Potential of the Medusa DMT for offshore geotechnical investigation

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ABSTRACT: The Medusa DMT is the newest fully automated version of the flat dilatometer popularly used in soil investigation. The Medusa DMT can operate autonomously without the traditional control unit, the gas tank and the pneumatic cable which is an advantage for offshore testing. The seismic version (Medusa SDMT) incorporates additional sensors for measuring the shear wave velocity. Due to improved accuracy in pressure measurements and controlled pressurization rate, the Medusa DMT is useful for testing soils frequently encountered in coastal and nearshore/offshore environments. This paper presents early findings obtained from field tests carried out in Norway at two benchmark Geo-Test Sites, Onsøy (soft clay) and Halden (silt), managed by the Norwegian Geotechnical Institute. The soils at these sites, though onshore, have marine origins and resemble the offshore soil conditions at several oil/gas fields in the North Sea. The findings shed light on the potential use of the Medusa DMT for offshore investigation.

1 Introduction

Offshore soil investigation requires robust, effective and (preferably) automated equipment due to challenging conditions. In this respect, the recently developed Medusa DMT offers promising potential as an innovative in-situ testing technology. The Medusa DMT was originally conceived for offshore testing (Marchetti, 2018), although so far it has been mostly used in onshore investigations.

The Medusa DMT is the fully automated version of the flat dilatometer (DMT), able to operate autonomously without the traditional control unit, the gas tank, and the pneumatic cable. The probe offers a significant advantage for deep (> 1000 m) offshore testing as it can operate cableless. Real-time data during test execution can still be obtained with the use of an electric cable. The seismic Medusa SDMT, which incorporates additional sensors for measuring the shear wave velocity, has already been employed (with electric cable) for testing in nearshore conditions at Vado Ligure, Italy, and in the water storage reservoir Raggal, Austria (Oberhollenzer et al., 2022).

Due to improved accuracy in pressure measurements and controlled pressurization rate, the Medusa DMT is useful for testing soils frequently encountered in coastal and nearshore/offshore environments.

This paper presents early findings obtained from Medusa SDMT tests performed in soft clays and silts through the Transnational Access project – JELLYFISh funded by H2020-GEOLAB (Monaco et al., 2023a). The tests were carried out in Norway at two well-known benchmark Geo-Test Sites, Onsøy (soft clay) and Halden (silt), part of the NGTS research infrastructure managed by the Norwegian Geotechnical Institute (NGI) (L'Heureux and Lunne, 2020). In this study, the field tests were performed at these onshore controlled environments to simplify the testing parameters and conditions and obtain basis information for subsequent planning of offshore testing. The soils at these benchmark sites, though onshore, have marine origins and resemble the offshore soil conditions at several oil/gas fields in the North Sea. The results provided by Medusa SDMT are compared to data obtained using the traditional pneumatic seismic dilatometer (SDMT), available from previous investigations. The preliminary findings obtained from this campaign shed light on the potential use of the Medusa DMT for offshore investigation.

2 Medusa DMT: equipment, test procedure and interpretation

The Medusa DMT (Marchetti, 2018; Marchetti et al., 2019) is a self-contained probe able to perform dilatometer tests using a standard blade without the pneumatic cable, the control unit and the gas tank required in the traditional pneumatic DMT. The main components are illustrated in Figure 1. A motorized syringe, driven by an electronic board powered with rechargeable batteries, hydraulically expands the membrane to obtain the DMT *A*, *B*, *C* pressure readings, which are acquired and stored automatically at each test depth (typically every 0.20 m). The automatic volume-controlled hydraulic pressurization of the membrane is highly repeatable and permits to impose a programmable timing (i.e., the recommended standard timing, or different timing corresponding to variable pressurization rates) to obtain the pressure readings. The probe can operate in cableless mode, which is a significant practical advantage in the offshore industry, and in general when performing deep investigations. An optional electric cable may be used to obtain real-time data during test execution.

The Medusa SDMT incorporates additional sensors and components for the measurement of the shear wave velocity V_S (Figure 1) in addition to the DMT measurements. The test procedure and interpretation for obtaining V_S measurements using the Medusa SDMT are the same as for the traditional SDMT (Marchetti et al., 2008).

