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Research article

Comparing seismic piezocone and seismic dilatometer test results for the characterization of a coastal silt deposit from Finland

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Abstract: This paper focused on the performance comparison of in situ testing methods for geotechnical characterization of a silt deposit at Haistila, in western Finland, in the vicinity of the coastal city of Pori. Soil conditions comprise a homogeneous, up to 9 m thick, slightly overconsolidated silt deposit. The Haistila test site is part of the ongoing FINCONE II research project funded by the Finnish Transport Infrastructure Agency (FTIA, Väylävirasto) and carried out by Tampere University. Testing included piezocone along with in situ measurements of shear wave velocity (SCPTU), in addition to laboratory testing, including index and consolidation tests, among others. Furthermore, seismic dilatometer testing (SDMT), using the novel Medusa SDMT equipment and technology, was carried out at Haistila. This work documents the first known application of the flat dilatometer test (DMT) in geotechnical investigations carried out in Finland. The paper critically compares the SCPTU and Medusa SDMT outcomes and their applicability in the determination of site-specific engineering properties of Haistila silt. SCPTU and Medusa SDMT provide a similar interpretation in terms of soil stratigraphy, drainage, constrained modulus, and hydraulic properties of the soil deposits, while some discrepancies can be noted for stress history and strength, probably in relation to the availability of site-specific correlations only for SCPTU. Finally, remarkable differences are notable for shear wave velocity data due to the use of the 1-receiver configuration for SCPTU and the 2-receiver configuration for Medusa SDMT.

Keywords: silt; in situ testing; piezocone; seismic dilatometer; geotechnical testing

1. Introduction

The geotechnical characterization of silty deposits is still poorly understood due to the high variability of the soil mixtures (from silty clays to silty sands) that makes the interpretation difficult using the approaches available for standard sands or clays (e.g., [1]). In this respect, during the last decades, different authors conducted in-depth studies to evaluate the effect of partial drainage on these "intermediate soils" using piezocone (CPTU, e.g., [2–6]) and flat dilatometer (DMT, e.g., [7–10]) tests at standard and non-standard CPTU/DMT penetration rates and DMT membrane pressurization rates. These preliminary findings underline the importance of assessing drainage conditions, measuring pore pressures, and performing dissipation tests in order to lead to more realistic estimates of geotechnical properties.

In Finland, extensive research has been done on the determination and modeling of clay parameters from seismic and standard piezocone as well as laboratory testing (e.g., [11–35]). Early studies focused on field and laboratory investigations at benchmark sites and on the effects of sample disturbance and strain-softening [11,12,15,16,24,26,28,31]. Subsequent research refined CPTU interpretation and developed correlations for strength and deformation properties [17,21,23,25,29,30,33], while improving test reliability and equipment performance [18,19,22]. Recent studies expanded the use of seismic and database approaches for parameter characterization [13,14,20,32] and integrated field and laboratory data into numerical and reliability analyses [27,34,35]. However, research on silt testing and parameters is limited. In Finland, the determination of design parameters for silts is often based on tabulated values suggested in the guidelines [36], which have been in use for decades. This is due to the challenges in retrieving high-quality samples of silts for laboratory testing and interpreting traditional site investigation methods used in Finland, such as Swedish weight sounding and static-dynamic cone penetration testing [37]. The estimates are often conservative and do not fully aim for an optimal geotechnical design.

Tampere University, in collaboration with the Finnish Transport and Infrastructure Agency, has been carrying out a project named FINCONE II (2021–2025). The aim is to study the properties of silty and, partly, sandy soils by means of piezocone and laboratory testing, and to develop correlations specific to Finnish silt, supported by artificial intelligence–based tools for modeling layers in stratified deposits and enhancing the definition of engineering properties. Some initial results of FINCONE II have been presented in [38] in relation to sampling issues in silty soils.

The paper focuses on the performance comparison of in situ testing methods for geotechnical characterization of a silt deposit at Haistila in western Finland, in the vicinity of the coastal city of Pori (Figure 1). For the first time in Finland, a seismic dilatometer test (SDMT) was carried out at Haistila, using the novel Medusa SDMT equipment and technology. Preliminary in situ (seismic piezocone SCPTU) and laboratory test results from the FINCONE II research project are presented. The paper critically compares the SCPTU and Medusa SDMT outcomes and their applicability in the determination of site-specific engineering properties of Haistila silt based on initial laboratory test results. Note that the site is characterized by a relatively homogeneous soil profile, making it a suitable location for testing and comparing different in situ investigation methods.

2. Geological settings at Haistila and general site description

The geological history of the Pori region, located in the coastal zone of Satakunta in western Finland (Figure 1), is deeply influenced by glacial and post-glacial processes that shaped the landscape and sediment distribution of the area [39]. During the last Ice Age, the region was covered by thick continental ice sheets, which sculpted the bedrock and deposited a range of sediments as they advanced and retreated. As the glaciers melted and the Baltic basin evolved, extensive fine-grained sedimentation occurred in the low-lying areas, especially along ancient water bodies and estuaries.

