The JELLYFISh Project: Medusa SDMT testing at the NGTS Geo-Test sites, Norway

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ABSTRACT

This paper presents an overview of the experimental activity and the main results obtained as part of the Transnational Access project – JELLYFISh funded by H2020-GEOLAB. The project is based on an extensive in-situ testing campaign with the Medusa SDMT, the newest fully automated version of the seismic dilatometer (SDMT). The campaign was carried out in June 2022 in different soil types at four well-known benchmark test sites in Norway: Halden (silt), Onsøy (soft clay), Tiller-Flotten (quick clay), and Øysand (sand). These benchmark sites, largely documented in previous research, are part of the Geo-Test Sites (NGTS) research infrastructure managed by the Norwegian Geotechnical Institute. The paper includes: (i) highlights of the JELLYFISh project, (ii) a brief description of the Medusa SDMT main features, (iii) a summary of the field testing program at the four sites, (iv) a comparison of the results provided by Medusa SDMT using alternative test procedures and by traditional (pneumatic) SDMT and (v) conclusions. The results of the project highlight that, due to improved accuracy of pressure measurements and controlled pressurization rate, the Medusa SDMT has the potential for providing significant advancement in soil characterization compared to the traditional SDMT technology. These capabilities are particularly useful when investigating soft clays (e.g., Onsøy) in which the measured pressures are typically very small, intermediate soils (e.g., Halden) in which non-standard test procedures using variable penetration/pressurization rates may be easily implemented, or sensitive clays (e.g., Tiller-Flotten) in which alternative test procedures may provide guidance for distinguishing quick and non-quick clays.

Keywords: flat dilatometer test; seismic dilatometer test; Medusa DMT; benchmark Geo-Test sites.

1. Introduction

The Critical Infrastructure (CI) of Europe in the water, energy, urban and transport sector is currently facing major challenges related to climate change, extreme weather, geo-hazards, aging and increased usage in combination with pivotal changes to meet long-term societal goals. The assessment and mitigation of multiple geo-hazards (e.g., subsidence, landslides, earthquake-induced liquefaction) are of primary importance for protecting communities and reducing damages in densely populated and risk-sensitive areas. Improvements in geotechnical approaches to enhance the resilience of the CI rely significantly on an in-depth understanding of soil behaviour.

GEOLAB (https://project-geolab.eu) is a 4-year project (2021-2025) funded by the European Union Horizon 2020 Research and Innovation Programme. The GEOLAB community of Research Infrastructures (RI) consists of 11 unique installations in Europe aimed to study subsurface behaviour and the interaction with structural CI elements and the environment. The overarching aim of GEOLAB is to perform ground-breaking research and to provide innovative solutions to address the challenges faced by CI owners of Europe.

Transnational Access (TA) is the backbone of GEOLAB. The aim of TA is to provide researchers (User Groups) from across Europe access to advanced RI facilities. The Transnational Access project JELLYFISh "A Just-released innovativE in-situ soiL testing technoLogY (Medusa DMT/SDMT) For enhancing the resilience of the critical InfraStructure in Europe" aims to advance the knowledge on the geotechnical characterization of different soil deposits (soft and quick clays, intermediate soils, sands) by use of innovative in-situ testing procedures. A significant recent development in in-situ testing technology is the Medusa DMT/SDMT which represents the last-generation, fully automated version of the flat/seismic dilatometer (DMT/SDMT). Through the TA project JELLYFISh, an extensive field testing campaign with the Medusa SDMT was carried out in June 2022 at benchmark test sites in Norway, part of the Geo-Test Sites (NGTS) research infrastructure managed by the Norwegian Geotechnical Institute (NGI) (L'Heureux and Lunne 2020). The NGTS RI includes six benchmark test sites, located in Norway and Svalbard, which have been developed as "field laboratories" for the testing and verification of innovative soil investigation methods and prototypes of geotechnical structures in different soil conditions. Four of these benchmark test sites, largely documented in previous research, were selected for the TA project JELLYFISh: Halden (silt), Onsøy (soft clay), Tiller-Flotten (quick clay), and Øysand (sand) (Fig. 1).

This paper presents an overview of the Medusa SDMT testing program and highlights the main findings at these test sites. The results provided by Medusa SDMT using innovative "non-standard" testing procedures are compared with those from the "standard" procedure, as well as with results obtained using the traditional pneumatic SDMT. Details on the testing program and field data were reported by Monaco et al. (2023a). Preliminary results on Onsøy and Halden sites were in addition presented in Monaco et al. (2023b, 2023c, 2023d).