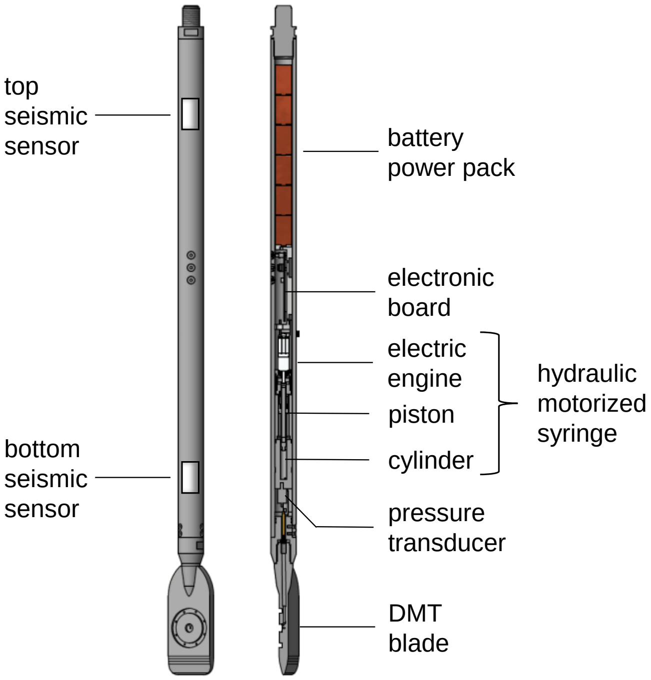

Figure 1. Medusa SDMT equipment

The standard Medusa DMT test procedure is the same as for the traditional pneumatic DMT (ASTM D6635-15; ISO 22476-11:2017(E)), using an internal automated pressurization system instead of an external manually operated pressure source and regulation system. After reaching the test depth, the penetration is stopped, and the dilatometer test cycle starts. The activated motorized syringe gradually increases the hydraulic pressure on 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 centre has expanded 0.05 mm against the soil, the *A*-pressure is recorded. After the *A*-reading, the motorized syringe continues to increase the pressure until the membrane has displaced 1.10 mm from its original position at the centre. At this instant, the second pressure reading *B* is recorded. The pressurization rate is regulated by the motorized syringe so that the *A*-pressure reading is obtained 15 s after start of pressurization and the *B*-pressure reading 15 s after the *A*-pressure reading, i.e., the timing prescribed by existing standards of the traditional pneumatic DMT (ASTM D6635-15; ISO 22476-11:2017(E)). As soon as the *B*-reading is obtained, the motorized syringe starts decreasing the oil pressure. If the *C*-pressure reading (optional) is required, the motorized syringe gradually applies a controlled depressurization after the *B*-reading and the membrane slowly returns to its initial position against the sensing disc. The *C*-reading is recorded as soon as the contact between the membrane and the sensing disc is reactivated.

Besides the standard procedure, the Medusa DMT permits to implement innovative non-standard test procedures and to perform additional measurements, which are not feasible with traditional pneumatic equipment. Two alternative procedures, i.e., the repeated *A*-readings procedure and the *A*-reading while penetrating procedure, differ from the standard procedure mainly in the technique used for acquiring the *A*-pressure readings. Details on these improvements can be found in Monaco et al. (2022) and Marchetti et al. (2022). Moreover, the highly accurate and repeatable time-for-reading setting facility provided by the Medusa DMT prompts for its use for performing dilatometer tests adopting variable pressurization rates (i.e., slower or faster than standard), also in combination with variable penetration rates. Variable-rate Medusa DMT testing can be useful to investigate intermediate soils such as silts, silty sands, sandy silts, clayey silts and other soil mixtures (Monaco et al., 2021).

The results presented in this paper were obtained at the Onsøy and Halden test sites using the Medusa SDMT equipment. In the following, the soundings are referred to as ‘Medusa SDMT’ when V_S measurements were taken, and as ‘Medusa DMT’ when the V_S was not measured. This study focuses on comparing the results obtained by Medusa SDMT and by traditional SDMT obtained in earlier investigations. For consistency, only the results obtained by the same standard test procedure are compared and discussed further in this paper.

The test results obtained by Medusa SDMT were processed using the same data reduction and interpretation formulae used for the traditional DMT test (Marchetti, 1980; Marchetti et al., 2001). The pressures *A*, *B*, *C* were converted into corrected pressures p_0, p_1, p_2 respectively by a calibration procedure to account for membrane stiffness. The corrected pressures were used to calculate four intermediate parameters, i.e., the material index I_D, the pore pressure index U_D, the horizontal stress index K_D, and the dilatometer modulus E_D, defined as follows:

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \tag{1}$$

$$U_D = \frac{p_2 - u_0}{p_0 - u_0} \tag{2}$$

$$K_D = \frac{p_0 - u_0}{\sigma'_{v0}} \tag{3}$$

$$E_D = 34.7\left(p_1 - p_0\right) \tag{4}$$

where u_0 is the pre-insertion pore pressure, and σ'_{v0} is the in-situ vertical effective stress.

These intermediate parameters are "objective" parameters, simply calculated from p_0, p_1, p_2. Interpreted soil parameters of common use (e.g., the undrained shear strength in clay s_u, the constrained modulus M, etc.) are derived from the intermediate parameters using established correlations.