The bedrock beneath the Pori region consists primarily of Precambrian rocks, including granites and metamorphic formations typical of the Svecofennian orogeny belt. However, a notable feature of the area is the presence of Satakunta sandstone, a quartz-rich sedimentary rock deposited in an ancient inland sea around 1300 million years ago. This sandstone underlies parts of the modern landscape and is locally overlain by thick glacial and post-glacial sediments. The bedrock is also dissected by deep fracture zones, which have influenced the development of sedimentary basins and controlled the distribution and thickness of younger deposits [39].

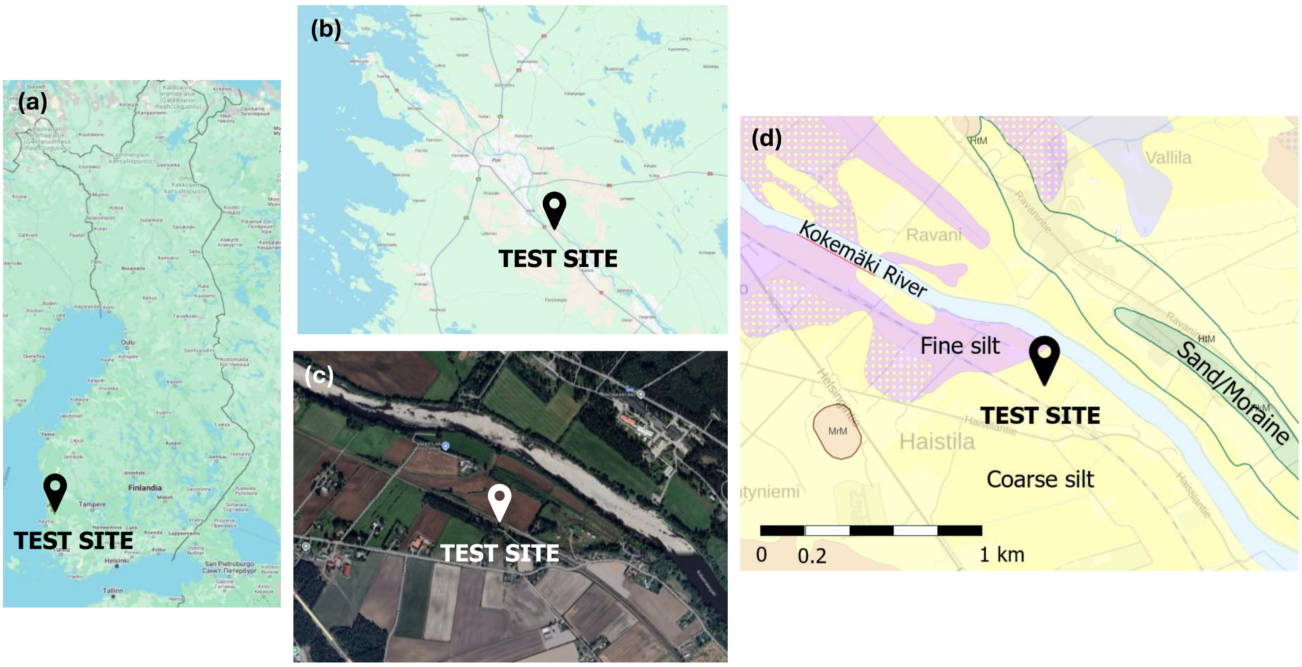

Figure 1. (a–c) Location of Haistila test site (Google Maps, coordinates 61.409080° N, 21.930159° E). (d) Surface geology (1 m depth) (GTK).

One of the most significant outcomes of this post-glacial phase was the deposition of fine-grained soils, including silts and clays, across large areas around Pori and the Kokemäki River delta. Meltwater from the retreating glacier transported and sorted sediments, depositing finer particles in quieter, low-energy aquatic environments. These silt-rich layers are typically found in former marine bays and glacial lake basins that later transformed into river valleys and coastal plains [39]. Figure 1d illustrates the surface geology in proximity to the test site. The map is extracted from the open-access repository by the Geological Survey of Finland (GTK; https://gtkdata.gtk.fi/maankamara/). The data map shows the sediment found as a basal deposit at a depth of 1 m below the ground level, thus indicating the presence of coarse silt at the Haistila test site.

In Pori, fine-grained soils, particularly silts, are widely distributed in low-lying topographic depressions and ancient shoreline environments. These deposits, often intermixed with clay and organic material, are underlain by older moraine and glaciofluvial formations. The stratigraphy reveals that the silts were mostly deposited in calm water conditions during the early phases of the Ancylus Lake and Litorina Sea stages of the Baltic Sea development. As land uplift continued due to isostatic rebound, these sediments were exposed and gradually became part of the modern river floodplains and agricultural fields [39].

In addition to post-glacial processes, local geological structures also influence the distribution of silty soils. The Pori area lies within a broader sedimentary basin shaped by deep bedrock fracture zones and glacial erosion. These depressions have acted as natural traps for fine sediments, contributing to the formation of thick silt sequences [39].