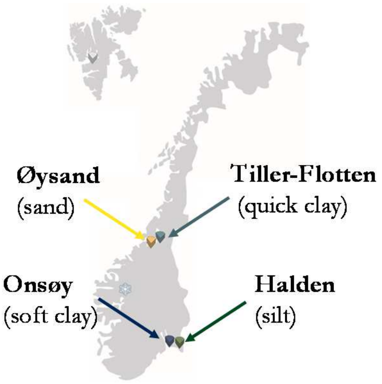

Figure 1. Location of the selected benchmark test sites.

2. Medusa DMT & SDMT: equipment, test procedures and data processing

The Medusa DMT (Marchetti 2018, Marchetti et al. 2019) is a self-contained probe, capable of operating autonomously using a standard blade without the pneumatic cable, the control unit and the gas tank required in the traditional pneumatic DMT (Fig. 2). 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. The readings are stored automatically at each test depth (typically every 0.20 m). The probe can operate in cableless mode, which is a significant practical advantage in the offshore industry and 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, in addition to the DMT measurements (Fig. 2).

The standard Medusa DMT test procedure is the same as the traditional pneumatic DMT test (ASTM D6635-15, ISO 22476-11:2017(E)). For the Medusa DMT this procedure relies on an internal automated pressurization system instead of an external manually operated pressure source and regulation system. The *A*-pressure is recorded when the membrane centre has expanded 0.05 mm against the soil from its initial position. After the *A*-reading the motorized syringe continues to increase the oil pressure, and the *B*-pressure is recorded when the centre of the membrane has expanded 1.10 mm from its original position. Soon after the *B*-reading the motorized syringe gradually applies a controlled depressurization, and the *C*-pressure is recorded when the membrane has returned to its initial position. The standard pressurization rate is regulated to obtain the *A*-pressure reading 15 s after start of pressurization and the *B*-pressure reading 15 s after the *A*-pressure reading.

Besides the standard procedure, the Medusa DMT can perform innovative non-standard test procedures and acquire additional measurements, which are not feasible with the traditional pneumatic DMT. Two alternative procedures are the repeated *A*-readings procedure (DMT-RA) and the *A*-reading while penetrating procedure (DMTA-WP). These procedures differ from the standard procedure mainly in the technique used for acquiring the *A*-pressure readings (Monaco et al. 2022, Marchetti et al. 2022). In the DMT-RA procedure the *A*-pressure is obtained by maintaining the membrane in equilibrium with the soil pressure at 0.05 mm distance from the sensing disc, with negligible horizontal displacement. At each test depth repeated sequential *A*-readings are taken by monitoring the total horizontal soil pressure against the membrane with time for a pre-set duration (e.g., 15 s as in the standard procedure). The *B* and *C* pressure readings are taken in the same way as in the standard procedure. The DMTA-WP procedure allows registering continuous measurements of the total horizontal pressure of the soil against the membrane by recording the *A*-pressures during probe penetration at a constant rate (typically the standard 20 mm/s penetration rate). The sequence of *A*-readings is generally taken over 1-m depth intervals (i.e., the typical length of push rods). During stops of penetration to add a push rod, *B* and *C* pressure readings may also be taken.

As an additional feature, the highly repeatable automatic volume-controlled hydraulic pressurization of the membrane allows implementing a programmable timing to obtain the pressure readings, i.e., either the standard timing or a modified timing for dilatometer tests with variable pressurization rates. Variable penetration rate can be combined with variable pressurization rate to investigate the behaviour of intermediate soils such as silts, silty sands, sandy silts and other soil mixtures (Monaco et al. 2021).

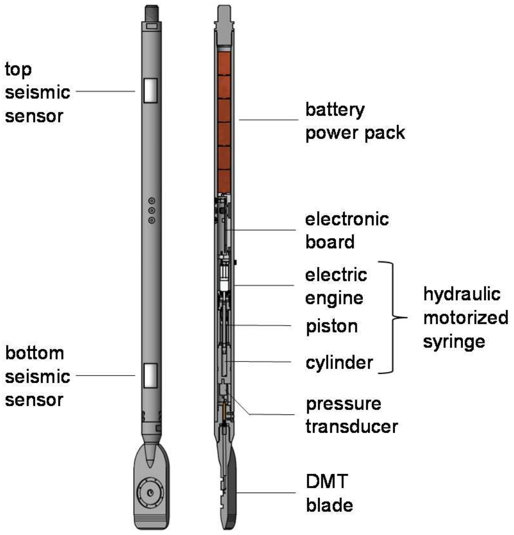

Figure 2. Main components of the Medusa SDMT probe.