Each intermediate parameter has some recognizable physical meaning and some engineering usefulness (Marchetti et al., 2001). I_D is used to identify the soil type (clay, silt, sand). Similarly to the Soil Behaviour Type index I_c derived from the cone penetration test (CPT), I_D is not a soil classification index based on real grain size distribution, but it reflects the mechanical soil behaviour. U_D is used to discern soil layers of different permeability. K_D is used to assess the stress history of a soil deposit, given that the depth profile of K_D is similar in shape to the profile of the overconsolidation ratio OCR. E_D is related to soil stiffness and is used, in combination with K_D and I_D, to estimate the constrained modulus M.

The profiles of the intermediate parameters I_D, U_D, K_D, E_D obtained at the Onsøy and Halden test sites are presented in the next sections. In the data processing, the in-situ u_0 profile was assumed based on available piezometer measurements, while σ'_{v0} was estimated from an approximate depth profile of the soil unit weight obtained from available DMT correlations.

3 **Medusa SDMT tests at Onsøy (soft clay)**

3.1 *Test site conditions*

The Onsøy site (Gundersen et al., 2019) is located in south-eastern Norway, about 100 km from Oslo, just north of Fredrikstad (Figure 2). It consists of 25-35 m thick marine clay deposit which is normally consolidated, but it exhibits overconsolidation due to ageing. The overconsolidation ratio OCR decreases from about 4 near the surface to 1.2 at 30 m depth.

The natural water content w varies between 40% and 70%, and the average plasticity index PI varies from about 45% in the upper 8 m to about 25-30% below 8 m. The sensitivity S_t is constant at around 6 down to about 13 m. Beyond this depth it increases to a value of 45 at approximately 19 m, becoming a quick clay just above bedrock.

The salt content of the pore water is an important characteristic of the Onsøy clay. The percolation of freshwater from the surface has caused an almost linear salinity increase from zero at the surface to 30 g/l at about 7.5 m depth. Beyond this depth, the salinity remains constant. Organic content values are around 0.8% in the top 9 m and around 0.6% below this depth.

The soils at the Onsøy site are marine clays (Lunne et al., 2003). Such clays were deposited during deglaciation and the early postglacial period (Holocene) at times of higher relative sea level. Marine clays are found extensively in Scandinavia and North America. The Onsøy clay has also many similarities to marine clays in, e.g., Japan and Southeast Asia, and is also remarkably similar to clays found offshore at the Troll, Gjøa, Luva and Aasta Hansteen oil and gas fields in the North Sea.

3.2 *Medusa SDMT campaign*

The field testing program at the Onsøy test site (Figure 2), performed in June 2022, consists of one Medusa SDMT sounding carried out by the standard procedure (ONSD02), two Medusa DMT soundings carried out using non-standard test procedures, i.e., the repeated *A*-readings procedure (ONSD03) and the *A*-reading while penetrating procedure (ONSD04), and one Medusa DMTA dissipation test (ONSD05). All Medusa (S)DMT soundings reached a depth of about 20 m and were located close to one traditional pneumatic SDMT sounding (ONSD01) performed by the NGI in 2018. Details on the Medusa SDMT testing program and results at Onsøy can be found in Monaco et al. (2023a).

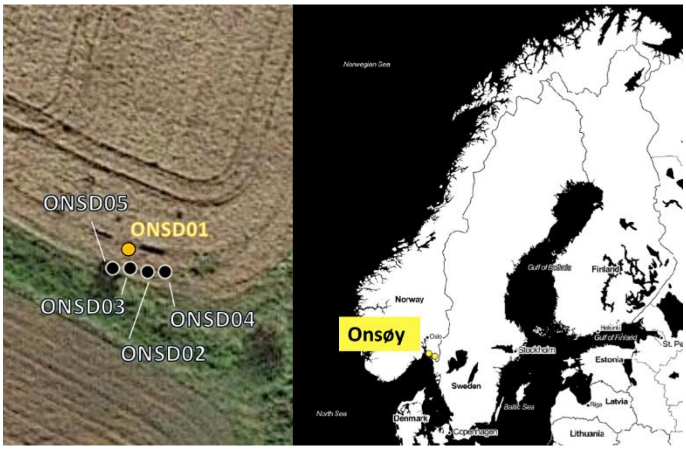

Figure 2. Location of Medusa (S)DMT (ONSD02–ONSD05) and traditional SDMT (ONSD01) soundings at the Onsøy test site

Figures 3 and 4 show the comparison of the results obtained by Medusa SDMT (ONSD02) and by traditional SDMT (ONSD01) using the same standard test procedure. Figure 3 shows the depth profiles of the corrected pressures p_0, p_1, p_2 and of the shear wave velocity V_S obtained by the two probes, while Figure 4 compares the resulting intermediate parameters I_D, U_D, K_D, E_D. The profiles of p_2 (Figure 3) and of the derived U_D (Figure 4) refer only to the Medusa SDMT, because p_2 was not measured with the traditional SDMT. In the data processing, the in-situ pore pressure u_0 profile, also plotted in the p_2 graph, was assumed as hydrostatic with a groundwater table at a depth of 1 m, based on available piezometer measurements at this site (Gundersen et al., 2019).