3. Site investigation and laboratory testing program

3.1. Medusa DMT/SDMT tests

The Medusa DMT (Figure 2a) 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 ([40,41]). 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 standard Medusa DMT test procedure is the same as for the traditional pneumatic DMT ([42,43]), 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 the start of pressurization and the *B*-pressure reading 15 s after the *A*-pressure reading. A high-accuracy absolute pressure transducer is used to measure the pressure generated by the motorized syringe and operating on the membrane. This sensor must provide pressure measurements with a resolution of 1 kPa, a reproducibility of 2.5 kPa, and an accuracy of at least 0.25% of the scale range. The pressure transducer has a standard scale range of 10 MPa. The automatic volume-controlled hydraulic pressurization of the membrane is highly repeatable and permits imposing 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 behavior of intermediate soils.

The Medusa SDMT incorporates additional sensors and components (Figure 2a) for the measurement of the shear wave velocity (V_s), in addition to the DMT measurements, as described by Marchetti et al. [44]. Shear wave velocity measurements are commonly performed at depth intervals of 0.50 m, while DMT readings are conducted every 0.20 m. The seismic module is a cylindrical element interposed between the bottom of the push rods and the DMT blade, equipped with two receivers fixed at a vertical distance of 0.50 m. The shear wave source, located at the ground surface, generally consists of a pendulum or manual hammer that strikes horizontally a rectangular steel plate pressed against the soil by the weight of a vertical load and oriented with its impact axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the generated shear wave. When a shear wave is generated at the surface, it first reaches the upper receiver and then, after a delay, the lower receiver. The seismograms acquired by the two receivers, amplified and digitized at depth, are transmitted to a computer at the surface for real-time interpretation of the V_S. The recorded signals are processed using the true-interval interpretation method (Figure 2b). V_S is obtained as the ratio between the difference in distance between the source and the two receivers (S_2–S_1) at the instant of the energization, assuming S_1 and S_2 as the straight shear wave travel paths, and the time delay in the arrival of the wave recorded at the lower and upper receiver (Δt), evaluated numerically using cross-correlation over the two wave traces.

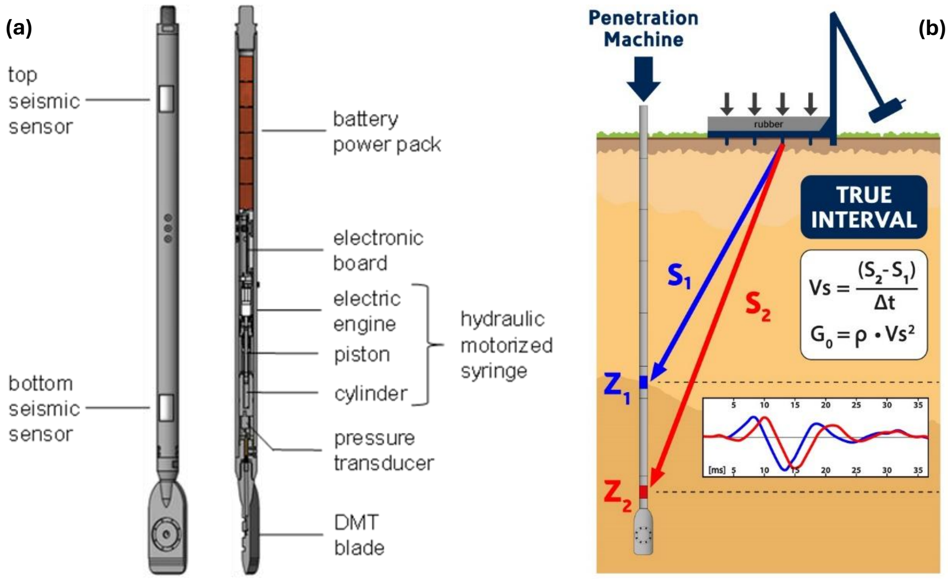

Figure 2. Medusa SDMT (a) equipment and (b) seismic test layout.

Considering the availability of both the seismic piezocone SCPTU and the Medusa SDMT tests at standard penetration rate (i.e., 20 mm/s) and at standard pressurization rate for the DMT membrane (i.e., time to *A*, *B* readings: 15 s), this paper focuses on the results obtained from the two different in situ test technologies in order to compare data interpretation. However, the Medusa SDMT testing program at Haistila also included four Medusa DMT tests performed by adopting slower (~4–5 mm/s) or faster (~67 mm/s) penetration rates than the standard, combined with slower (~7.5 s) or faster (~30 s) membrane pressurization rates than the standard. In addition, Medusa DMTA dissipation tests were carried out in three soundings at fixed depths (3.2, 4.2, 5.4, 6.2, and 7.2 m). All the Medusa DMT/SDMT soundings reached a depth of 10 m and were located in proximity to the SCPTU sounding.