The field data obtained from Medusa DMT can be processed and interpreted in the same way as those provided by the traditional DMT test (Marchetti 1980, Marchetti et al. 2001). The pressures *A*, *B*, *C* are corrected into p_0, p_1, p_2 by calibration to account for membrane stiffness. The corrected pressures are used to calculate four intermediate parameters: the material index I_D reflecting soil type behaviour, the pore pressure index U_D depending on soil permeability, the horizontal stress index K_D related to the stress history of the deposit, and the dilatometer modulus E_D related to soil stiffness. Common soil parameters (e.g., the undrained shear strength in clay s_u, the constrained modulus *M*, etc.) are derived from the intermediate parameters using well established correlations. The test procedure and interpretation for obtaining V_S using the Medusa SDMT are the same as for the traditional SDMT (Marchetti et al. 2008).

The results presented in this paper were obtained at the Halden, Onsøy, Tiller-Flotten and Øysand 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. In the data processing, the in-situ pre-insertion pore pressure u_0 profile was interpreted based on available piezometer measurements. For a preliminary assessment, the in-situ vertical effective stress σ'_{v0} was calculated based on an estimate of the soil unit weight obtained from available DMT correlations.

3. Medusa SDMT tests at Halden (silt)

3.1. Test site conditions

The Halden test site is located in south-eastern Norway, approximately 120 km south of Oslo (Fig. 1). The stratigraphy includes four soil units down to 20 m depth (Blaker et al. 2019):

- Unit I: silty-clayey loose to medium dense sand, extending to about 4.5-5 m depth;
- Units II and III: clayey silt, separated into two soil units based on in-situ and index test results but regarded as the same material with the same geologic origin; the silt extends to about 15-16 m depth and becomes sandier close to this depth;
- Unit IV: low to medium strength clay.

The overconsolidation ratio *OCR* is estimated in the range 1 to 1.3. The fines content in silt (Units II and III) is generally higher than 80%, slightly decreasing towards the interface with Unit IV. The clay content (particle size < 0.002 mm) is constant at around 8% in Units II and III. The natural water content *w* generally decreases with depth from about 31% at 4 m to about 26% at 16 m depth. The sensitivity S_t in silt is around 2-7.

3.2. Testing program and results

The field testing program at Halden (Table 1) included one "baseline" Medusa SDMT sounding (HALD02) carried out following the standard procedure and four variable-rate Medusa DMT soundings (HALD03 – HALD06) carried out at penetration rates slower and faster than standard, combined with standard or non-standard (slower or faster) pressurization rates which were regulated by pre-setting different time intervals for the *A* and *B* pressure readings. Several Medusa DMTA dissipation tests were also carried out. All Medusa (S)DMT soundings reached a depth of about 19-20 m and were performed close to one traditional pneumatic SDMT sounding (HALD01) carried out by the NGI in 2018.

Table 1. Summary of Medusa (S)DMT tests at Halden

Sounding ID	Test type	Penetration rate (mm/s)	Time to *A*-reading (s)	Time to *B*-reading (s)
HALD02	standard (baseline)	20	15	15
HALD03	slow rate	2	15	15
HALD04	slow rate/ slow press	2	30	30
HALD05	fast rate	86	15	15
HALD06	fast rate/ fast press	75	7.5	7.5

Fig. 3 shows the depth profiles of the DMT pressure readings p_0, p_1, p_2 and the intermediate parameters I_D, U_D, K_D. To assess the combined effects of both variable penetration and pressurization rate, only the results obtained from the standard "baseline" HALD02 compared with the "slowest" HALD04 (slow penetration/pressurization rate) and the "fastest" HALD06 (fast penetration/pressurization rate) are shown in Fig. 3. The results obtained by traditional SDMT (HALD01) are also plotted in Fig. 3 for comparison with the results obtained by Medusa SDMT (HALD02) using the same standard test procedure. The profiles of p_2 and the derived U_D refer only to the Medusa SDMT, because p_2 was not measured with the traditional SDMT (as in all the other test sites). The in-situ u_0 profile, shown in the p_2 graph, was assumed as non-hydrostatic with a groundwater table at 1.30 m, based on piezometer measurements. Fig. 3 highlights the following trends:

(a) In silt (Units II and III) the p_0 obtained using slow penetration/pressurization rates are lower than the p_0 obtained using the standard rates. This can be explained considering that in fine-grained soils p_0 (total pressure) incorporates the excess pore pressure Δu induced by blade penetration: the slower the penetration rate, the lower will be Δu, hence p_0. An opposite trend was expected for the p_0 obtained using fast penetration/ pressurization rates, as Monaco et al. (2021) reported in a different silt deposit in Italy. However, at Halden the "fastest" p_0 are nearly coincident with the baseline values suggesting that the standard penetration/pressurization rates impose fully undrained conditions, which do not evolve to "more undrained" using faster rates. A similar explanation can be applied for p_1.

