre
- Seismograms recorded at each test depth

9.2 Presentation of test results

All measured and calculated values of test results shall be presented in form of both numerical and graphical output (depth profiles).

The numerical output shall include:

- values of field pressure readings *A*, *B* and (optional) *C* at each depth
- calibration values ΔA and ΔB used to calculated the corrected pressures
- values of corrected pressures p_0, p_1 and (optional) p_2 at each depth
- values of total vertical stress σ_{v0}, pore pressure u_0 and effective vertical stress σ'_{v0} at each depth
- values of calculated intermediate parameters, i.e. material index I_D, horizontal stress index K_D, dilatometer modulus E_D and (optional) pore pressure index U_D, at each depth
- values of interpreted parameters obtained using widely accepted correlations (Figure 8.1), i.e. soil type description, constrained modulus *M*, undrained shear strength s_u in clay, etc. at each depth
- (optional) values of *A*-pressure readings versus elapsed time *t* measured during dissipation tests and corresponding *A* – log *t* plot at each dissipation test depth
- for seismic tests: values of V_S at each depth

The graphical output shall include at least the depth profiles of the main parameters, plotted using an appropriate axis scaling.

It is recommended to present side by side plots of the corrected field readings (p_0, p_1, p_2), of the calculated intermediate parameters (I_D, K_D, E_D, U_D) and of the interpreted parameters versus depth.

The DMT graphical output recommended in the ISSMGE TC16 Report (Marchetti et al. 2001) displays the depth profiles of four parameters (I_D, *M*, s_u, K_D), generally believed to be the most significant to plot for reliability, expressivity, and usefulness. In particular the profile of K_D, though not a common soil parameter, should be displayed as generally helpful in "understanding" the site history, being similar in shape to the *OCR* profile. It is also recommended that the diagrams be presented side by side, and not separated, because it is beneficial for the user to see the diagrams together.

Diagrams showing the results of Medusa DMT test cycles at selected test depths may also be included, if significant. Such diagrams show the *A*, *B*, *C* pressure readings, as well as automation parameters (membrane contact status, syringe piston position, engine current) plotted versus time *t*, assuming $t = 0$ when penetration stops and the test cycle begins.

For Medusa SDMT tests, the depth profile of V_S should also be plotted. Diagrams showing the seismograms at selected test depths, as recorded and re-phased according to the calculated delay, may also be included, if significant.

Example of graphical presentation of Medusa DMT test results are shown in Sections 11 and 12.

10 Main improvements of the Medusa DMT technology compared to the traditional pneumatic DMT

The Medusa dilatometer has several advantages over the traditional pneumatic flat dilatometer equipment, both in terms of simplification of the probe and test procedure, and in terms of increased accuracy of the measurements (Marchetti et al. 2019). The major advantages are listed here below.