3.2. Seismic piezocone (SCPTU) tests

The penetrometer adopted in this study is characterized by a 60° apex angle, a 10 cm^2 base, and a 150 cm^2 sleeve area. Recorded measurements during testing include cone tip resistance q_c, sleeve friction f_s, and pore pressure u_2 measured above the tip. It consists of an electronically instrumented probe with a nominal q_c, f_s, and u_2 maximum capacity of 50, 1.6, and 2.5 MPa, respectively. Measurement accuracy is 5 kPa for q_c (0.01%), 0.04 kPa for f_s (0.0025%), and 0.04 kPa for u_2 (0.0015%). The high accuracy of the penetrometer is the result of the embedded sensor types and their configurations. In particular, the q_c and f_s load cells are characterized by four strain gauges wired into a Wheatstone bridge configuration. The bridge is compensated with four modules: two for the material elastic modulus temperature compensation, one for the zero-offset correction, and the last one for zero-offset temperature compensation. The Wheatstone Bridge circuit consists of two simple series-parallel arrangements of resistances connected between a voltage supply terminal and ground, producing zero voltage difference between the two parallel branches when balanced. It has two input terminals and two output terminals consisting of four resistors configured in a diamond-like arrangement. This configuration allows for high accuracy in the measurement. Similarly, the sensor consists of a silicon piezoresistive load cell in the Wheatstone bridge configuration. The penetrometer is further equipped with a seismic module, which allows the measurement of shear (V_s). The seismic input is sent by a hammer drop generated at the surface at about 2 m horizontal distance from the receiver. The recorded signals, including both right and left sides of the beam, are processed using the pseudo-interval interpretation method according to Campanella and Stewart [45]. The cross-correlation of signals at adjacent depths is determined by shifting the lower signal, relative to the upper signal, in steps equal to the time interval between the digitized points of the signals. At each shift, the sum of the products of the signal amplitudes at each interval gives the cross-correlation for the shift. After shifting through all time intervals, the cross-correlation can be plotted versus the time shift, and the time shift giving the greatest sum is taken as the time shift interval used to calculate the interval velocity. Beyond the use of the cross-correlation, the V_s values are checked, also finding the peaks of succeeding signals in depth. Equipment calibration and testing at Haistila were carried out according to ISO 22476-1 standard [46] and ASTM D7400/D7400M-19 [47].

3.3. Available laboratory tests

The preliminary laboratory test results at the Haistila test site presented in this study include index tests, particle size distribution, and constant rate of strain (CRS) oedometer tests. An extensive laboratory testing campaign is ongoing and planned to be completed in the future; it will include triaxial, fall cone, and bender element tests. Sampling at Haistila was carried out to a depth of ≈7.5 m below ground level using the large 132 mm diameter Laval-type thin-walled open-drive sampler developed by Tampere University. The sampler and sampling procedure are described in detail by Di Buò et al. [24].

Figure 3 illustrates particle size distribution curves at four depths, between 2.65 and 7.3 m. The soil matrix mainly consists of silty material, with the size of fine-grained particles reducing with depth. The shallow sample at 2.65 m contains 27% of sand, while the sand percentage in the deeper samples is <10%. Clay content is negligible above 4 m, while it increases with depth from 2% to 8%.

Figure 4 summarizes measured index and oedometer parameters at Haistila. The bulk unit weight is in the range γ = 15.6–18.5 kN/m^3, with the highest values measured in the shallow sandy layer and at depth of 7.3 m. The unit weight trend is in line with the measured natural water content (w), showing the lowest value (34%) close to the surface, increasing with depth up to 64% before decreasing to 40%

at 7.3 m depth. The plasticity index *PI*, calculated as the difference between the liquid limit (*LL*) and the plastic limit (*PL*), is in the range of 3%–24 %, with the highest value measured at ≈6 m depth.

The preconsolidation stress (σ'_p) inferred from CRS tests is in the order of 90–125 kPa, without showing a well-defined trend with depth. The soil appears to be slightly overconsolidated, with pre-overburden pressure ($POP = \sigma'_p - \sigma'_{v0}$, where σ'_{v0} is the in situ vertical effective stress) of 50–70 kPa. This is possibly the result of a combination of ageing and erosion across the Kokemäki river valley and is in line with the overconsolidation of soft clays from the coastal areas of Finland (e.g., [29]). Note that the oedometer curves display a change in curvature in the natural ε_a-σ'_{v0} plot when transitioning from the overconsolidated to the normally consolidated state. The strain reached at preconsolidation stress is in the range 5%–7%.