(b) In sand p_2 closely approximates the in-situ pore pressure u_0, while in clay $p_2 > u_0$ due to Δu induced by blade penetration. Consistently, the p_2 obtained in silt using slow penetration/pressurization rates are lower than the p_2 obtained using the standard rates, reflecting lower Δu induced by penetration. As for p_0, the p_2 from fast penetration/pressurization rates are substantially equal to the baseline p_2.

(c) In sand (Unit I) and clay (Unit IV) the p_0, p_1, p_2 obtained at different penetration/pressurization rates remain substantially unchanged, indicating fully drained or fully undrained response, respectively, under any test rate conditions.

(d) The material index I_D is an indicator of soil type (clay, silt, sand) which broadly reflects soil behaviour rather than real grain size distribution, while the pore pressure index U_D can help to differentiate between drained, undrained or partially drained soil behaviour (Marchetti et al. 2001). In silt (Units II and III) the slower the penetration/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. On the other hand, no apparent evolution towards more "undrained" conditions is observed when using faster penetration/pressurization rates.

(e) For the standard test conditions I_D fails to correctly identify the silty Units II and III, which are wrongly classified as "very clayey" clays. Such misinterpretation, sometimes observed in the transition region of silt-mixture soils (Marchetti et al. 2001, Marchetti 2015, Marchetti and Monaco 2018), is attributed to partial dissipation of the Δu induced by penetration in the time interval from p_0 to p_1. Consequently, p_1 will not be the "proper match" of p_0 and all the parameters proportional to $(p_1 - p_0)$, namely I_D, will be "too low". Partial drainage effects in silts, reflected by I_D values close to zero, are more pronounced in Unit III than in Unit II. Such persistent very low I_D are a "signature" feature, indicative of silts in the "niche" of partial drainage. In such silts the soil parameters obtained by common DMT interpretation are misleading.

(f) The profiles of p_0 and p_1 obtained by standard "baseline" Medusa SDMT and traditional SDMT are very close to each other in silt (Units II and III). The pressures increase with depth, but with a lower slope in Unit III. 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 sand above 5 m (Unit I) and in clay below 16-17 m (Unit IV).

4. Medusa SDMT tests at Onsøy (soft clay)

4.1. Test site conditions

The Onsøy site is located in south-eastern Norway, about 100 km far from Oslo (Fig. 1). It consists of a 25-35 m thick marine clay deposit. The stratigraphy in the area investigated in this project (south-east corner) includes four soil units down to 20 m depth (Gundersen et al. 2019):

- Unit I: weathered clay crust, 1 m thick;
- Unit II: clay of high to very high plasticity, extending to about 10.5 m depth;
- Unit III: clay of medium to high plasticity, extending to about 19-20 m depth;
- Unit IV: clay of higher sensitivity.

The deposit is normally consolidated, but it exhibits overconsolidation due to aging. The *OCR* decreases from about 4 near the surface to 1.2 at 30 m depth. The values of *w* vary between 40% and 70%, and the *PI* between about 45% in the upper 8 m and 25-30% below 8 m. The sensitivity S_t is constant at around 6 down to about 13 m, then S_t increases to 45 at approximately 19 m, becoming a quick clay near 28 m depth. 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 0.6% below this depth.

4.2. Testing program and results

The field testing program at Onsøy (Table 2) comprised 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. 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.

Table 2. Summary of Medusa (S)DMT tests at Onsøy

Sounding ID	**Test type**	**Time to *A*-reading (s)**	**Time to *B*-reading (s)**
ONSD02	standard (baseline)	15	15
ONSD03	repeated *A*-readings	continuous for 15 s	15
ONSD04	*A*-reading while penetrating	continuous during probe penetration	every 1 m depth

Fig. 4 shows the depth profiles of p_0, p_1, p_2 and the derived I_D, U_D, K_D obtained from the standard "baseline" ONSD02 compared with the non-standard ONSD03 (DMT-RA) and ONSD04 (DMTA-WP). For ONSD03, the *A*-pressure value used in data processing is the final value recorded 15 s after start of pressurization. The results obtained by traditional SDMT (ONSD01), for comparison with those obtained by the standard Medusa SDMT (ONSD02), are also shown in Fig. 4. The in-situ u_0 profile, shown in the p_2 graph, was assumed as hydrostatic with a groundwater table at 1 m depth, based on piezometer measurements. Fig. 4 highlights the following trends:

(a) The profiles of p_0 obtained by Medusa (S)DMT using the three different test procedures are very similar, despite the different techniques adopted for measuring the *A*-pressure. The profiles of p_1 and p_2 obtained by all Medusa (S)DMT test procedures 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 other two procedures.