- The Medusa DMT automation setup eliminates the pneumatic-electric cable, the control unit and the gas tank required in the traditional pneumatic DMT configuration.
- The overall equipment occupancy is reduced to the size of the standard blade with a rod connected on its top, for a total height of about 1 m.
- The integration of both pressure generation and measurement functions at depth, instead of at ground surface, overcomes any possible problem of pressure equalization along the pneumatic cable that may occur using the traditional equipment.
- The probe may operate in cableless mode, which is a significant practical advantage, especially in the offshore industry. An optional electric cable may be used for obtaining real-time results during test execution.
- The DMT and more recently the SDMT have been increasingly used worldwide in offshore investigations (Marchetti 2018), mainly nearshore with limited water depth (max 50 m). A strong limitation for deep DMT testing is the need of the pneumatic cable, necessary to supply the pressure from a gas tank at surface down to the blade at depth. Available experience has shown that pressure differences at the opposite ends of the cable, adopting the standard pressurization rates, are generally acceptable if the soil is not extremely soft and if the cable length is limited to 100-150 m. However in deep offshore testing the pressure equalization is likely to be an issue, because the soil is typically very soft, especially at shallow depths below the seafloor, and the cable must be very long to cover the sum of the water and penetration test depths. The cableless mode of the Medusa DMT overcomes this issue and also simplifies adaptability to wireline configuration (Failmezger et al. 2008).
- The pressurization rate of the membrane is independent of the operator. The automatic volume controlled procedure of membrane pressurization operated by the motorized syringe, run by an algorithm coded in the firmware, is highly repeatable and capable to impose the correct timing to obtain the *A, B, C* pressure readings, strictly according to the specifications of the standard test procedure, or any other required timing, with an accuracy of about ± 1 s (not possible with gas inflation, due to its high compressibility).
- The capability of the Medusa DMT of measuring (virtually continuously) the total horizontal pressure against the membrane with time enables new research possibilities.
- Dissipation tests for estimating the in situ coefficients of consolidation and permeability (Marchetti and Totani 1989, Totani et al. 1998) may be conducted also in intermediate permeability soils (silts and silty sands), thanks to the high reactivity of the motorized syringe in following the horizontal pressure decay (repeated *A*-pressure readings may be obtained up to 3 readings per second). Differently, using the traditional pneumatic equipment, which typically allows to obtain the first *A*-reading of the sequence not before 15 s, DMTA dissipation tests are feasible only in low permeability soils (clays and silty clays).
- Short *A*-dissipations, consisting in repeated *A*-pressure readings (without expansion of the membrane from *A* to *B*) for a couple of minutes, may be executed to detect intermediate or partially draining soil layers (Marchetti 2015, Marchetti and Monaco 2018). The duration of such short *A*-dissipations (much shorter than standard dissipation tests that provide the entire *A*-decay curve) is sufficient to discover

whether an appreciable reduction of the total contact pressure A, reflecting pore pressure dissipation, occurs during the test. This may occur in a relatively narrow subset of "niche silts" (Marchetti et al. 2001), for which the interpretation of soil parameters from DMT data would require specific corrections (Schnaid et al. 2018). The Medusa DMT may routinely perform short A-dissipations before recording each standard A-pressure reading, which is taken 15 s after reaching the test depth. In clays no appreciable pore pressure dissipation occurs in 15 s and the A-pressure readings remain nearly constant, indicating fully undrained conditions, while a substantial reduction of A in 15 s prompts for partial drainage.

- The use of the Medusa DMT for the characterization of intermediate soils (silty sands, silts, sandy silts) has been increasingly investigated in recent research (Schnaid et al. 2016, 2018, 2021). Preliminary results presented by Monaco et al. (2021) support the potential use of the Medusa DMT for performing dilatometer tests adopting variable pressurization rates, also combined with variable penetration rates, in intermediate soils. This potential descends from the highly accurate and repeatable time-for-reading facility provided by the instrument.
- The Medusa DMT may be used to obtain continuous measurements of the total horizontal pressure during penetration (equivalent A-reading at t = 0 instead of t = 15 s). These measurements could potentially provide more realistic estimates of the in-situ stress state and at-rest lateral earth pressure coefficient (K_0).
- The increased accuracy of pressure measurements and controlled pressurization rate provided by the Medusa DMT makes this instrument particularly useful for testing very soft or even nearly liquid soils, in which the measured pressures are typically very small. As an example, Marchetti et al. (2021) found, in an extremely soft soil site in Brazil, that the scatter in the difference ($p_1 - p_0$) observed using the traditional DMT equipment was largely reduced using the Medusa DMT.
- The technical features of the Medusa DMT are particularly suitable for testing soils which are usually difficult to characterize using common in situ techniques, such as mine tailings (Schnaid 2021).
- The seismic version of the Medusa DMT (Medusa SDMT), currently at the testing stage, will add the possibility of measuring the shear wave velocity V_S in addition to DMT measurements.

The main disadvantage of the Medusa DMT compared to the traditional pneumatic DMT configuration is the quantification of the cost in case of rupture of the rods and loss of the probe. A DMT blade is less expensive than a Medusa DMT. Additionally, the membrane replacement in the Medusa DMT is not straightforward as for a pneumatically operated blade, as the saturation of the liquid in the syringe and in the blade must be carefully accomplished.

