Use of Medusa DMT in alluvial silty sediments of the Po river valley

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ABSTRACT: This paper illustrates the results of flat dilatometer (DMT) and piezocone (CPTU) tests carried out to characterize the behavior of alluvial silty sediments of the Po river valley (Italy). Several tests were executed by use of the new Medusa DMT equipment, a self-contained cableless probe able to autonomously perform dilatometer tests using a blade of standard dimensions. The pressurization is applied using a hydraulic motorized syringe, which enables volume control during membrane expansion and permits to regulate accurately the timing to obtain the *A* and *B* pressure readings. Non-standard innovative testing procedures were applied in the intermediate soils. In particular, the Medusa DMT tests were executed adopting variable penetration rates combined with variable pressurization rates. The results illustrated in the paper support the potential of this approach for characterizing the in-situ behavior of intermediate soils.

Keywords: intermediate soils, flat dilatometer test, Medusa DMT, piezocone test, variable penetration rate

1. Introduction

Intermediate soils (silts, silty sands, sandy silts and other soil mixtures) are very commonly encountered either in natural depositional environment or as a result of man-made activity (hydraulic fills, dredging sediments, mine tailings). Due to the variability of their main properties, the experimental behavior of these soils is still relatively poorly understood and their characterization is a challenging issue, due to difficulties in undisturbed sampling, testing and interpretation of both laboratory and in situ experimental data. The existing interpretation approaches, typically developed for standard sands and clays, show severe limitations for practical applications when applied to such "non-standard geomaterials" [1].

Grain size characteristics of these sediments cause the permeability k to fall in the so-called intermediate range (i.e. 10^{-5} to 10^{-8} m/s), with significant implications on the in situ behavior at given loading rates. For example, well-known and widely-used site investigation techniques such as the cone/piezocone penetration test (CPT/CPTU) and the flat dilatometer test (DMT) are very likely to be affected by partial drainage effects, thus making unreliable the idealized assumption of a sharp distinction between drained (sands) and undrained (clays) testing conditions. Accordingly, the application of existing analytical or empirical correlations to field data can lead to unrealistic estimates of geotechnical properties.

This issue has been tackled mostly with reference to the interpretation of cone penetration tests. Research has shown that a proper analysis of field data for soil classification and mechanical characterization should rely on a preliminary assessment of the drainage conditions, as discussed by [1, 2] and many others, hence efforts have been made to identify probable consolidation patterns during cone penetration. In particular, following [3], piezocone tests carried out at non-standard penetration rates have been recognized as an effective way to analyze the effect of partial drainage on CPT/CPTU measurements and to detect the transition point from undrained to partially drained and drained responses [4].

Partial drainage effects during dilatometer testing have been so far generally disregarded, apart from very recent studies [5, 6]. Unlike CPT/CPTU measurements, partial drainage effects in DMT are related not only to blade penetration velocity, but also to the membrane inflation rate. According to the standard procedure, the first pressure reading *A* is obtained within about 15 s after stopping the blade at each depth, whilst the second pressure reading *B* is taken 15 s after *A*. Both *A* and *B* are total stress measurements, affected by generation and subsequent dissipation of excess pore pressure during penetration and before/during membrane expansion.

Assessment of drainage conditions from in situ tests would generally require pore pressures to be measured, which is not a standard practice in the DMT. Modified research DMTs have been developed in order to monitor the pore pressure, to evaluate rate effects during the test and thus to identify the soil classes where partial drainage may affect significantly DMT results [5]. Indeed, recent research has recognized that partial drainage may induce significant errors in the interpretation of DMT data in silts, but a systematic procedure to evaluate such effect on test results is far from being fully developed. A challenge for the standard DMT, not provided with a pore pressure transducer, is how to produce a unified interpretation criterion that allows drainage conditions to be identified or (even better) to be controlled.

This study illustrates the preliminary results of an in-situ investigation campaign in an intermediate soil deposit, comprising DMT measurements performed using both standard and non-standard test procedures (variable penetration rate and variable pressurization rate). These measurements were obtained by use of the newly developed Medusa DMT equipment (described in the following section), a self-contained cableless probe able to autonomously perform dilatometer measurements using a blade of standard dimensions. Hydraulic pressurization is achieved with a motorized syringe, which enables volume controlled expansion of the membrane and permits to regulate accurately the timing to obtain the *A* and *B* pressure readings. This capability appeared particularly valuable for the intended use of the instrument (performing dilatometer tests with variable pressurization rates) pursued in this study.