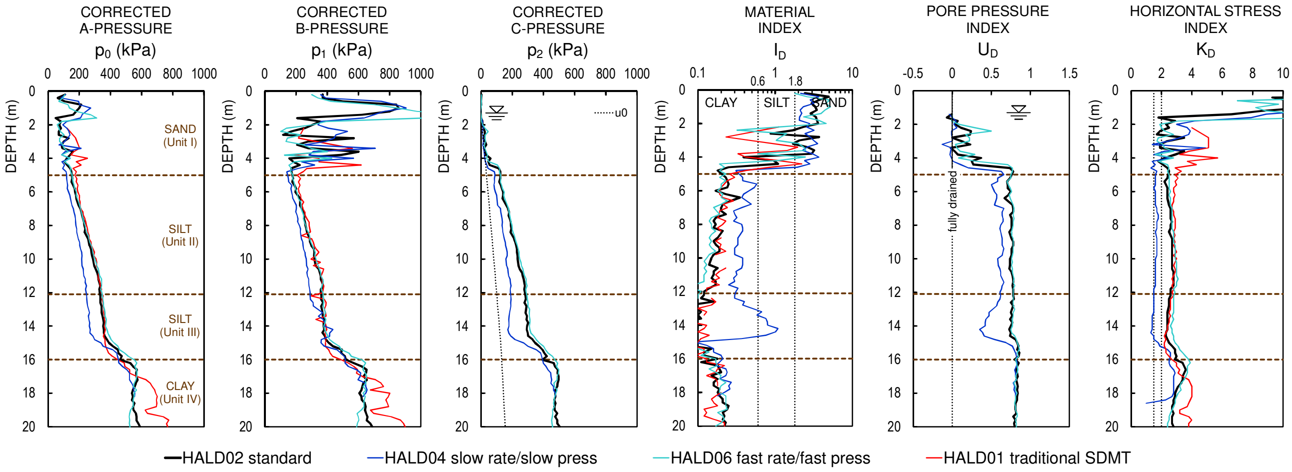

Figure 3. Halden test site – Combined effects of variable penetration and pressurization rates on Medusa (S)DMT results and comparison with traditional SDMT (schematic soil stratigraphy after Blaker et al. 2019).

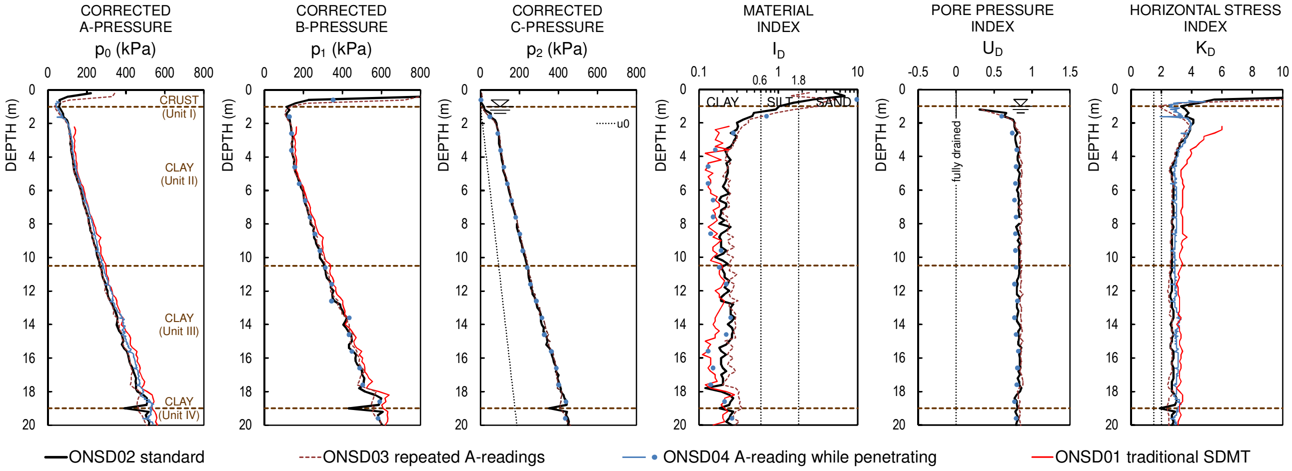

Figure 4. Onsøy test site – Medusa (S)DMT results obtained by different test procedures and comparison with traditional SDMT (schematic soil stratigraphy after Gundersen et al. 2019).

(b) Some inconsistency between the values obtained by different test procedures is observed in the profiles of I_D, which depends on the difference ($p_1 – p_0$). In fact, the I_D calculated from p_0 and p_1 acquired by the DMTA-WP procedure appear significantly lower than the I_D provided by the other two procedures. This discrepancy could be due to the fact that in the DMTA-WP procedure the *A*-pressure is measured at time $t = 0$ instead of $t = 15$ s, resulting in lower values of the difference ($p_1 – p_0$). For low I_D values such incongruity is amplified by the log scale. The values of K_D, which depends only on p_0, do not seem influenced by the adopted test procedure.