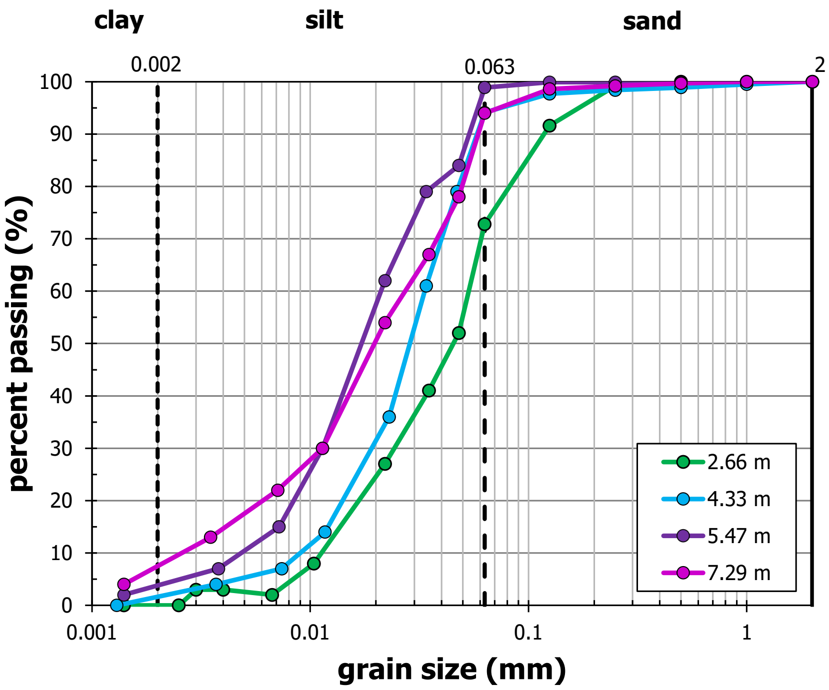

Figure 3. Particle size distribution at Haistila.

Figure 4 further illustrates the constrained modulus *M* and the vertical hydraulic conductivity k_v at the in situ vertical effective stress based on CRS test results. The values of *M* range between 1.75 and 2.5 MPa, slightly increasing with depth, while k_v falls in the range from 2×10^{-8} to 2×10^{-9} m/s, decreasing with depth.

4. Results

Figure 5 and Figure 6 summarize the results of the basic measurements acquired by both the in situ test equipment and the related interpretation for the drainage conditions and soil type at the Haistila site. Given the homogeneity of the site, only one benchmark SCPTU and Medusa DMT at standard rates are used for comparison.