2. Medusa DMT equipment and test procedure

The Medusa DMT is the combination of the flat dilatometer with a hydraulic automation and measuring system for autonomously performing DMT tests [7]. Fig. 1 shows the main components of the instrument. A rechargeable battery pack powers an electronic board, connected to a pressure transducer and to a custom designed motorized syringe. The firmware coded in the electronics activates the motorized syringe for generating the pressure required to obtain the DMT readings. The maximum operating pressure is 25 MPa. A high accuracy pressure transducer is used to measure 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's firmware with the same criteria used for the traditional pneumatic DMT equipment.

When the Medusa DMT is operated cableless, a programmable period (T_{MCP}) determines when to start each measurement cycle. In the first part of the period, the *A*, *B*, *C* readings are taken and stored in the EPROM memory. The system will then stay in an idle state, waiting for the penetration to the next test depth. A typical period for T_{MCP} is of 1 minute, where the measurements are taken in the first 30 seconds and the device is idle in the remaining seconds for completing the period. During these additional 30 seconds the instrumentation is

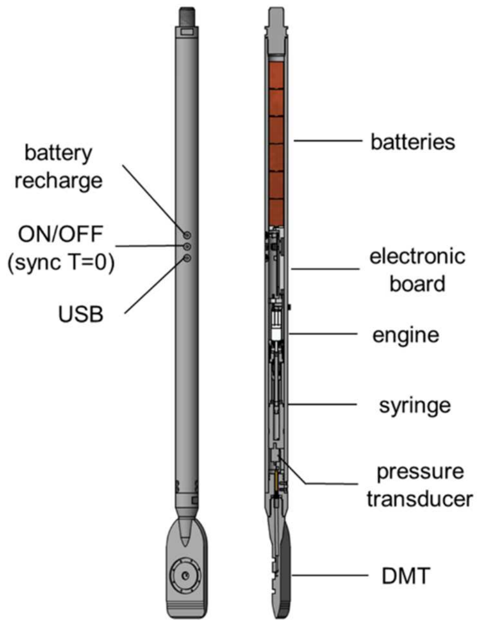

Figure 1. Main components of the Medusa DMT.

advanced to the next test depth. The time origin for the synchronization (T = 0) is set with the ON/OFF switch. The USB connection enables to program test parameters, such as T_{MCP}, and to download the data at the end of the test, when the probe is retrieved.

The Medusa DMT may also operate with an electric cable running from a computer laptop at ground surface down to the probe at depth. In this configuration, the operator may activate the measurement cycle from the computer as soon as the test depth is reached. During the cycle all automation parameters, such as the battery status, the voltage and current provided to the engine, the position of the piston of the motorized syringe, the probe inclination and other additional information, are available in real time. The DMT parameters, in particular the current pressure and membrane contact status, are displayed in real time during the measurement, as for the traditional DMT pneumatic technology.

In the standard DMT test procedure, the blade is advanced into the ground at a constant penetration rate (2 cm/s), the penetration is stopped at each test depth (typically every 0.20 m) and the membrane is inflated by use of gas pressure to take two pressure readings: (1) the *A*-pressure, required to just begin to move the membrane against the soil, and (2) the *B*-pressure, required to move the center of the membrane 1.1 mm against the soil. A third pressure reading, (3) the *C*-pressure, can optionally be taken by slowly deflating the membrane soon after *B* until it makes contact again with its seat.

Current DMT standards (ASTM D6635-15 [8], ISO 22476-11:2017(E) [9]) contain detailed specifications and acceptable tolerances concerning the pressurization rate for obtaining the *A* and *B* pressure readings. Such prescriptions are related to the gas compressibility, inherent in the traditional pneumatic DMT equipment. According to [9], the pressurization rate shall be such that the *A*-pressure reading is obtained within approximately 15 s after stopping the blade at each test depth and the *B*-pressure reading (expansion from *A* to *B*) within approximately 15 s after the *A*-reading. As a consequence, the rate of pressure increase is very slow in weak soils and faster in stiff soils. The C-reading is obtained within approximately 30 s after the B-reading.

For the Medusa DMT the firmware embedded in the electronic board implements the procedure for inflating and deflating the DMT membrane. The hydraulic pressurization of the motorized syringe actuates a volume controlled expansion of the membrane, which enables to impose a programmable timing for achieving the readings. Therefore the Medusa DMT is capable to perform dilatometer tests with the recommended timing suggested in the international standards. At the same time, the highly accurate and repeatable time-for-reading facility provided by the instrument prompts for its potential use for performing dilatometer tests adopting variable pressurization rates in intermediate soils.

The motorized syringe, controlled by the electronic board, is also able to maintain the membrane in equilibrium with negligible displacements of the membrane. This capability enables to obtain continuous measurements of the total horizontal pressure of the soil against the membrane. The Medusa DMT may then be used to obtain continuous measurements of the total horizontal pressure during penetration (equivalent A-reading at T = 0 seconds instead of T = 15 seconds), thus providing useful indications for the assessment of the in-situ stress state and the at-rest lateral earth pressure coefficient (K_0).