(c) The profiles of p_0 and p_1 obtained by Medusa SDMT and traditional SDMT using the same standard procedure are very close to each other. The almost linear increases of p_0 and p_1 are typical of normally consolidated clay deposits. Some difference is more evident when these pressures are combined in terms of intermediate parameters. Indeed, the I_D acquired by traditional SDMT appear lower than the I_D provided by Medusa SDMT (again, for low I_D such inconsistency is amplified by the log scale). The same trend is also observed, to a lesser extent, in the profiles of K_D. Such discrepancy may be attributed to inherently different technical features of the Medusa SDMT and the traditional SDMT equipment: (1) with the Medusa SDMT the pressure is generated and measured in the probe at depth rather than at ground surface, eliminating any pressure equalization problem at the opposite ends of the pneumatic cable that may occur with the traditional equipment; (2) the automated membrane inflation and the incompressibility of the pressurizing fluid (oil) enable the Medusa SDMT to enforce the standard pressurization rate with high precision and repeatability. These capabilities of the Medusa SDMT improve significantly the accuracy of the pressure measurements especially in very soft soils, which become immune to possible inflation rate variations during test execution.

5. Medusa SDMT tests at Tiller-Flotten (quick clay)

5.1. Test site conditions

The Tiller-Flotten site is located about 10 km south of Trondheim, in mid-Norway (Fig. 1). It consists of a 50 m thick deposit of marine clays including highly sensitive clays (quick clays). The stratigraphy is divided into two main units down to 20 m depth (L'Heureux et al. 2019):

- Unit I: desiccated/weathered clay to about 2 m depth;
- Unit II, separated in two sub-units of similar clay content and structure but different sensitivity: low to medium sensitive clay (Unit IIA) from about 2 m to 7.5 m depth; very sensitive quick clay (Unit IIB), often with $S_t > 100$, below 7.5 m.

The *OCR* is about 2 in the upper 10 m and between 1.5-2 below this depth. The apparent overconsolidation is attributed to a complex depositional and stress-strain history. The clay content ranges between 45% and 70%. The *w* decreases from 40-50% in the upper 5 m to 30-35% at 20 m depth. The *PI* is about 20% in Unit IIA and 8-15% in Unit IIB.

5.2. Testing program and results

The field testing program at Tiller-Flotten (Table 3) comprised one Medusa SDMT sounding carried out by the standard procedure (TILD02), one Medusa DMT sounding carried out using the *A*-reading while penetrating procedure (TILD03), and one Medusa DMTA dissipation test. All Medusa (S)DMT soundings reached a depth of about 20 m and were located close to one traditional pneumatic SDMT sounding (TILD01) performed by the NGI in 2017.

Table 3. Summary of Medusa (S)DMT tests at Tiller-Flotten

Sounding ID	Test type	Time to *A*-reading (s)	Time to *B*-reading (s)
TILD02	standard (baseline)	15	15
TILD03	*A*-reading while penetrating	continuous during probe penetration	every 1 m depth

In Fig. 5 the depth profiles of p_0, p_1, p_2 and I_D, U_D, K_D obtained from the standard "baseline" TILD02 are compared with the profiles obtained by the non-standard TILD03 (DMTA-WP), as well as by the traditional SDMT (TILD01). The in-situ u_0 profile, shown in the p_2 graph, was assumed as non-hydrostatic with a groundwater table at 1.50 m, based on piezometer measurements. Fig. 5 highlights the following trends:

(a) The profiles of p_0 obtained by Medusa (S)DMT using the standard procedure (TILD02) and the DMTA-WP procedure (TILD03) are very similar in non-quick clay (Unit I), as observed in Onsøy clay (Fig. 4), but become substantially different when penetrating into the quick clay (Unit II). Such anomalous trend could possibly reflect the difference in soil sensitivity. The diverse response in terms of total horizontal pressure against the probe measured during stops of penetration or during continuous penetration may be a consequence of the different soil remoulding induced by the two procedures. This preliminary finding suggests that the comparison of profiles of p_0 obtained by Medusa SDMT using the standard and the DMTA-WP procedures could be tentatively used for distinguishing quick and not-quick clays, as an integration to existing approaches (L'Heureux et al. 2019).

(b) As noted at the Onsøy site (Fig. 4), the I_D calculated from p_0 and p_1 data acquired by the DMTA-WP procedure are significantly lower (even close to zero) than the I_D provided by the standard procedure. Differently from Onsøy, at Tiller-Flotten also the K_D seem to be influenced by the adopted test procedure.