Figure 3 shows that the profiles of p_0, p_1, p_2 obtained by Medusa SDMT and traditional SDMT are very close to each other. The almost linear increases of corrected pressures are typical for normally consolidated clay deposits. The profiles of V_S are also quite similar between the Medusa SDMT and traditional SDMT. Some differences are more evident when the p_0, p_1, p_2 pressures are combined to estimate the intermediate parameters (Figure 4). The values of I_D obtained by traditional SDMT appear lower than the I_D provided by Medusa SDMT, although such difference is amplified by the logarithmic scale of the graph. The same trend is also observed, to a lesser extent, in the profiles of E_D (Eq. 4), which depends on the difference $(p_1 - p_0)$ as I_D (Eq. 1) and of K_D (Eq. 3), which depends only on p_0. Such discrepancy may be attributed to inherently different technical features of the two probes, summarised as follows.

(1) With the Medusa SDMT the pressure is generated and measured in the probe at depth, eliminating any pressure equalisation problem at the opposite ends of the pneumatic cable that may occur with the traditional equipment, especially when using long cables.

(2) The automated membrane inflation and the incompressibility of the pressurizing fluid (oil) enable the Medusa SDMT to apply the standard pressurization rate with high precision and repeatability. By contrast, with the traditional equipment, the non-automated regulation of the gas flow for obtaining the pressure readings exactly at the standard timing (*A*-reading 15 s after stop, *B*-reading 15 s after *A*-reading) relies to some extent on the skill of the operator. This could be a critical issue in soft soils, in which the *A*-pressures are very low and accordingly the pressurization rate should be extremely slow.

These capabilities of the Medusa SDMT significantly improve the accuracy and repeatability of the measurements, especially in soft soil deposits that are frequently encountered in coastal and nearshore/offshore environments.

Preliminary comparisons of soil parameters obtained at the Onsøy test site from the interpretation of Medusa SDMT, traditional SDMT and a variety of in-situ and laboratory tests in past investigations are presented in Monaco et al. (2023b). Further research is ongoing.