As in the standard pneumatic DMT, the A, B, C readings must be corrected with the calibration offsets ΔA and ΔB to obtain p_0, p_1, p_2, respectively [10]. All subsequent steps of data processing and interpretation of soil parameters, based on the corrected pressures p_0, p_1, p_2, are the same as for the traditional pneumatic DMT equipment.

Details on calibration chamber and field validation of the Medusa DMT can be found in [7] and [11].

The Medusa DMT has several 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 [11]. The major advantages are listed here below.

(a) 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 gas tank, the control unit and the pneumatic cables are no longer required.

(b) 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.

(c) The pressure is generated and measured locally at depth, not at ground surface. This eliminates any possible problem of pressure equalization along the pneumatic cable of the traditional equipment.

(d) The pressurization rate of the membrane is independent of the operator. The automatic (volume controlled) procedure of membrane pressurization operated by the motorized syringe is highly repeatable and capable to impose the correct timing to obtain the A and B pressure readings, strictly according to the specifications of the international standards or any other required timing.

(e) The capability of the Medusa DMT of measuring (virtually continuously) the total horizontal pressure against the membrane with time enables new research possibilities.

(f) Short A-dissipations, consisting in repeated A-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 [12, 13]. The duration of such short A-dissipations (much shorter than conventional DMT-A 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. The Medusa DMT permits to execute routinely short A-dissipations before recording each standard A-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-readings remain nearly constant, indicating fully undrained conditions, while a substantial reduction of A in 15 s prompts for partial drainage.

3. Test site

A test site located near Bondeno (Ferrara, Italy) was selected as relevant for investigating intermediate soil behavior and in situ partial drainage effects.

The site is located in an area which in May 2012 was strongly affected by a seismic sequence culminated in two main shocks, occurred on May 20th (M_w 5.8) and May 29th (M_w 5.6), with epicenters located at about 15 km and 24 km respectively from the test site. Both main shocks induced important secondary effects at the surface over the entire area, such as widespread liquefaction, revealed by sand boils and ground failures, associated with extensive ground deformations.

Subsequently, several in-depth investigation campaigns were carried out in the area. Among them, it is worth mentioning the experimental programme implemented in the neighboring riverbank of the Canale Diversivo di Burana, located in Bondeno, which was extensively investigated through boreholes, piezocone and seismic dilatometer tests, static and dynamic laboratory tests [14, 15, 16, 17]. This wide and varied testing programme revealed a widespread presence of mixed soils in the shallow subsoil layers. Indeed, the riverbank system was found to consist of alternating sands, silty sands and sandy silts, partly forming the artificial bank and partly referable to flood plain environment; these sediments exhibit an intermediate mechanical response and presumably experienced liquefaction during the 2012 earthquake. Further, following the ongoing seismic microzonation studies of Bondeno municipality, [18] performed a seismic dilatometer test with the acquisition of both P-wave and S-wave velocities to study soil deposits related to the hydrographic evolution of the Po river and its Apennine tributaries, such as the Panaro river. More recently, an extensive and varied set of site investigations was carried out at a nearby site for a large full-scale blast test experimental program, as described in detail by [19].

The results of in situ and laboratory tests available from previous independent investigations carried out at neighboring sites were used as a helpful starting point for selecting the test site and planning the in situ testing program for this study.

As commonly found in the area, the selected test site is characterized by the presence of alluvial silty sediments of the Po river valley, including intermediate soil deposits containing non-plastic fines.

Details on the geological setting of the area can be found in [20, 21]. The sedimentary units accumulated during the late Pleistocene and Holocene. Several generations of fluvial channel deposits were fed from the south by the Apennine streams and from the west by the Po river. The fluvial sediments belong to different depositional environments and ages. Surface manifestations of liquefaction triggered by the May 2012 earthquakes (sand boils) occurred along paleochannel deposits.

The soil profile basically includes an upper unit, about 9 m thick, composed of clays and silts followed by sandy silts, and a lower unit consisting of medium-grained sands and silty sands, about 20 m thick.

In this study, attention is focused on the topmost 5 m of the soil profile. The piezocone profiles of Fig. 2, obtained from a test carried out in the study area at a standard rate of penetration (20 mm/s), detail the following stratigraphic arrangement (from top to bottom):

– top soil from the ground surface to about 0.8 m;
– silts from 0.8 to 3.6 m;
– silty sands below 3.6 m

The groundwater table is found at about 0.4 m below the ground surface.

The application to CPTU data of the classification method developed by [22] reveals a pronounced intermediate nature of the sediments between 0.8 and 3.6 m in depth. Fig. 3 shows indeed that most of the experimental points fall in the domains of silts (1a) and transitional soils (3), the latter including a wide variety of soil mixtures (i.e. clayey sands, silty sands, silty sands with clay, clayey sands with silt). In these soils, partial drainage is very likely to occur during cone penetration. At the same time, soils below 3.6 m are classified as "essentially drained sands" (domain no. 2), apart from a few points corresponding to a pronounced dilative behavior.