(c) The profiles of p_0 and p_1 obtained by Medusa SDMT and traditional SDMT using the same standard procedure are similar. However, the I_D acquired by traditional SDMT are substantially lower than the I_D provided by Medusa SDMT and unreliable. Such discrepancy may be attributed to the different technical features of the Medusa SDMT and the traditional SDMT equipment, as already observed for the Onsøy site.

6. Medusa SDMT tests at Øysand (sand)

6.1. Test site conditions

The Øysand site is located about 15 km south-west of Trondheim, in mid-Norway (Fig. 1). It consists of a very thick deposit of fluvial material underlain by deltaic and marine sediments. Due to its geological history, the deposit includes several loose to medium dense sand layers and is characterized by significant lateral variability. The stratigraphy down to 20 m depth can be divided into two main units (Quinteros et al. 2019):

- Unit I: fine to coarse gravelly sand (fluvial deposit) extending down to about 6-10 m depth;
- Unit II: fine to medium silty sand, sand and silt (deltaic soils) including silty-clayey layers.

The fines content is highly variable, ranging from 2% to 80% in different layers. The silt content (particle size 0.06-0.002 mm) is less than 10% in Unit I, and ranges from 25% to 75% in Unit II.

6.2. Testing program and results

The field testing program at Øysand (Table 4) included one "baseline" Medusa SDMT sounding (OYSD04) carried out by the standard procedure and one variable-rate Medusa DMT sounding (OYSD06) carried out by adopting penetration and pressurization rates faster than standard. The soundings started from about 6.2 m depth, from the bottom of holes pre-drilled to bypass the upper gravelly sand layer, and reached a depth of about 19 m. The Medusa (S)DMT soundings were located close to one traditional pneumatic SDMT sounding (OYSD01) performed by the NGI in 2017.

Table 4. Summary of Medusa (S)DMT tests at Øysand

Sounding ID	Test type	Penetration rate (mm/s)	Time to *A*-reading (s)	Time to *B*-reading (s)
OYSD04	standard (baseline)	20	15	15
OYSD06	fast rate/ fast press	55	7.5	7.5

Fig. 6 shows the comparison of the results obtained from the standard "baseline" OYSD04 and from OYSD06 (fast penetration/pressurization rate). The results obtained by traditional SDMT (OYSD01), to be

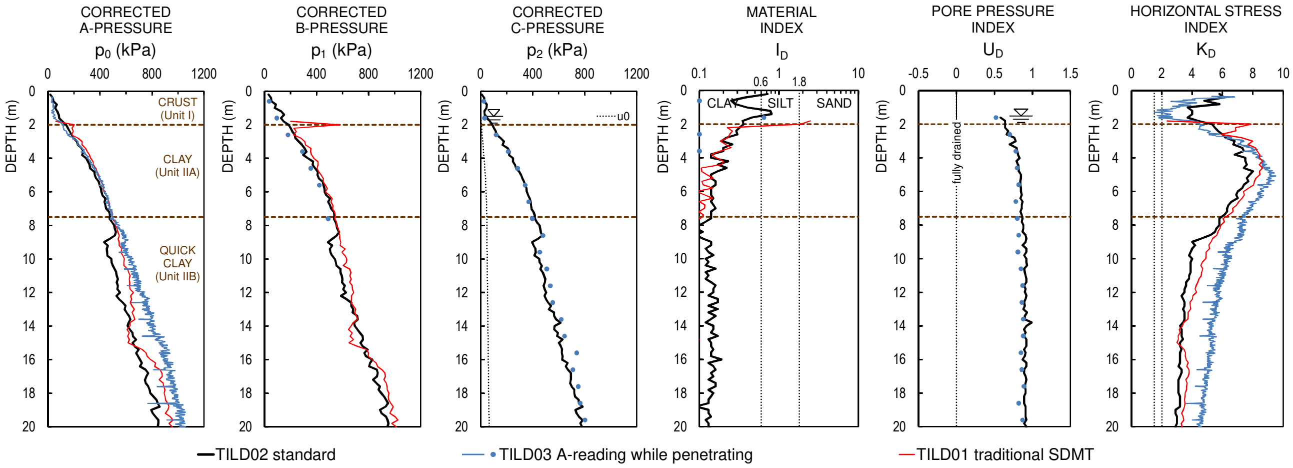

Figure 5. Tiller-Flotten test site – Medusa (S)DMT results obtained by different test procedures and comparison with traditional SDMT (schematic soil stratigraphy after L'Heureux et al. 2019).