11 Validation of the Medusa dilatometer test

11.1 Preliminary calibration chamber testing

Preliminary testing of the Medusa dilatometer in calibration chamber is described by Marchetti (2018). A simplified calibration chamber (Figure 11.1) was specifically designed and constructed for testing the Medusa DMT up to a maximum pressure of 25 MPa. The calibration chamber was filled mostly with water (≈ 90%) and the rest with air. A connection on the cap of the chamber was used to pressurize the chamber with gas. The cap of the calibration chamber was designed in order to allow to place the blade inside the chamber and all the other Medusa DMT components outside of the chamber.

The cabled version of the Medusa DMT was used to monitor the pressure applied to the membrane and its contact status with time. Figure 11.2 shows the timing diagram of a full DMT cycle performed by the Medusa DMT with the calibration chamber pressurized at about 450 kPa. In particular, Figure 11.2 shows, besides the measured pressures A, B, C, also some of the automation parameters recorded during the same test cycle, namely the DMT membrane contact status (ON/OFF) and the voltage/current provided to the engine.

Preliminary experimental results in the calibration chamber have shown high accuracy and repeatability of the pressure measurements in the order of ± 1 kPa.

Calibration chamber testing has also indicated that the A-pressure readings may be obtained in about 1-2 s from the start of the test cycle and B-pressure readings in about 4-5 s after A, independent of the pressure values and without loss in accuracy. Such rapid test execution facility may be particularly useful in intermediate soils, where partial drainage effects may be accounted for, e.g. by adopting a pressurization rate faster than the standard rate.

Figure 11.1. Calibration chamber used for preliminary tests on the Medusa DMT (Marchetti 2018)