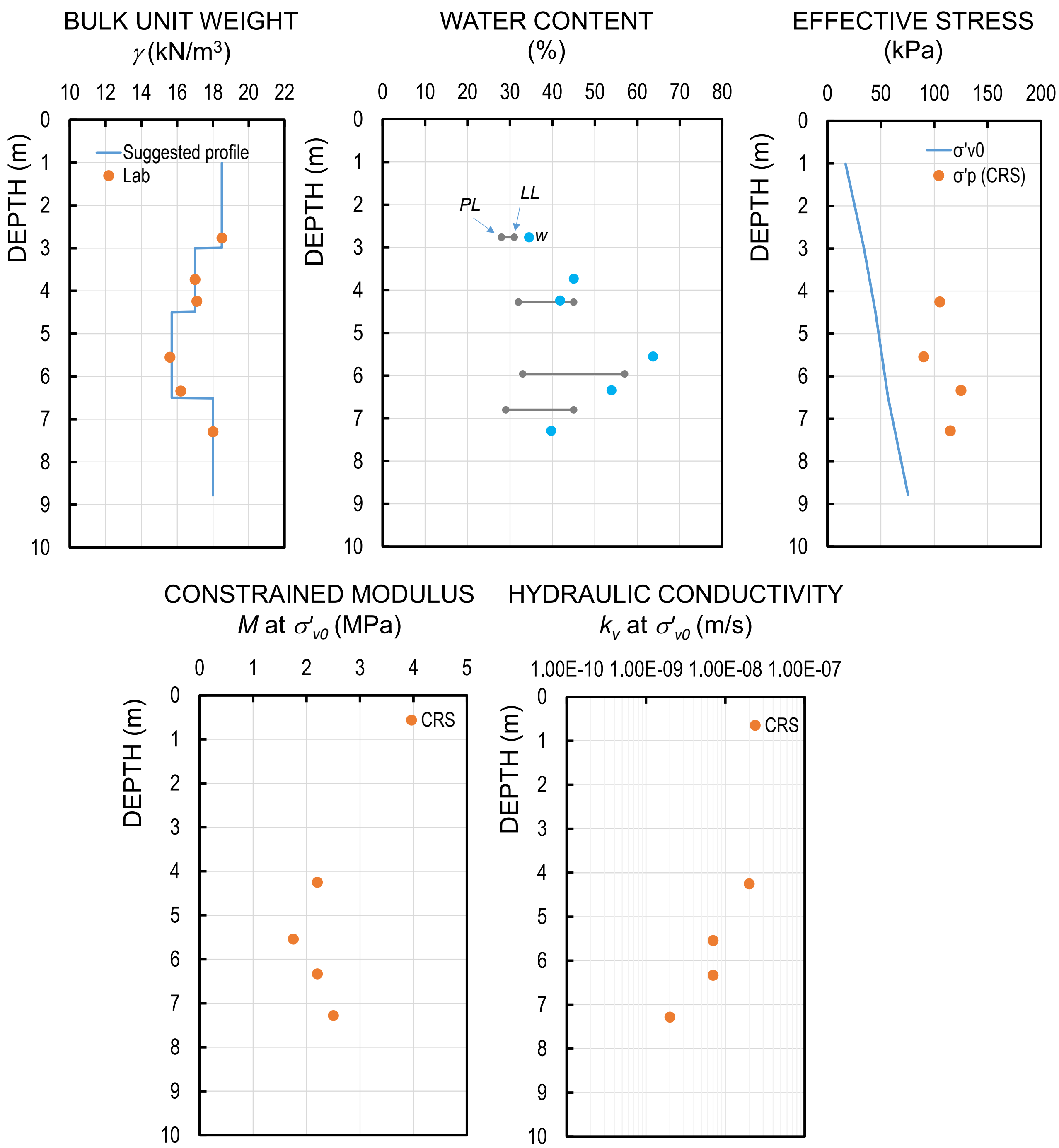

Figure 4. Soil properties at Haistila.

Figure 5 provides, for the SCPTU, the corrected cone resistance (q_t), the pore pressure (u_2) combined with the hydrostatic pore water pressure (u_0), the pore pressure ratio (B_q), and the soil behavior type index (I_c) according to [48]. Moreover, Figure 6 plots, for the Medusa SDMT, the first and second corrected pressure readings (p_0 and p_1), the third corrected reading (p_2) superimposed on the u_0 profile, the pore pressure index (U_D), and the material index (I_D) according to [49]. Both I_c and I_D profiles, indicators of mechanical soil response and not strictly of grain size, agree to identify sands and silty sands in the upper 3.5 m depth, followed by a silt mixture, variable from clayey silt to silty clay, up to 10 m depth. B_q and U_D can also help to enhance the characterization of the soil behavior provided by I_c and I_D, as recently suggested by Benoît and Souza ([50]): the sands and silty sands result in fully drained ($B_q \sim 0$ and $U_D \sim 0$), while in the silt mixture, both B_q and U_D profiles move gradually toward an undrained behavior up to 6.5 m. In the bottom layer, the SCPTU and Medusa SDMT interpretations show some discrepancies in terms of drainage, probably in relation to some lithological variability, even though SDMT testing was carried out within a radius of 5 m from the benchmark SCPTU location. The groundwater table is located at 0.85 m below the ground surface according to piezometer measurements, as detected by u_2 and, even more clearly, by p_2 in the drained layers.

The SCPTU and Medusa SDMT data were elaborated using both the unit weight (γ) provided by interpretation of the in situ tests (i.e., γ_{CPT} for the SCPTU according to Mayne [51] and γ_{DMT} for the Medusa SDMT according to [52]) and laboratory tests (γ_{lab}). Figure 7 shows the unit weight profiles estimated from SCPTU and Medusa SDMT combined with the laboratory measurements. Both the in situ predictions fit quite well with the laboratory data at 5.55 and 6.34 m, while some discrepancies are observable in the silty sands and in the upper and lower portions of the silt mixture. These differences may have a potential impact on the derived geotechnical parameters and, consequently, on the engineering design. Therefore, it can be suitable to estimate the geotechnical parameters using the unit weight from in situ tests as a first attempt, and then to update the calculations using the unit weight from laboratory tests, if available. In this respect, Haistila data were elaborated using both approaches.