4. Medusa DMT testing program

The in situ testing program at the selected site aimed to characterize the behavior of the intermediate soils found at shallow depths by use of Medusa DMT and CPTU, adopting non-standard innovative testing procedures.

A series of Medusa DMT tests was carried out by the standard procedure and by varying penetration rate, membrane inflation rate and time delay before membrane expansion. In particular, the Medusa DMT tests were executed both using the standard procedure and adopting variable penetration rates (slower and faster than standard), combined with variable pressurization rates (slower and faster than standard) achieved by regulating different time-for-reading intervals after stopping the blade at the test depth. Parallel CPTUs at different penetration rates were also carried out, in order to identify the consolidation trend of the upper 3.6 m subsoil and possibly the actual drainage degree during standard tests. However, the detailed analysis of this CPTU database is outside the scope of this article.

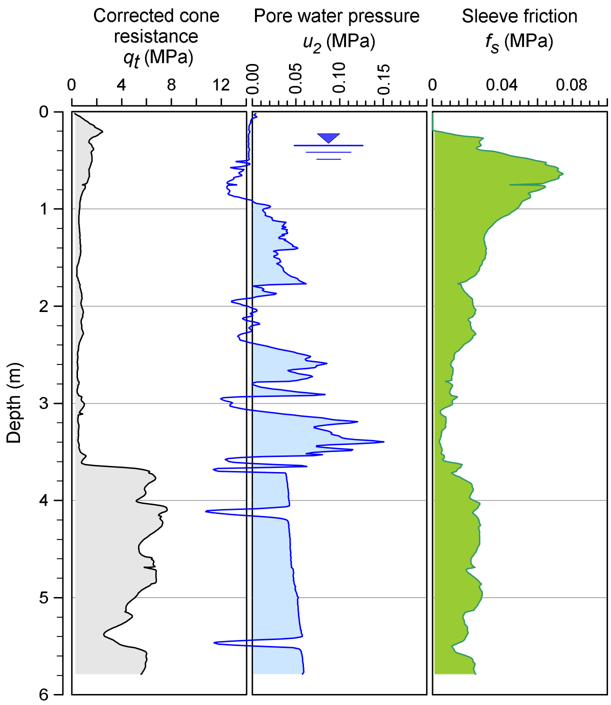

Figure 2. Log profile of a representative standard-rate CPTU.

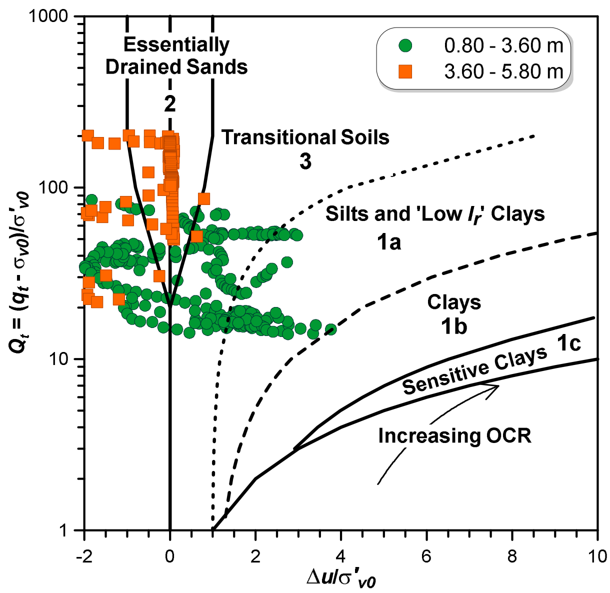

Figure 3. Classification results using the Schneider et al. (2008) [22] chart.

Since the aim of the testing program was to investigate the behavior of the shallow intermediate soil sediments, the maximum test depth was limited to about 5 m below the ground surface. The distance between the soundings varied between about 1.5 m and 4 m. Details on the Medusa DMT testing program are summarized in Table 1.

The first sounding (DMT 1), with standard penetration rate (2 cm/s) and standard timing for DMT readings, was carried out using the "traditional" procedure, in which the *A*-reading is taken when the membrane is expanded horizontally 0.05 mm against the soil, by continuously adjusting the pressurization rate to obtain the *A*-reading about 15 s after stopping the blade at the test depth and then the *B*-reading about 15 s after *A*.