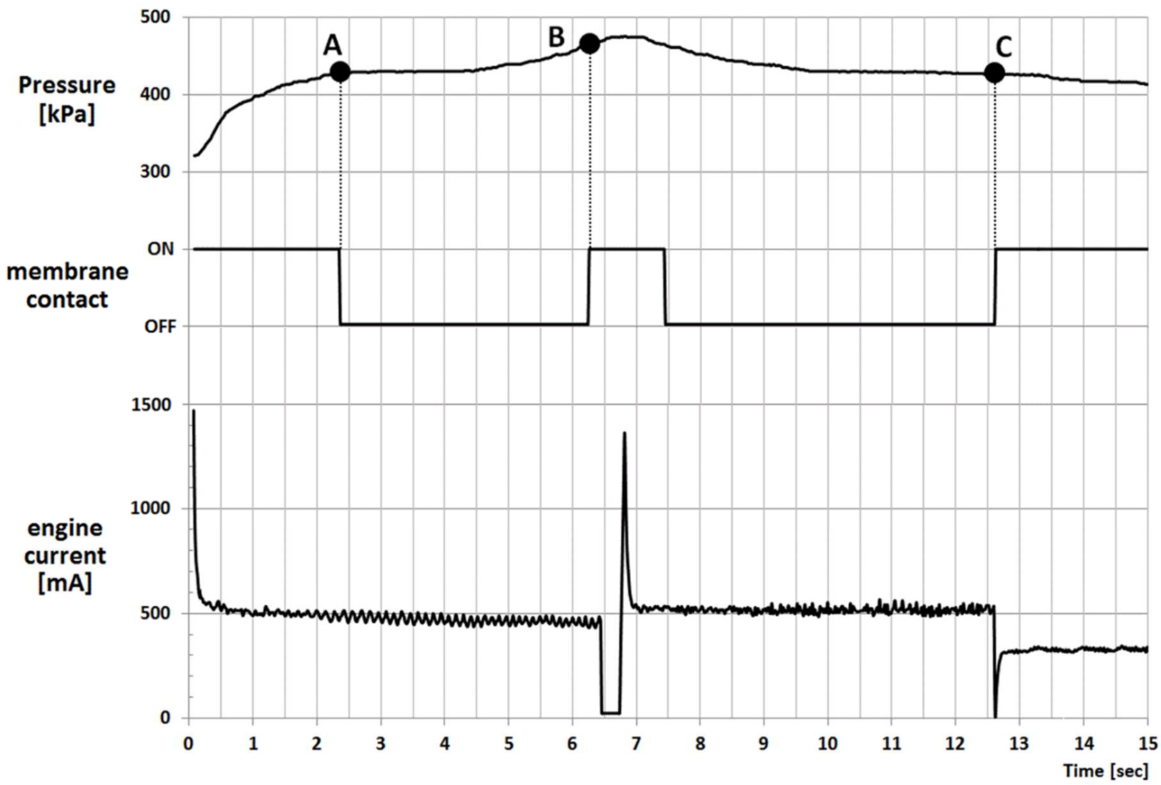


Figure 11.2. Diagram of pressure, membrane contact status and engine current versus time in a full DMT cycle using the Medusa DMT in the calibration chamber pressurized at about 450 kPa (Marchetti 2018)

Another information acquired during preliminary testing is that the limited amount of liquid that may be injected by the syringe prevents overinflation of the membrane, which may change the membrane calibration values or damage it permanently.

Additional experiments are necessary to evaluate if there is a reasonably accurate relation between the volume of the liquid injected by the syringe, inferred from the measured position of the syringe piston, and the membrane displacement during expansion. If such a relation were available, it would be possible to estimate the full load-displacement curve for each Medusa DMT test cycle.

11.2 <u>Preliminary field validation</u>

The first validation of the Medusa DMT in the field was carried out in 2016 at the test site of Cesano, Rome (Italy). The results obtained using the Medusa DMT were compared with the results obtained using the traditional pneumatic DMT equipment in an adjacent sounding (Marchetti 2018). A fairly good agreement was observed between parameters obtained from the interpretation of the parallel test data provided by the two instruments, using for both common DMT data reduction formulae and correlations (Marchetti 1980, Marchetti et al. 2001).

Additional measurements with the Medusa DMT were carried out at the same test site of Cesano in 2018, aimed at assessing the applicability of short *A*-dissipation tests carried out before expanding the membrane to the *B*-position.

Figure 11.3 (Marchetti et al. 2019) shows the results of a short *A*-dissipation test of duration about 120 s performed before the expansion of the membrane. In particular, Figure 11.3a shows the pressure readings versus time. The black line is the pressure applied by the motorized syringe to the membrane. Each blue dot superimposed on the black line in the first ≈ 120 s represents one *A*-pressure reading. After the initial *A*-dissipation the membrane is expanded to the *B*-pressure and then the system is deflated. The *C*-pressure reading is the last blue dot on the right of the graph.

The other graphs in Figure 11.3 show some of the automation parameters recorded during the same test cycle, namely the DMT membrane contact status ON/OFF (Figure 11.3b), the position of the piston of the motorized syringe (Figure 11.3c), and the voltage/current provided to the engine (Figure 11.3d). In the first 120 s the electronic board drives the syringe to take rapid consecutive *A*-readings. Figure 11.3b shows the corresponding oscillation of the membrane contact between ON and OFF. Each *A*-reading is taken in the transition from ON to OFF. Figure 11.3d shows the high reactivity of the engine driving the motorized syringe for the *A* repetitions. The constant value of the position of the syringe piston shown in Figure 11.3c clearly indicates that the membrane does not apply displacement to the soil during the short dissipation test of 120 s. Thus the recorded *A*-pressure readings represent the decay of the total horizontal soil pressure against the membrane.

Such decay curve is more clearly visible in Figure 11.4, where only the *A*-dissipation readings in the first ≈ 120 s are plotted versus time (same data as in Figure 11.3a, but plotted on an expanded vertical scale and a semilogarithmic horizontal scale). This plot format highlights the typical initial trend of an *A*-decay curve. The graph clearly shows that the dissipation was interrupted, although still in progress, indicating that the behaviour of the soil is partially drained.