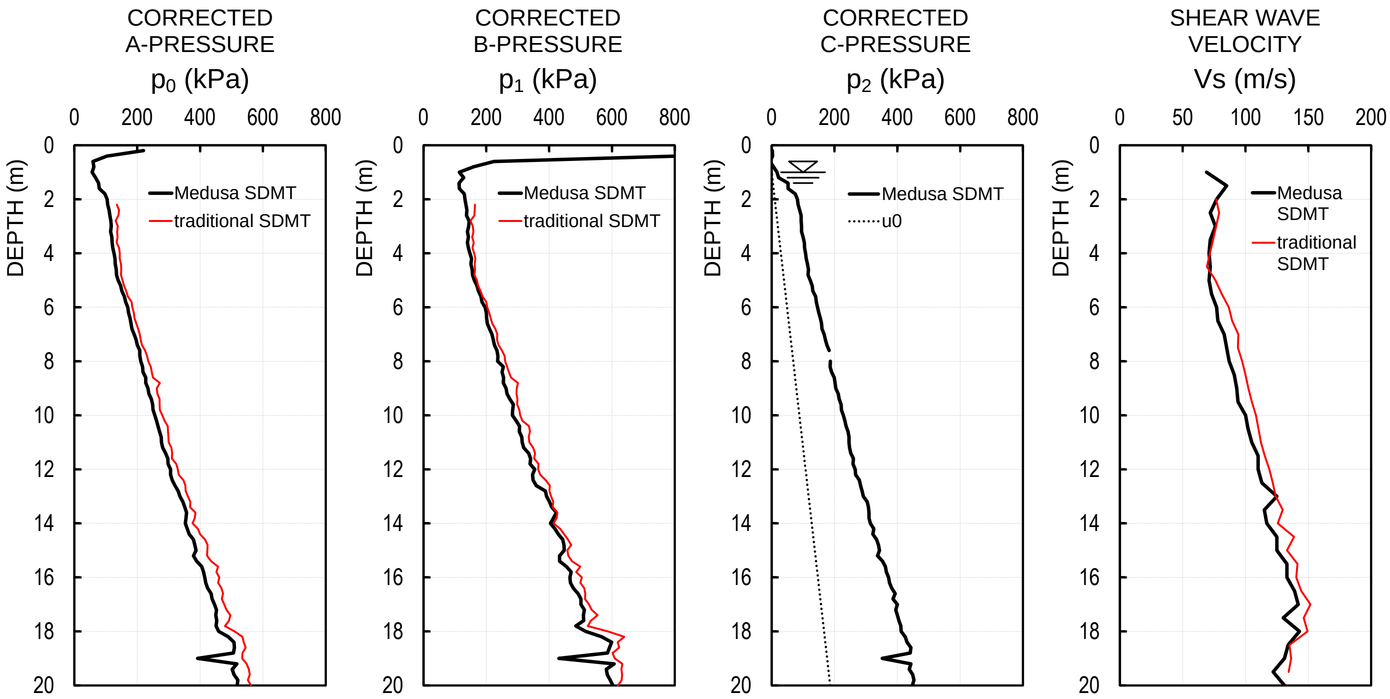

Figure 3. Comparison of the profiles of p_0, p_1, p_2, V_S obtained by Medusa SDMT and traditional SDMT at the Onsøy test site

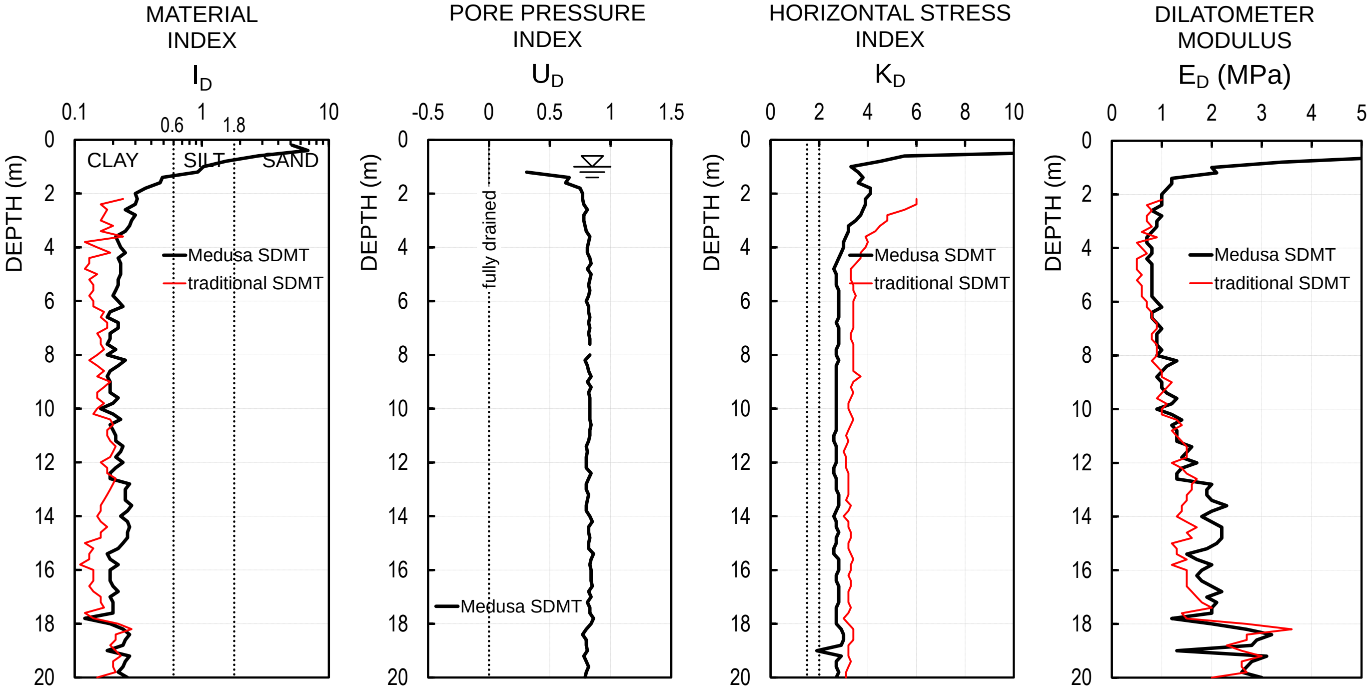

Figure 4. Comparison of the profiles of the intermediate parameters I_D, U_D, K_D, E_D obtained by Medusa SDMT and traditional SDMT at the Onsøy test site

4 Medusa SDMT tests at Halden (silt)

4.1 *Test site conditions*

The Halden test site is located in south-eastern Norway, approximately 120 km south of Oslo. This site has been characterized by combining the results of several geological, geophysical and geotechnical site investigation tools. A complete list of all geophysical, in-situ and laboratory tests conducted at the site, with general test procedure references and key parameters are presented in Blaker et al. (2019).