Table 1. Summary of variable rate Medusa DMT testing program

Test ID	Depth (m)	Test type	Penetration rate (cm/s)	Time to *A*-reading after stop (s)	Time to *B*-reading after *A* (s)	*A*-reading procedure
DMT 1	5.20	standard	2	15	15	traditional
DMT 2	5.20	slow rate	0.2	15	15	modified
DMT 3	5.20	slow rate/slow press	0.2	30	30	modified
DMT 4	5.20	fast rate	6	15	15	modified
DMT 5	5.20	fast rate/fast press	6	7.5	7.5	modified
DMT 6	5.00	standard	2	15	15	modified

The subsequent soundings, both "slow" (DMT 2, DMT 3) and "fast" (DMT 4, DMT 5), were carried out by using a different, recently developed "modified" procedure for obtaining the *A*-reading, which consists of performing a timed series of *A*-readings while the membrane is maintained in equilibrium with negligible horizontal displacement. This procedure allows a more accurate control on the selected timing for the *A*-reading, improved repeatability of the measurements and faster test execution. The procedure for the *B*-reading remains unchanged.

An additional sounding (DMT 6) with standard penetration rate and standard timing for DMT readings was finally carried out with the "modified" *A*-procedure, at about 1.5 m distance from the corresponding sounding (DMT 1) performed with the "traditional" procedure. The results of DMT 1 and DMT 6 were compared to evaluate the influence on the measurements of the procedure adopted for obtaining the *A*-readings. The comparison indicated that the results obtained by the "traditional" and "modified" procedure are substantially the same. Therefore in this study, in order to assess the response of the intermediate soils to variable rate testing conditions, DMT 6 was adopted as the reference standard test for comparing the "slow" (DMT 2, DMT 3) and "fast" (DMT 4, DMT 5) tests carried out with the same "modified" *A*-procedure.

5. Results and discussion

The results obtained from the variable rate Medusa DMT testing program are summarized in Figs 4, 5, 6 and 7, in terms of profiles with depth of the three corrected DMT pressure readings p_0, p_1, p_2, as well as of the material index I_D and the pore pressure index U_D obtained using common interpretation formulae [10].

To investigate the effect of the penetration rate alone, Fig. 4 shows the comparison of the results obtained from tests carried out by varying only the penetration rate (standard 2 cm/s in DMT 6, "slow" 0.2 cm/s in DMT 2, "fast" 6 cm/s in DMT 4) and maintaining the standard pressurization rate (*A*-reading at 15 s after stop, *B*-reading at 15 s after *A*).

Fig. 4 shows that the values of p_0 and p_1 obtained using different penetration rates in silts, down to 3.6 m depth, are substantially similar. Nevertheless some differences can be noticed, especially between 0.8 and 2 m: p_0, and to a lesser extent p_1, obtained from DMT 2 using a slow penetration rate (0.2 cm/s) are slightly lower than the corresponding values obtained from DMT 6 using the standard penetration rate (2 cm/s), while p_0 and p_1 obtained from DMT 4 using a fast penetration rate (6 cm/s) are slightly higher than the standard DMT 6 values. This trend can be explained considering that p_0 is a total pressure, which in fine-grained soils incorporates the excess pore pressure Δu induced by blade penetration: as expected, the higher the penetration rate, the higher will be Δu, hence p_0. The pressure p_1, obtained 15 s after p_0 by expanding the membrane, is reasonably less influenced by Δu induced by penetration.

Also the trend of the p_2 values in silts supports this explanation. In fact, as discussed by [10], it is known that in sand p_2 closely approximates the in-situ equilibrium pore pressure u_0, while in clay $p_2 > u_0$ due to Δu induced by blade penetration. As shown in Fig. 4, in comparison to the p_2 obtained at the standard 2 cm/s penetration rate, the p_2 obtained at 0.2 cm/s penetration rate are lower, reflecting lower Δu induced by slower penetration, while the p_2 obtained at 6 cm/s penetration rate are higher, reflecting higher Δu induced by faster penetration.

In the sand below 3.6 m depth the p_0 and p_1 obtained at different penetration rates show a large variability, with no clearly detectable trend, in apparent contrast with the expected behavior. It must be noted, however, that the corresponding values of p_2 remain substantially unchanged and close to u_0, indicating fully drained response. Considering this aspect, based also on available knowledge of this sand deposit from nearby investigations, it is presumed that the variability of p_0 and p_1 in sand does not depend on the penetration rate, but on the variability of the sand properties, even within a short distance. Differently, the silts above 3.6 m depth appear fairly homogeneous, therefore some trends can be identified in response to the different test rate.