The above experimentation at the site of Cesano, supplemented by additional testing at different sites, provided the basis for coding the DMT Repeated *A*-readings procedure (§ 6.4.2), including a short *A*-dissipation before expanding the membrane to the *B*-position, as an accepted routine test procedure.

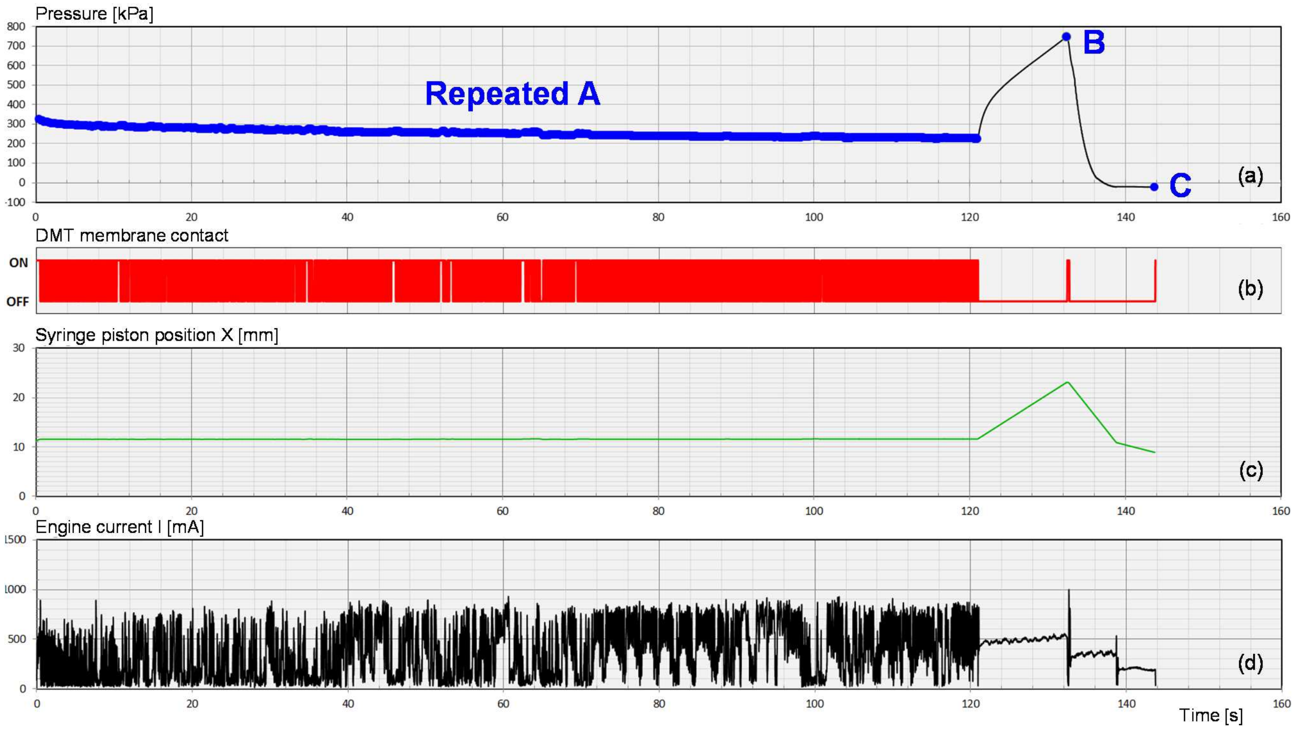


Figure 11.3. Results of a short *A*-dissipation test prior to membrane expansion obtained by Medusa DMT at the site of Cesano, Rome, Italy (Marchetti et al. 2019): (a) pressure and *A*, *B*, *C* readings, (b) membrane contact status, (c) syringe piston position, and (d) engine current. All data are plotted versus time (t = 0 when penetration stops and the test cycle begins).