The stratigraphy of the Halden test site was reconstructed by Blaker et al. (2019) based on a combined interpretation of all available in-situ and laboratory testing data. The ground condition down to 20 m at this site is divided into four soil units. The topmost layer (Unit I) consists of a silty-clayey loose to medium dense sand, extending to about 4.5–5 m depth. Unit I rests above clayey silt which extends down to about 15–16 m depth. This clayey silt is separated into two soil units (Units II and III) based on the results of in-situ and index tests but is regarded as the same material with the same geologic origin. The silt becomes sandier closer to the lowermost Unit IV, which consists of low to medium strength clay.

The soil unit weight here is approximately $\gamma = 19$ kN/m^3 down to 11-12 m depth, and increases to 20 kN/m^3 from there to 20 m depth. The fines content in the two silt units (Units II and III) is generally higher than 80%, slightly decreasing towards the interface with the clay in Unit IV. The clay content (particle size < 0.002 mm) is fairly constant at around 8% in Units II and III, classifying this as a clayey silt according to ISO 14688-1:2017. The measured natural water contents w generally decrease with depth from about 31% at 4 m depth to about 26% at 16 m. *OCR* is a challenging parameter to estimate for silts, but various tests suggest that the range of 1.0 to 1.3 at Halden is considered reasonable (Blaker et al., 2019). The undrained shear strength increases from around 20-40 kPa on top of silt units at 5 m depth to 60-90 kPa at 15 m depth. The remoulded undrained shear strength lies around 5-15 kPa, and the sensitivity is around 2-7. The effective friction angle lies around 36°, with cohesion $c' = 0$, from triaxial test on block samples.

A widely accepted particle size classification defines silt as particles in the range of 0.002 mm and 0.063 mm, and these particles are typically transported by moving currents (e.g., rivers and creeks) and settle in still water. As such, silt deposits are often found all over the world in conjunction with fjords, estuaries and lakes. Besides natural depositional environments, intermediate soils are commonly encountered as a result of man-made activity (hydraulic fills, dredging sediments, mine tailings). Thus testing of the Medusa DMT at the Halden test site shed lights on the possible uses of this innovative tool in similar environments, for example, in projects related to dams, water reservoirs and embankments.

4.2 *Medusa SDMT campaign*

The field testing program at Halden (Figure 6), performed in June 2022, consists of one Medusa SDMT sounding carried out by the standard procedure (HALD02), four Medusa DMT soundings carried out using non-standard pressurization and/or penetration rates (HALD03, HALD04, HALD05, HALD06), and several Medusa DMTA dissipation tests. All Medusa (S)DMT soundings reached a depth of about 19–20 m and were located close to one traditional pneumatic SDMT sounding (HALD01) performed by the NGI in 2018. Details on the Medusa SDMT testing program and results at Halden can be found in Monaco et al. (2023a).

Figure 6. Location of Medusa (S)DMT (HALD02–HALD06) and traditional SDMT (HALD01) soundings at the Halden test site

Figures 7 and 8 show the comparison of the results obtained by Medusa SDMT (HALD02) and by traditional SDMT (HALD01) using the same standard test procedure. The schematic stratigraphy consisting of four soil units reconstructed by Blaker et al. (2019), as previously described, is also indicated in the graphs. Figure 7 shows the depth profiles of p_0, p_1, p_2 and V_S, while Figure 8 shows the comparison of the intermediate parameters I_D, U_D, K_D, E_D. The profiles of p_2 (Figure 7) and the derived U_D (Figure 8) refer only to the Medusa SDMT, because p_2 was not measured with the traditional SDMT. In the data processing, the in-situ pore pressure u_0 profile, also shown in the p_2 graph, was assumed as non-hydrostatic with a groundwater table at a depth of 1.30 m, based on piezometer measurements performed during the Medusa SDMT campaign and on pore pressure data records available from NGI (Blaker et al., 2019).

Figure 7 shows that the profiles of p_0, p_1, p_2 obtained by Medusa SDMT and traditional SDMT are very close to each other in the silt units (Units II and III). The pressures increase with depth, but with a lower slope in Unit III (from around 11 to 15 m depth, with some transition between 15 and 17 m just above Unit IV). Interestingly, a similar trend is observed in the available results obtained at Halden from piezocone and other in-situ tests. Some scatter is observed in the sand unit above 5 m (Unit I) and in the clay unit below 16–17 m (Unit IV). The profiles of V_S (Figure 7) show a similar trend but a nearly constant shift down to about 17 m depth, possibly due to interpretation.

The most salient evidence clearly emerging from Figure 8 is that the soil classification provided by I_D fails to correctly identify the silt units (Units II and III), which are wrongly classified as "very clayey" clay. Such anomalous finding in silts has been already observed (Marchetti et al., 2001; Marchetti, 2015; Marchetti and Monaco, 2018) and can be explained as follows.