Besides the variation of the DMT pressure readings p_0, p_1, p_2, it is also helpful to inspect their combination in terms of material index I_D and pore pressure index U_D. The material index I_D is an indicator of soil type (clay, silt, sand), while the pore pressure index U_D can help discern between drained, undrained or partially drained soil behavior [10]. The trends in the silt (above 3.6 m depth) appear realistic:

– the slower the penetration rate, the more "drained" the test, with lower p_2 and U_D (moving to the left towards the "fully drained" $U_D = 0$ vertical line); accordingly, I_D moves to the right towards the "sand" region;
– vice versa, the faster the penetration rate, the more "undrained" the test, with higher p_2 and U_D (moving to the right away from the "fully drained" $U_D = 0$ vertical line); accordingly, I_D moves to the left towards the "clay" region.

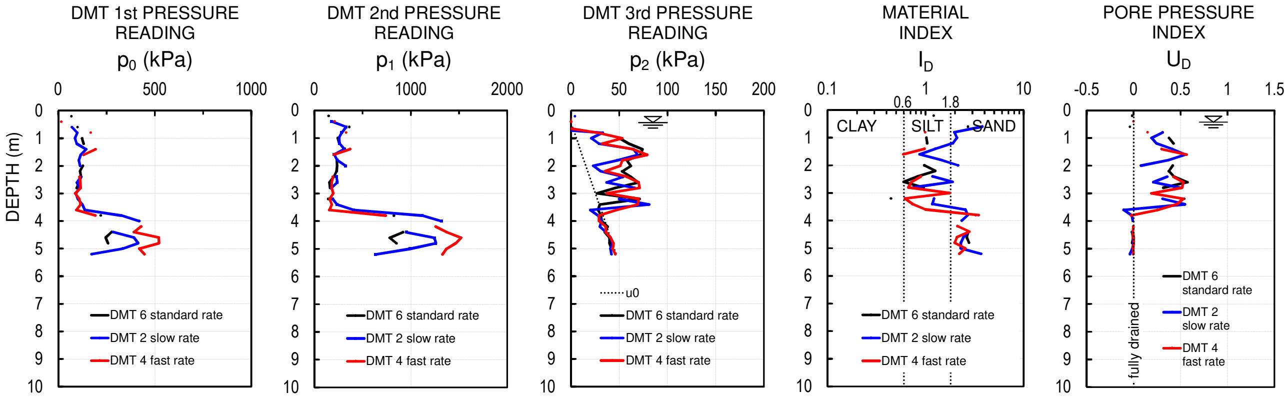

Figure 4. Effect of variable penetration rate on Medusa DMT results (standard pressurization rate).

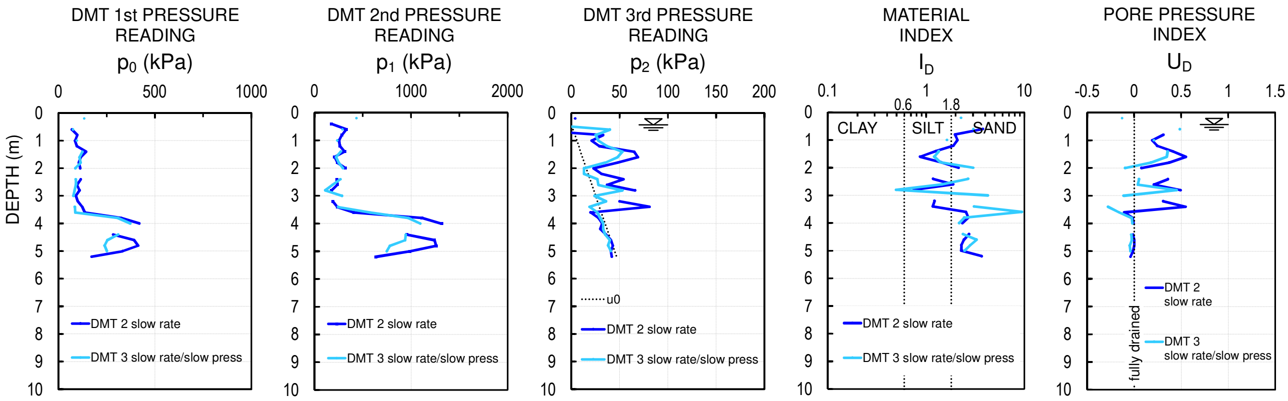

Figure 5. Effect of variable pressurization rate on Medusa DMT results (slow penetration rate).