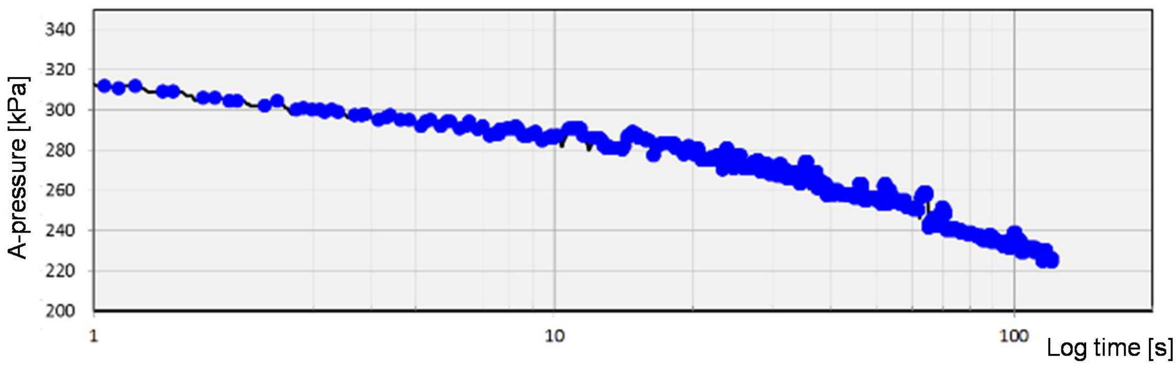


Figure 11.4. Detail of the *A*-pressure versus log time measurements during a short *A*-dissipation test prior to membrane expansion at the site of Cesano, Rome, Italy (same data as in Figure 11.3a, Marchetti et al. 2019)

12 Medusa DMT testing at the Fucino – Telespazio benchmark test site

In September 2020 a field testing campaign was carried out at the Fucino – Telespazio (Italy) test site, aimed to validate, compare and correct, if needed, the Medusa DMT test procedures to be included in this report.

The location of the test site was selected to ensure both relative simplicity of geotechnical conditions (i.e. relatively homogenous soil deposit) and ease of interpretation (i.e. pre-existing laboratory and field data). These conditions may be found in a variety of geotechnical testing sites available in Europe (as documented in the 1st International Symposium on GeoTest sites ISGTS, Oslo, 2019).

One suitable benchmark test site in Italy, meeting the above requirements and located only about 70 km far from L'Aquila, is the national research site of Fucino – Telespazio, which was selected for this field testing campaign. This well-documented research test site was extensively investigated at the end of the '80s by means of several in situ and laboratory tests carried out by various international research groups (Burghignoli et al. 1991). Earlier experimentation with the flat dilatometer at this site was reported by Marchetti (1980). Subsequently the same site was selected for testing with the seismic dilatometer (Foti et al.

2006, Marchetti et al. 2008). Medusa DMT testing at the same site ideally links past experience and recent technological developments.

The Fucino – Telespazio test site is constituted by a thick deposit of geologically normally consolidated, cemented, quite homogeneous soft lacustrine clay of high plasticity. Details on the site characterization, outside the scope of this report, may be found in the above referenced papers and in the available literature.

The experimental program at the Fucino – Telespazio test site, carried out in the week 22-25 September 2020, included one "traditional" pneumatic DMT sounding, carried out using the SDMT equipment (SDMT 1), and three Medusa DMT soundings (Medusa 1, Medusa 2, Medusa 3). All soundings were performed at close mutual distance and to a depth of 30 m.

The three Medusa DMT soundings were carried out using the three different test procedures described in § 6.4, which differ essentially for the technique adopted for measuring the *A*-pressure:

Medusa 1: Standard DMT procedure (STD) described in § 6.4.1, with *A*-pressure measured 15 s after start of pressurization

Medusa 2: DMT Repeated *A*-readings procedure (DMT-RA) described in § 6.4.2, with initial series of *A*-readings for T_{diss} = 15 s

Medusa 3: DMT *A*-reading while penetrating procedure (DMTA-WP) described in § 6.4.3, with continuous *A*-readings during penetration

The test results obtained from all soundings (SDMT 1, Medusa 1, Medusa 2, Medusa 3) were processed using the same data reduction formulae used for the traditional DMT test, summarized in Figure 8.1.