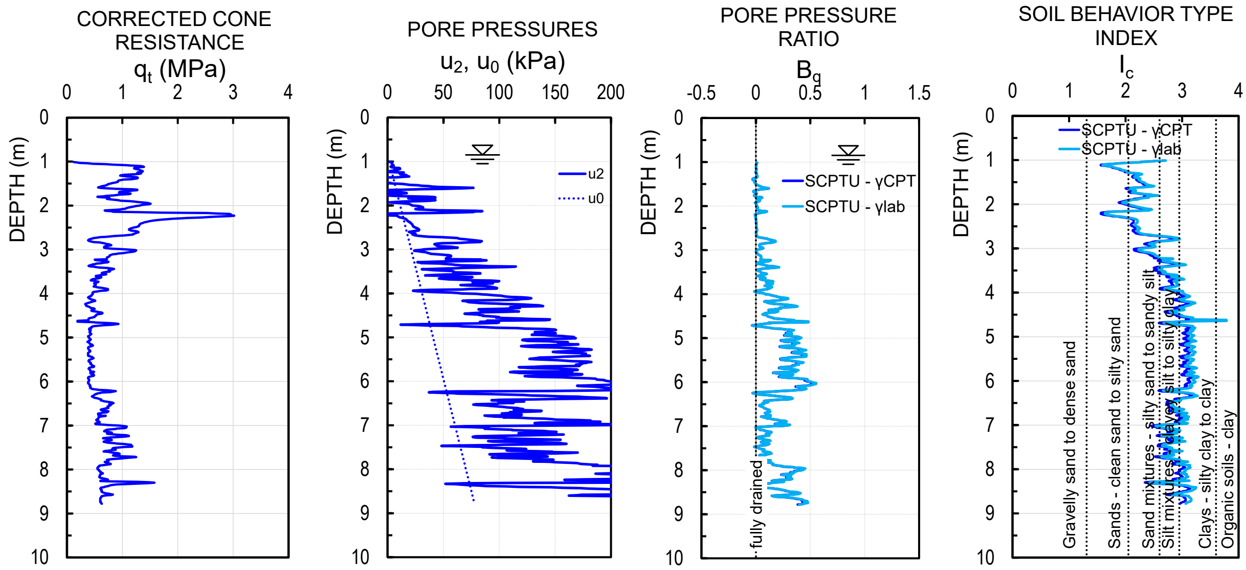

Figure 5. In situ CPTU measurements, drainage, and soil type interpretation.

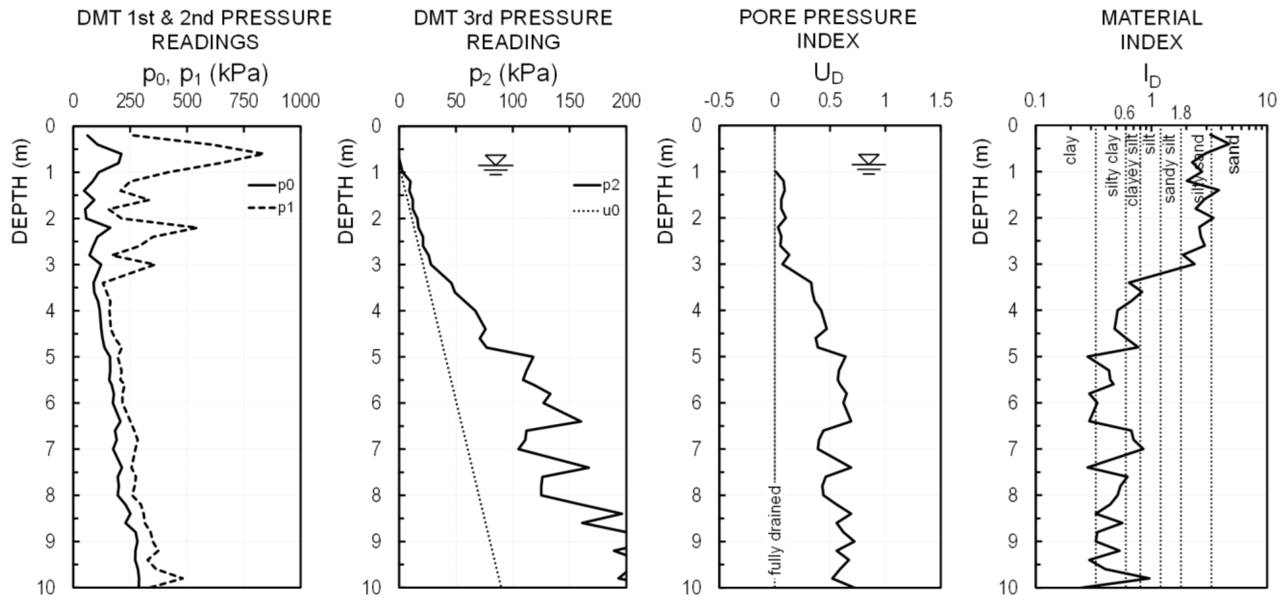

Figure 6. In situ Medusa DMT measurements, drainage, and soil type interpretation.

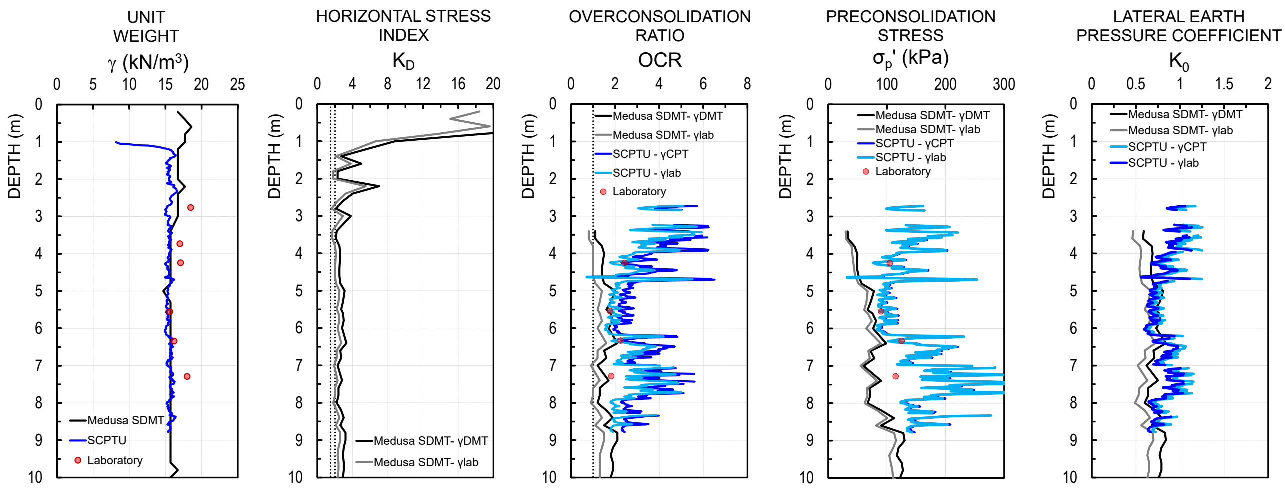

Figure 7. Comparison of unit weight and stress history parameters using SCPTU, Medusa SDMT, and laboratory tests.