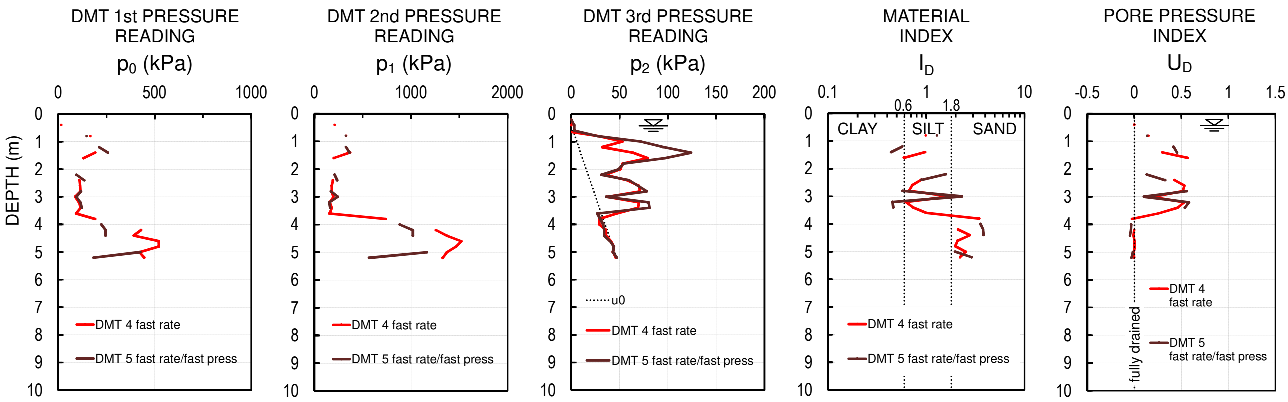

Figure 6. Effect of variable pressurization rate on Medusa DMT results (fast penetration rate).

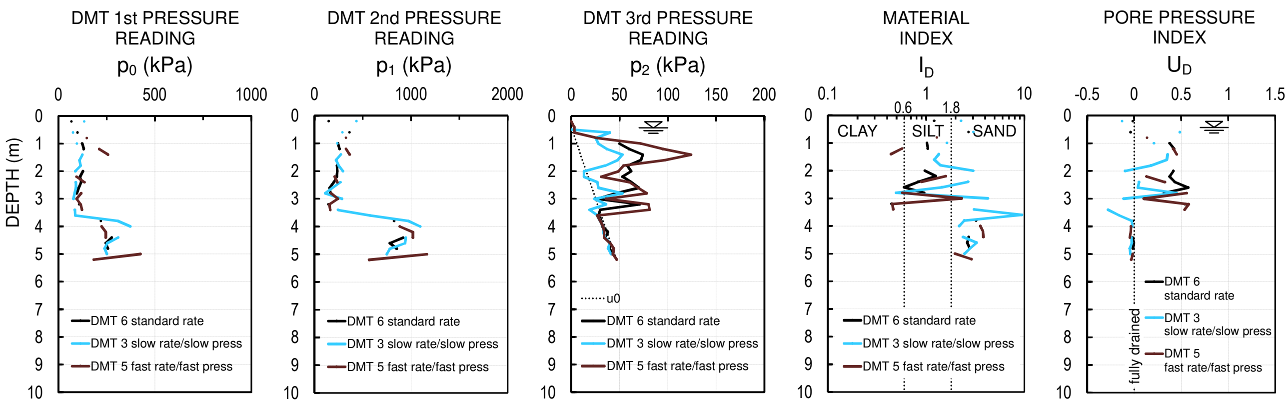

Figure 7. Combined effects of variable penetration rate and variable pressurization rate on Medusa DMT results.

In the sand (below 3.6 m depth) I_D shows some minor variation (attributed to soil variability), while U_D remains always ≈ 0, indicating correctly "fully drained" behavior for any penetration rate.

To investigate the effect of the pressurization rate alone, Fig. 5 and Fig. 6 show the comparison of the results obtained from tests carried out by varying only the pressurization rate, maintaining the same penetration rate ("slow" or "fast", respectively).

Fig. 5 compares the results obtained from the two soundings carried out at the same "slow" penetration rate (0.2 cm/s), DMT 2 at standard pressurization rate (*A*-reading 15 s after stop, *B*-reading 15 s after *A*) and DMT 3 at slow pressurization rate (*A*-reading 30 s after stop, *B*-reading 30 s after *A*). Fig. 5 shows that the values of p_0 obtained from DMT 3 using a slower pressurization rate (half than standard) are slightly lower than the corresponding values obtained from DMT 2 using the standard pressurization rate, while the p_1 are substantially unchanged. This trend can be explained considering that in fine-grained soils a slower pressurization rate should reduce the amount of generated excess pore pressure Δu, thus reducing the measured total pressure p_0: the slower the pressurization rate, the lower will be Δu, hence p_0. The pressure p_1 is less influenced by Δu. The trend of the p_2 values in silts supports this explanation: the slower the pressurization rate, the more "drained" the test, with lower p_2 and U_D (moving to the left towards the "fully drained" $U_D = 0$ vertical line); accordingly, I_D moves to the right towards the "sand" region.