For the sounding Medusa 2 (DMT-RA), the *A*-pressure reading used in data processing is the last value obtained from the *A*-dissipation series, i.e. the *A*-pressure recorded 15 s after start of pressurization.

In the processing of data from all soundings the groundwater table was assumed at a depth z_w = 0.60 m below the ground surface, as indicated by the *C*-pressure readings performed in the very few thin sand layers.

Figure 12.1 shows the comparison of the results obtained by Medusa DMT using the three different test procedures and the results obtained by traditional DMT, in terms of depth profiles of the corrected *A*, *B*, *C* pressure readings p_0, p_1, p_2 (Figure 12.1a), the intermediate parameters I_D, U_D, K_D, E_D (Figure 12.1b) and the most significant interpreted parameters (*OCR*, K_0, s_u, *M*, Figure 12.1c) determined using the correlations listed in Figure 8.1.

The profiles of p_0 obtained by Medusa DMT using the three different test procedures (STD, DMT-RA, DMTA-WP) are very similar, despite the different techniques adopted for measuring the *A*-pressure, and in good agreement with the profile of p_0 obtained by traditional DMT.

The profiles of p_1 and p_2 obtained by Medusa DMT (all test procedures) and traditional DMT are nearly coincident. The values of p_1 and p_2 obtained by the DMTA-WP procedure are discontinuous, because in this case the *B* and *C* pressure readings are performed at depth intervals of 1 m, instead of 0.20 m as in the STD and DMT-RA procedures.

Among the intermediate and interpreted parameters, only the profiles of I_D and, to a lesser extent, E_D and *M*, i.e. the parameters depending on the difference ($p_1 - p_0$), show some inconsistency between the values obtained by different test procedures. In particular, the values of I_D calculated from p_0 and p_1 data acquired by the DMTA-WP procedure appear significantly lower than the I_D values provided by the STD and the DMT-RA procedures. This discrepancy could be due to the fact that in the DMTA-WP procedure the *A*-pressure is measured at t = 0 instead of t = 15 s, resulting in lower values of the difference ($p_1 - p_0$), and for low I_D values such incongruity is amplified by the logarithmic scale. The above issue requires additional insight.

