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Characterization of intermediate soils by innovative in-situ testing procedures using Medusa DMT

Caractérisation des sols intermédiaires par des procédures innovantes d'essais in-situ à l'aide de la Medusa DMT

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ABSTRACT: This paper illustrates early findings obtained using the Medusa DMT/SDMT – the newest fully automated version of the flat/seismic dilatometer – at the benchmark silt test site of Halden, Norway, part of the Geo-Test Sites (NGTS) research infrastructure managed by the Norwegian Geotechnical Institute. The comparison of results obtained by Medusa (S)DMT tests carried out adopting standard and variable penetration/pressurization rates permits to identify some trends in response to different test rates in the silt layers. These preliminary results support the potential of this approach for improving the in-situ characterization of intermediate soils.

RÉSUMÉ: Cet article illustre les premiers résultats obtenus à l'aide du Medusa DMT/SDMT – la version la plus récente entièrement automatisée du dilatomètre plat/sismique – sur le site d'essai de référence (limon) de Halden, Norvège, qui fait partie de l'infrastructure de recherche Geo-Test Sites (NGTS) gérée par Norwegian Geotechnical Institute. La comparaison des résultats obtenus par essais Medusa (S)DMT réalisés en adoptant des taux de pénétration/pressurisation standard et variables permet d'identifier certaines tendances en réponse à des taux d'essai différents dans les couches limoneuses. Ces résultats préliminaires attestent le potentiel de cette approche pour améliorer la caractérisation in-situ des sols intermédiaires.

Keywords: Intermediate soils; in-situ testing; Medusa DMT; benchmark 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. Improvements in geotechnical approaches to enhance the resilience of the CI rely significantly on an in-depth understanding of soil behaviour. A major challenge, due to uncertainties in assessing partial drainage effects, is the characterization of intermediate soils (silty sands, silts, sandy silts, and other soil mixtures), frequently encountered in densely populated and risk-sensitive areas. The results presented in this paper were obtained as part of 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) funded by H2020-GEOLAB. The project is based on an extensive in-situ testing campaign with the Medusa DMT/SDMT – the newest fully automated version of the flat/seismic dilatometer – 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. In particular, this paper presents early findings obtained from Medusa (S)DMT tests carried out in silts at the Halden test site, adopting both standard and variable penetration/pressurization rate test procedures.

2 MEDUSA SDMT EQUIPMENT AND TEST PROCEDURE

The Medusa DMT (Figure 1) 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. A motorized syringe hydraulically expands the membrane to obtain the DMT *A*, *B*, *C* pressure readings, which are acquired and stored automatically at each test depth. The probe can operate in cableless mode. An optional electric cable may be used to obtain real-time data during test execution. The Medusa SDMT incorporates additional sensors and components (Figure 1) for the measurement of the shear wave velocity, in addition to the DMT measurements. 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. 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. The automatic volume-controlled hydraulic pressurization of the membrane is highly repeatable and permits to impose a programmable timing to obtain the pressure readings, i.e., the standard timing or different time intervals corresponding to variable pressurization rates. This capability of the Medusa DMT has prompted its use for performing dilatometer tests adopting variable pressurization rates, in combination with variable penetration rates, to investigate the behaviour of intermediate soils.

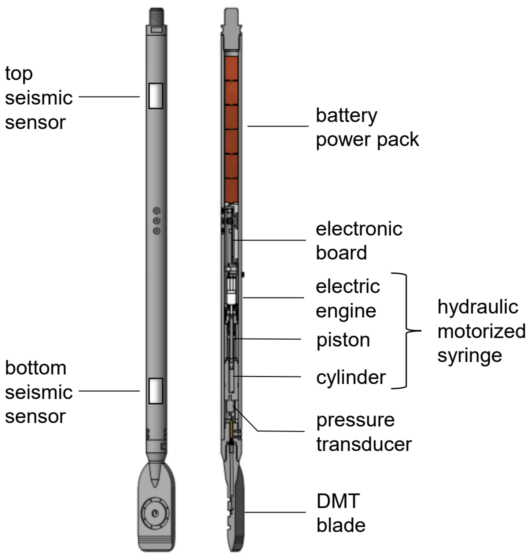

Figure 1. Medusa SDMT equipment.

3 MEDUSA SDMT TESTS AT HALDEN

3.1 Test site conditions

The Halden test site is located in south-eastern Norway, approximately 120 km south of Oslo. This site has been thoroughly characterized by geological, geophysical and geotechnical in-situ and laboratory tests. The stratigraphy of the Halden test site, reconstructed based on all available data (Blaker et al., 2019), includes four soil units down to 20 m:

- 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 soil unit weight is approximately 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 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 fairly constant at around 8% in Units II and III. The natural water content generally decreases with depth from about 31% at 4 m to about 26% at 16 m depth. The overconsolidation ratio is estimated in the range 1 to 1.3. The undrained shear strength in silt increases from 20-40 kPa at 5 m 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 from triaxial tests on block samples lies around 36°, with cohesion c' = 0.