Fig. 6 compares the results obtained from the two soundings carried out at the same "fast" penetration rate (6 cm/s), DMT 4 at standard pressurization rate (*A*-reading 15 s after stop, *B*-reading 15 s after *A*) and DMT 5 at fast pressurization rate (*A*-reading 7.5 s after stop, *B*-reading 7.5 s after *A*). Fig. 6 shows that the values of p_0 and p_1 obtained from DMT 5 using a faster pressurization rate (double than standard) are nearly coincident with the corresponding values obtained from DMT 4 using the standard pressurization rate. In this case, it appears then that the influence on p_0 and p_1 of the pressurization rate, combined with "fast" penetration rate, is limited. A noticeable influence instead can be observed in the p_2 values in silts, especially at depths between 1 and 1.8 m, where p_2 obtained at a faster pressurization rate is higher than p_2 obtained at the standard pressurization rate (in agreement with a small p_0 increment in the same depth interval). Here the trend is that, the faster the pressurization rate, the more "undrained" the test, with higher p_2 and U_D (moving to the right away from the "fully drained" $U_D = 0$ vertical line); accordingly, I_D moves to the left towards the "clay" region.

In both Fig. 5 and Fig. 6, again, in the sand below 3.6 m depth the p_0 and p_1 obtained at different pressurization rates, for the same "slow" and "fast" penetration rates respectively, show a large variability, while the corresponding values of p_2 remain substantially unchanged and close to u_0, indicating fully drained response. Accordingly, U_D remains always ≈ 0, indicating correctly "fully drained" behavior for any pressurization rate, while I_D shows some minor variation. As previously observed for the variable penetration rate test results (Fig. 4), it is presumed that the variability of p_0 and p_1 in sand in Figs 5 and 6 does not depend on the pressurization rate, but on the variability of the sand properties.

Fig. 7 summarizes the combined effects of both variable penetration rate and variable pressurization rate. The results obtained from the reference standard DMT 6 (standard penetration rate 2 cm/s, standard pressurization rate *A*-reading 15 s after stop, *B*-reading 15 s after *A*) are compared with the "slowest" DMT 3 (slow penetration rate 0.2 cm/s, slow pressurization rate *A*-reading 30 s after stop, *B*-reading 30 s after *A*) and the "fastest" DMT 5 (fast penetration rate 6 cm/s, fast pressurization rate *A*-reading 7.5 s after stop, *B*-reading 7.5 s after *A*).

Fig. 7 confirms even more evidently the trends observed in silts (above 3.6 m depth):

- the slower the penetration and pressurization rate, the more "drained" the test, with lower p_2 and U_D (moving to the left towards the "fully drained" $U_D = 0$ vertical line); accordingly, I_D moves to the right towards the "sand" region;
- the faster the penetration and pressurization rate, the more "undrained" the test, with higher p_2 and U_D (moving to the right away from the "fully drained" $U_D = 0$ vertical line); accordingly, I_D moves to the left towards the "clay" region.

This finding reinforces the use of the pore pressure index U_D to discern between drained, undrained or partially drained soil behavior. Additional support is provided to viewing the material index I_D, introduced as an indicator of soil type (clay, silt, sand), as a parameter which broadly reflects some "soil behavior type", including "sand-like" or "clay-like" behavior of intermediate soils.

In Fig. 7 in the sand below 3.6 m of depth the p_0 and p_1 obtained at different penetration and pressurization rates show a large variability, while the corresponding values of p_2 remain substantially unchanged and close to u_0, indicating fully drained response. Accordingly, U_D remains always ≈ 0, indicating correctly "fully drained" behavior for any penetration and pressurization rate. The I_D values show some minor variation, but always within the "sand" region. Fig. 7 supports further the assumption that the variability of p_0 and p_1 in sand does not depend on the variable penetration and pressurization rates, but on the variability of the sand properties within the test area.

6. Conclusions

The preliminary results presented in this paper support the potential use of the Medusa DMT for performing dilatometer tests adopting variable pressurization rates in intermediate soils. This potential descends from the highly accurate and repeatable time-for-reading facility provided by the instrument.

The results obtained at the selected test site indicate that, in intermediate silts, it is possible to identify some trends in the variation of the DMT measurements, in particular p_2 and the derived pore pressure index U_D, in response to variable-rate testing conditions. In fact, a slower (than standard) penetration and/or pressurization rate "shifts" the interpretation towards drained behavior, while a faster (than standard) penetration and/or pressurization rate "shifts" the interpretation towards undrained behavior. In sand p_2 and U_D remain substantially unchanged, indicating fully drained response for any penetration and/or pressurization rate.

Future developments of the research will include the comparison of the results obtained by Medusa DMT at variable penetration and pressurization rates with the results obtained from parallel CPTUs carried out at variable penetration rates. This comparison will permit to improve the interpretation of CPTU and DMT in intermediate soils, in order to better capture the main soil behavior features. In perspective, the combination of variable-rate DMT and CPTU tests could be viewed as a promising innovative approach for characterizing the in-situ behavior of intermediate soils.

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