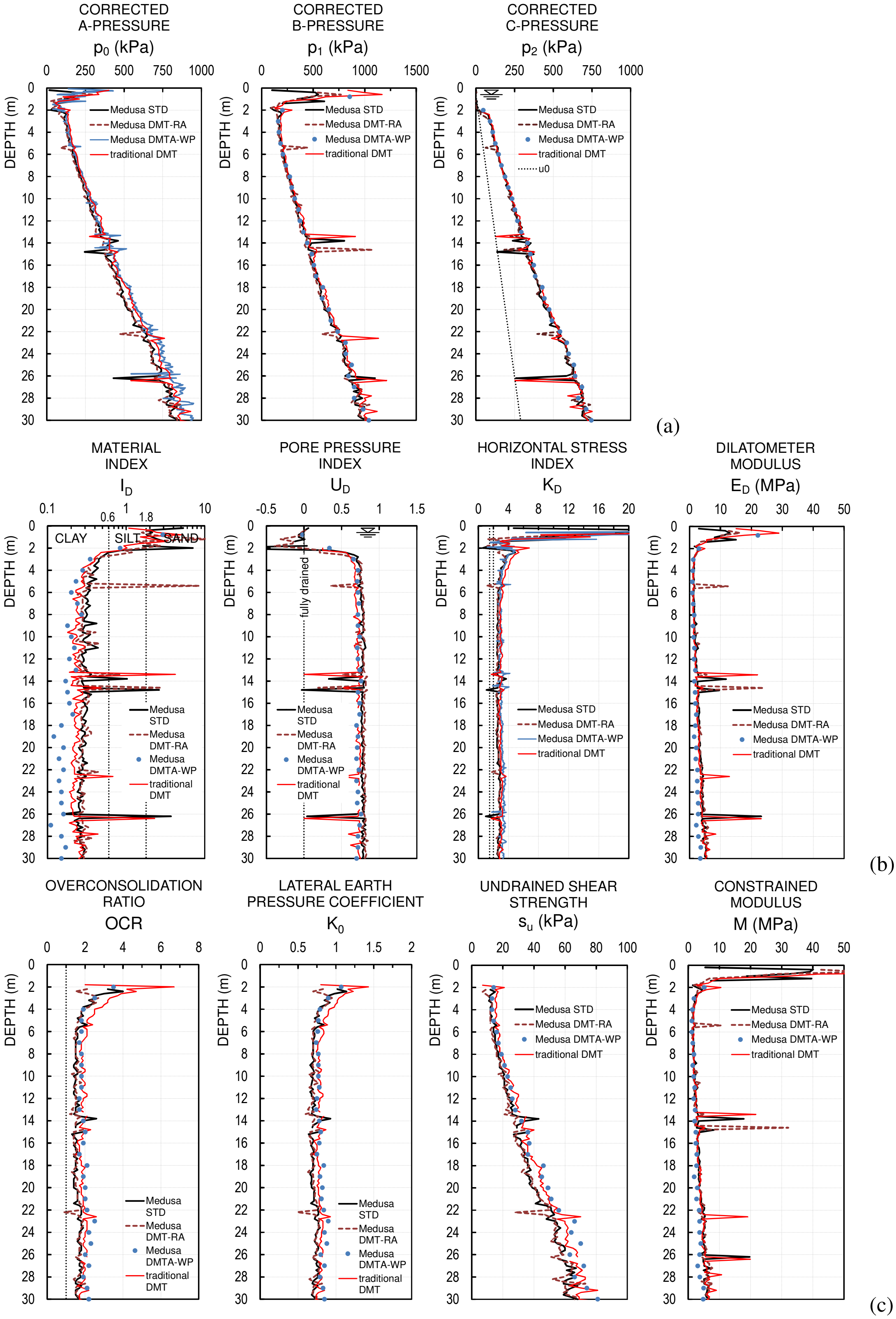


Figure 12.1. Comparison of results obtained by Medusa DMT using different test procedures and by traditional DMT at the research test site of Fucino – Telespazio (September 2020)

13 Concluding remarks

The Medusa DMT is a self-contained, fully automated probe able to autonomously perform standard dilatometer tests without the pneumatic cable, the control unit and the gas tank required in the traditional pneumatic DMT configuration. A motorized syringe, driven by an electronic board powered with rechargeable batteries, hydraulically expands the membrane to obtain the *A*, *B*, *C* pressure readings, which are acquired and stored automatically at each test depth.

The probe may operate in cableless mode, which is a significant practical advantage, especially in the offshore industry and for deep investigations. An optional electric cable may be used to obtain real-time data and for monitoring automation parameters during test execution.

The Medusa DMT automation setup implies several distinctive advantages over the traditional pneumatic equipment, both in terms of simplification of the probe and test procedure, and in terms of increased accuracy of the measurements.

Preliminary validations at different test sites, including the Fucino – Telespazio (Italy) benchmark test site, have indicated good agreement of the results provided by the Medusa DMT compared to the results obtained using the traditional pneumatic DMT equipment.

The Medusa DMT also provides the possibility of performing additional measurements, not feasible with the traditional pneumatic DMT equipment. One notable feature is the capability of measuring (virtually continuously) the total horizontal pressure against the membrane with time at a stationary test depth, to obtain information on soil response in terms of fully drained / partially drained / undrained behaviour, or during penetration of the probe, to obtain information on the in-situ stress state.

The increased accuracy of pressure measurements and controlled pressurization rate provided by the Medusa DMT makes this instrument particularly useful for testing soils which are usually difficult to characterize using common in situ techniques, such as very soft or even nearly liquid soils, mine tailings and intermediate soils (sandy silts to silty sands).

The seismic version of the instrument (Medusa SDMT), currently at the testing stage, will add the possibility of measuring the shear wave velocity V_S in addition to the DMT measurements, greatly enhancing the field of potential applications.

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