3.2 Medusa (S)DMT testing program

The field testing program at Halden (Figure 2) included one Medusa SDMT sounding (HALD02) carried out by the standard procedure and four Medusa DMT soundings (HALD03 – HALD06) carried out adopting variable penetration rates (slower and faster than standard), combined with variable pressurization rates (slower and faster than standard) achieved by regulating different time intervals for the *A* and *B*

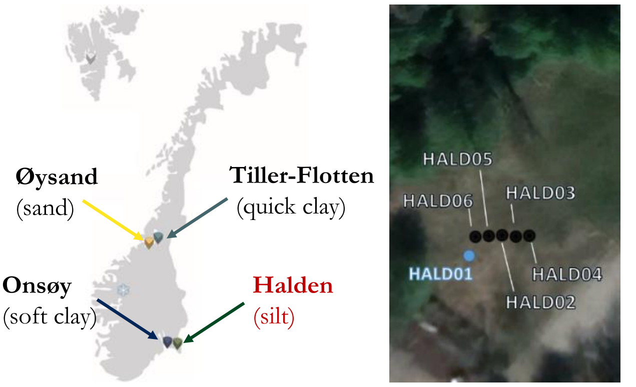

Figure 2. Location of Medusa (S)DMT (HALD02–HALD06) and traditional SDMT (HALD01) at Halden.

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

pressure readings (Table 1). Several Medusa DMTA dissipation tests were also carried out. 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. More details can be found in Monaco et al. (2023).

3.3 Medusa (S)DMT test results

Figure 3 summarizes some significant results obtained from Medusa (S)DMT tests at Halden, in terms of depth profiles of the DMT pressure readings p_0, p_1, p_2 (A, B, C corrected for membrane stiffness), as well as of the material index I_D and the pore pressure index U_D (Marchetti, 1980; Marchetti et al., 2001). 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 rate/slow press) and the "fastest" HALD06 (fast rate/fast press) are shown in Figure 3. The in-situ pore pressure u_0 profile, shown in the p_2 graph, was assumed as non-hydrostatic with a groundwater table at 1.30 m (u_0 = 155 kPa at 20 m depth), based on piezometer measurements. Figure 3 highlights that:

(a) The p_0 obtained using slow penetration/ pressurization rates in silt (Units II and III) 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 observed by Monaco et al. (2021) 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. Similar considerations apply 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 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 discern 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 silt Units II and III, which are wrongly classified as "very clayey" clays. Such misinterpretation, sometimes observed in the transition region of silt-mixture soils, 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 parameters obtained by common DMT interpretation are misleading.

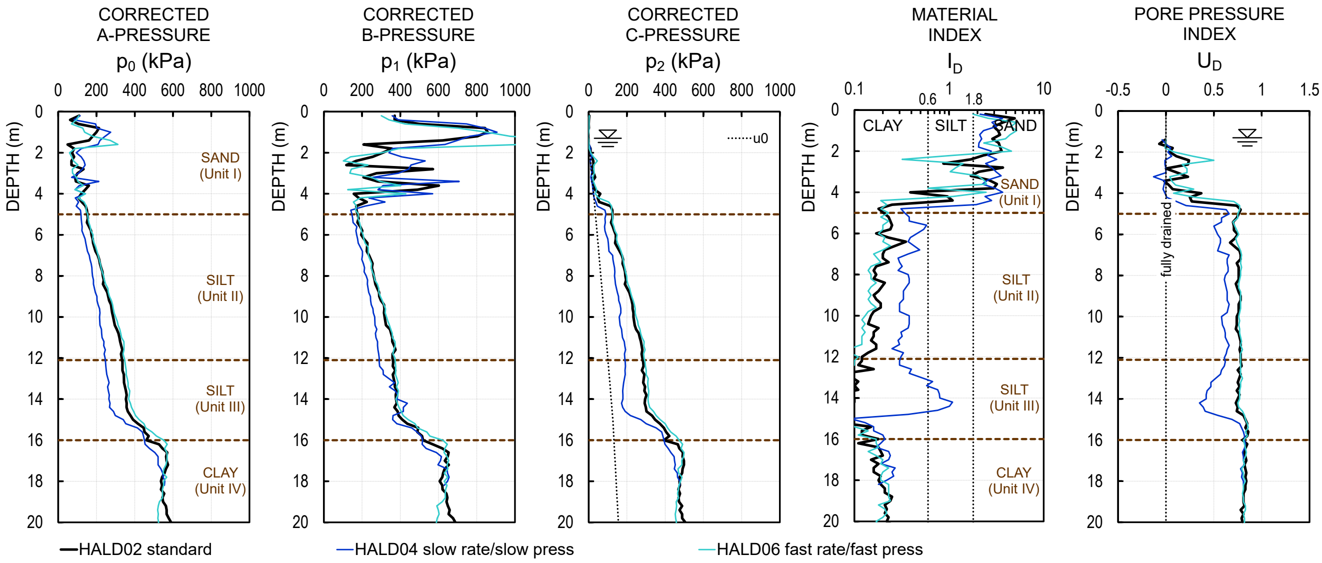

Figure 3. Combined effects of variable penetration and pressurization rates on Medusa (S)DMT results at the Halden test site (schematic soil stratigraphy after Blaker et al., 2019).

4 CONCLUSIONS

The preliminary results obtained at the Halden test site support the potential use of the Medusa (S)DMT for investigating the behaviour of intermediate soils by adopting variable penetration/pressurization rates. At Halden it was found that a slower (than standard) penetration/pressurization rate "shifts" the interpretation towards drained behaviour, while a faster (than standard) penetration/pressurization rate provides the same results obtained using the standard rates. This suggests that in the Halden silt the standard test rates impose fully undrained conditions, which do not evolve to "more undrained" using faster rates as observed in different silt deposits (Monaco et al., 2021). These results, combined with data available from previous investigations at the Halden site (e.g., variable-rate piezocone tests, Carroll and Paniagua, 2018) and from other well-documented silty sites, provide a basis for improving the in-situ characterization of intermediate soils.

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