While in sands and clays the DMT test conditions can be reasonably assumed either fully drained or fully undrained, in the transition region of silt-mixture soils the DMT results may be influenced by partial drainage. The DMT pressure readings A and B (corrected into p_0 and p_1) are obtained 15 s and 30 s after penetration respectively. In silts, partial dissipation of the excess pore pressure induced by the blade penetration may occur in the time interval from A to B. Consequently, p_1 will not be the "proper match" of p_0 but it will be "too low" (p_1 could be nearly equal or even less than p_0). In turn, also "too low" will be the difference $(p_1 - p_0)$ and all the derived parameters proportional to $(p_1 - p_0)$, namely I_D (Eq. 1) and E_D (Eq. 4). In particular, I_D will possibly end up in the extreme left hand of its scale ($I_D = 0.1$ or less). Figure 8 shows that partial drainage effects in silts, reflected by I_D values close to zero, are more pronounced in Unit III than in Unit II.

As noted by Marchetti (2015), a persistent very low I_D value is a "signature" feature, indicative of silts in the "niche" of partial drainage. In such "niche" silts, the values of I_D and E_D, as well as the derived parameters obtained by common interpretation (e.g., the constrained modulus M, Marchetti, 1980), are misleading and should not be used as such, unless some correction is applied (Schnaid et al., 2016, 2018).

These findings confirm the well-known difficulty in the characterisation of intermediate soils by in-situ testing, resulting in a persisting lack of established correlations to derive important engineering parameters.

Research is in progress to investigate the use of the results of variable-rate Medusa DMT tests carried out at Halden, in combination with in-situ and laboratory test results available from previous investigations (in particular variable-rate piezocone tests, Carroll and Paniagua, 2018; Augustesen et al., 2022), for improving the characterisation of silty soils. This innovative approach is promising thanks to the highly accurate and repeatable time-for-reading setting facility provided by the Medusa DMT, and could not be pursued with the traditional pneumatic DMT.

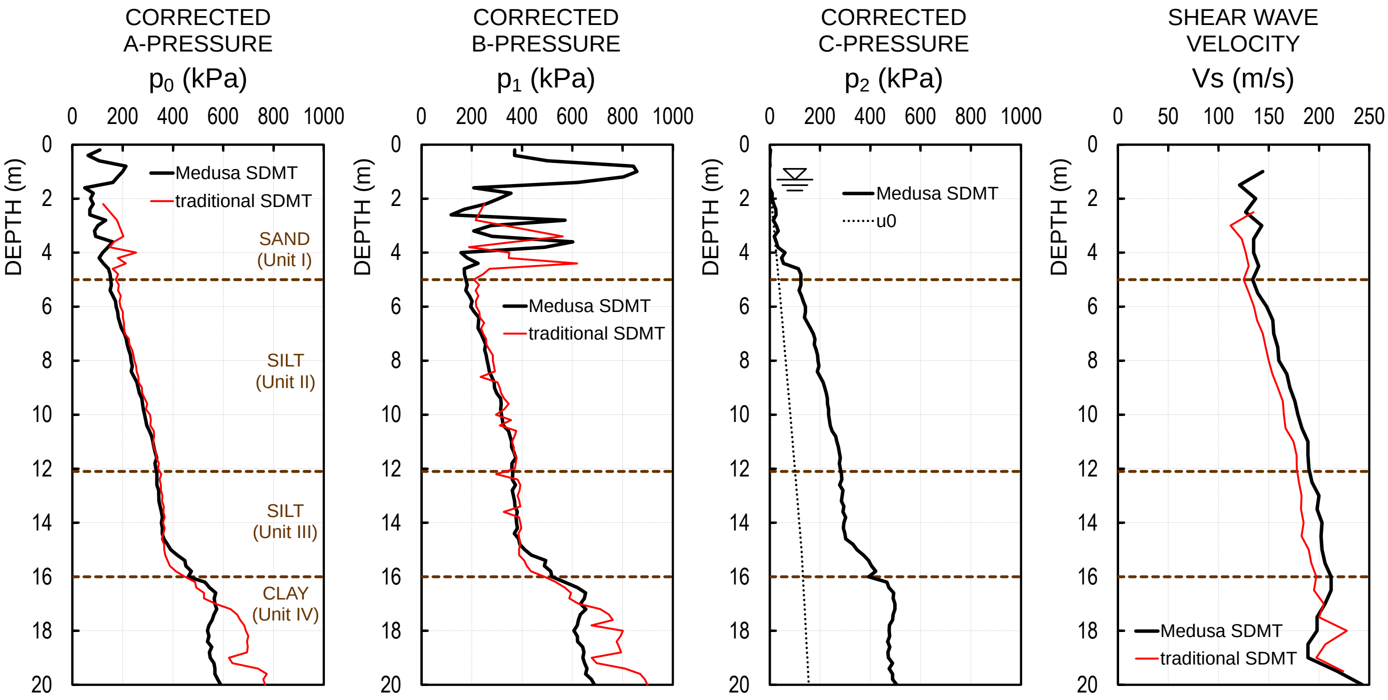

Figure 7. Comparison of the profiles of p_0, p_1, p_2, V_S obtained by Medusa SDMT and traditional SDMT at the Halden test site