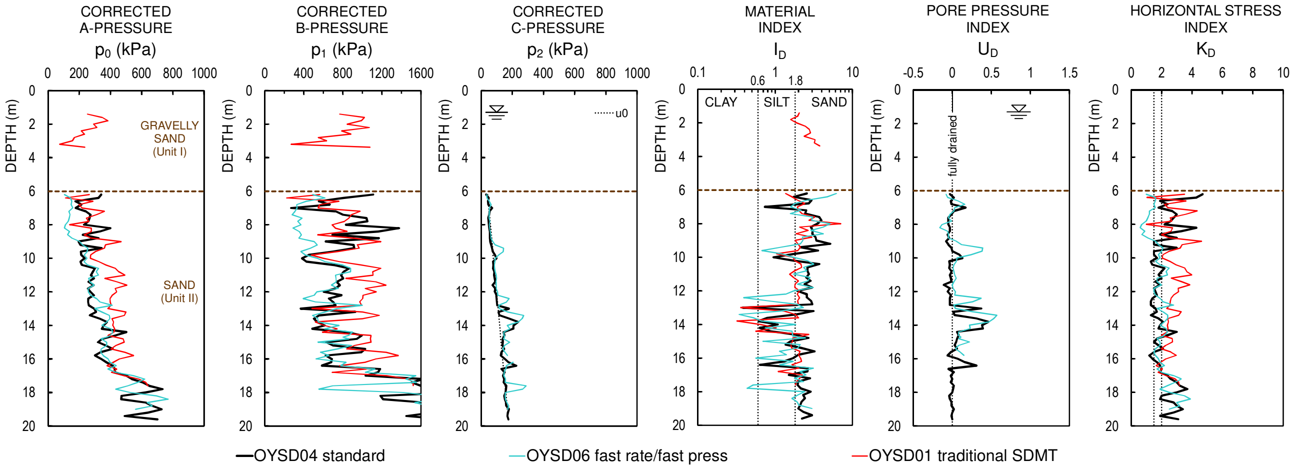

Figure 6. Øysand test site – Medusa (S)DMT results obtained at standard vs. faster penetration/pressurization rates and comparison with traditional SDMT (schematic soil stratigraphy after Quinteros et al. 2019).

compared with those provided by the standard Medusa SDMT (OYSD04), are also plotted in Fig. 6. The in-situ u_0 profile, shown in the p_2 graph, was assumed as hydrostatic with a groundwater table at 1.90 m, based on piezometer measurements. Fig. 6 highlights the following trends:

(a) In sand and silty sand (Unit II) the p_0, p_1, p_2 obtained using fast penetration/pressurization rates are very similar to the values obtained using the standard rates. This suggests that, differently from the Halden silt, the imposed variable penetration/pressurization rates do not modify the drainage conditions.

(b) The p_2 profile closely approximates the in-situ pore pressure u_0 and the derived $U_D \approx 0$ indicates fully drained response under any test rates, apart from a few silty layers where $p_2 > u_0$ and $U_D > 0$.

(c) The soil type classification based on I_D appears substantially correct.

(d) The profiles of p_0 and p_1 obtained by Medusa SDMT and traditional SDMT are substantially similar. Some scatter, observed at various depths, could be due to the variability of the sand deposit.

7. Conclusions

Benchmarking is of paramount importance for testing and validating innovative soil investigation methods. In this respect, the experimental program using Medusa SDMT at four NGTS Geo-Test Sites carried out in the H2020-GEOLAB TA project JELLYFISh could uniquely benefit of the availability of an existing large and consistent database obtained in past investigations from a variety of high quality in-situ and laboratory tests.

The soil deposits investigated in this project are commonly encountered in risk-sensitive areas. Improved soil characterization is a crucial step to identify and mitigate multiple geo-hazards that may severely impact the CI in Europe.

The technical features of the Medusa SDMT enable implementation of alternative test procedures and to perform additional measurements which are not feasible with the traditional pneumatic SDMT equipment. The increased accuracy of pressure measurements and controlled pressurization rate are particularly useful for testing very soft soils, in which the measured pressures are typically very small. The most promising achievements of this project derive from the application of innovative "non-standard" testing procedures in challenging geomaterials (i.e., intermediate soils, quick clays), which are usually difficult to characterize using common in-situ techniques. In intermediate soils Medusa SDMT tests carried out at variable penetration/ pressurization rates enable to identify some trends in soil response (e.g., a slower penetration/pressurization rate 'shifts' the interpretation towards drained behaviour). In sensitive clays, differently from non-sensitive clays, the continuous measurement of the total horizontal pressure during Medusa SDMT penetration provides significantly different pressure values compared to the standard procedure, suggesting a potential new approach for identification / mapping of quick clays.

Research is in progress aiming to analyse in-depth the Medusa SDMT data set obtained at the NGTS Geo-Test Sites, based on comparison with high quality in-situ and laboratory test data available from past investigations.

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