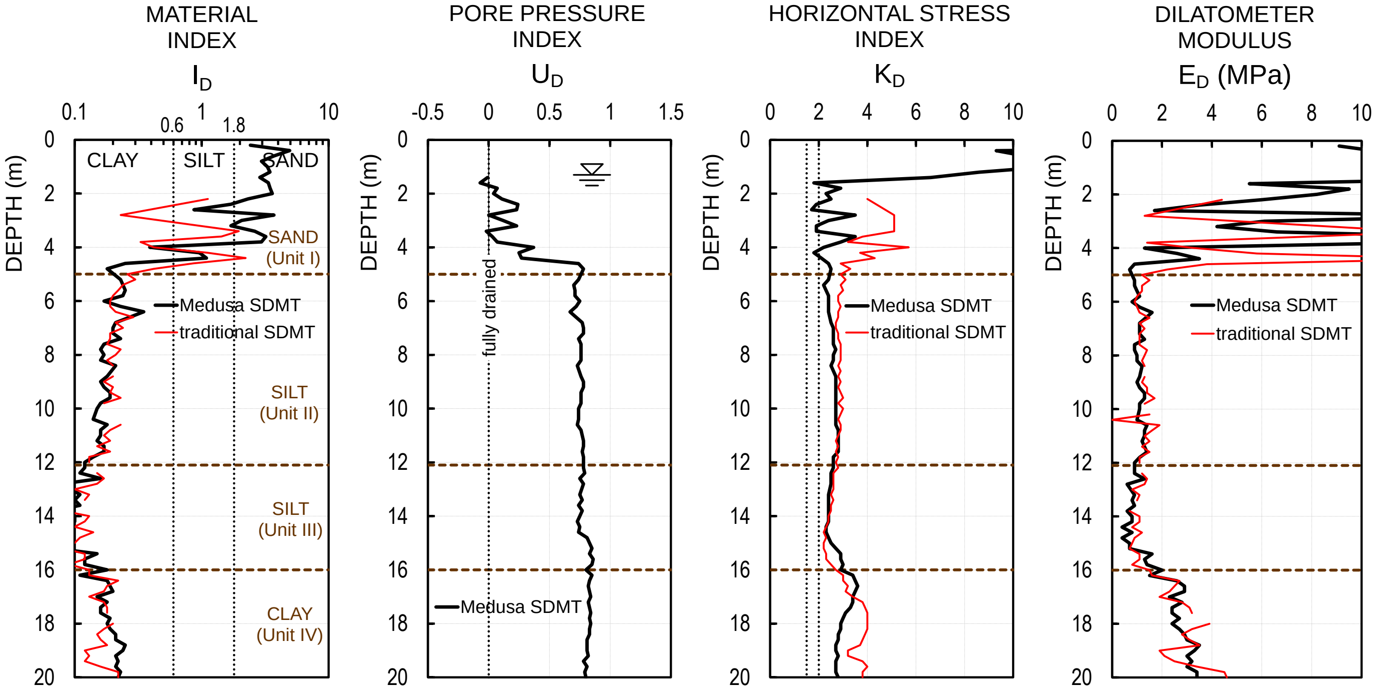

Figure 8. Figure 4. Comparison of the profiles of the intermediate parameters I_D, U_D, K_D, E_D obtained by Medusa SDMT and traditional SDMT at the Halden test site

5 Conclusions

The preliminary findings described in this paper, obtained from the investigation campaign carried out at two well-known benchmark Geo-Test Sites in Norway, shed light on the potential use of the Medusa DMT for offshore investigation. The soils at the Onsøy and Halden sites, though onshore, have marine origins and resemble the offshore soil conditions at several oil/gas fields in the North Sea. Performing the field tests in these onshore controlled environments permits simplifying the testing parameters and conditions, and obtaining basis information for subsequent planning of offshore testing. Knowledge of soil behaviour and engineering properties in similar materials is paramount for the design and construction of infrastructure projects, both onshore and offshore.

Due to improved accuracy in pressure measurements and controlled pressurization rate, the Medusa DMT is useful for testing soils frequently encountered in coastal and nearshore/offshore environments.

In particular, the Medusa DMT eliminates any pressure equalisation problem at the opposite ends of the pneumatic cable that may occur with the traditional DMT equipment, allowing the probe to reach high depths typical of offshore applications. Moreover, the automated Medusa DMT membrane inflation and the incompressibility of the pressurizing fluid (oil) enforce the standard pressurization rate with high precision and repeatability.

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