Figure 7 also plots the stress history parameters. According to [49], for the Medusa SDMT test, the horizontal stress index (K_D) is provided in all soil types, while the overconsolidation ratio ($OCR = \sigma'_p/\sigma'_{v0}$), the preconsolidation stress (σ'_p), and the lateral earth pressure coefficient (K_0) are estimated in cohesive soils ($I_D < 1.2$). With reference to the SCPTU test in cohesive soils ($I_c > 2.6$), OCR and σ'_p are evaluated according to Di Buò et al. [25], while K_0 is estimated using Kulhawy and Mayne [53]. The interpretation of the stress history parameters from Medusa SDMT data appears sensitive to the selection of the unit weight. In fact, the K_D, OCR, σ'_p, and K_0 profiles are slightly higher when using γ_{DMT} than γ_{lab}. For the SCPTU, these differences are less pronounced when looking at the OCR interpretation, and the σ'_p profiles using γ_{CPT} and γ_{lab} are almost coincident.

Finally, data from oedometer tests are reported in Figure 7. Laboratory measurements indicate that the silt mixture results are slightly overconsolidated ($OCR \sim 1.72$–2.43). This behavior is partly captured by the in situ test methods: for the silt mixture between 4.25 and 6.33 m depth, the SCPTU agrees with the laboratory data in terms of *OCR* using γ_{lab}, and of σ'_p using both γ_{CPT} and γ_{lab}, while the Medusa SDMT approximates better the laboratory *OCR* only between 5.54 and 7.28 m depth using γ_{DMT} rather than using γ_{lab}. This discrepancy may be related to the use of *OCR* and σ'_p site-specific correlations calibrated in Finnish soils for the SCPTU, while similar calibrations are absent for the Medusa SDMT, this being the first time that dilatometer testing is performed in Finland. The only "geographically closer" *OCR* site-specific correlations from DMT were developed in Norway by Lacasse and Lunne [54] and Lunne et al. [55], but they are not applicable at the Haistila site since they are valid for clays.

Figure 8 shows the shear strength parameters estimated using the fall cone test data. The profile of the undrained shear strength (s_u) is obtained for the SCPTU according to [29], using the SHANSEP-based equation (1):

$$\frac{s_u}{\sigma'_v} = \left(\frac{s_u}{\sigma'_v}\right)_{NC} \cdot OCR^m = S \cdot OCR^m \tag{1}$$

where $S = (s_u/\sigma'_{v0})_{NC}$ is the normalized normally consolidated undrained shear strength, *OCR* is the overconsolidation ratio, and *m* is a stress exponent. For Finnish clays, D'Ignazio et al. [29] suggested $S = 0.24$ and $m = 0.76$. For $m = 1$, $s_u = S{\cdot}\sigma'_p$. For Finnish clays with $OCR < 4$, D'Ignazio and Länsivaara [14] suggested $S = 0.23$.

The N_{kt} values in Figure 8 are calculated according to equation (2):

$$N_{kt} = \frac{q_t - \sigma_v}{s_u} \tag{2}$$

where σ_v is the total vertical stress. Values of N_{kt} in the range 15–21 are observed, in line with Finnish engineering practice in soft clays and silts, with N_{kt} increasing with increasing *OCR* as highlighted by D'Ignazio and Lehtonen [35].

The s_u from the Medusa SDMT is interpreted according to Marchetti [49] with a formula similar to equation (1), where *OCR* is taken into account. The s_u predictions from Medusa SDMT and SCPTU are close only between 5.0 and 6.2 m depth, and both are non-sensitive to the selection of the unit weight. Laboratory data points are also superimposed on the in situ estimations considering $s_u \sim 0.23\ \sigma'_p$ [14]. As already obtained for the stress-history parameters, the SCPTU data fit well with the laboratory measurements, while the Medusa SDMT results underestimate the oedometer data. This behavior can again be related to the absence of site-specific correlations in Finland. As recently underlined by Monaco et al. [56], the Marchetti [49] equation depends on the normally consolidated strength $(s_u/\sigma'_{v0})_{NC}$ that is assumed to be equal to 0.22, based on in situ and laboratory tests performed on Italian clays. Therefore, this value may need to be calibrated in Finland for SDMT, as similarly done in Norway by Lacasse and Lunne [54]. Nevertheless, the main misalignment between the SCPTU and SDMT s_u interpretations is in the different *OCR* values used as an input to the transformation models.

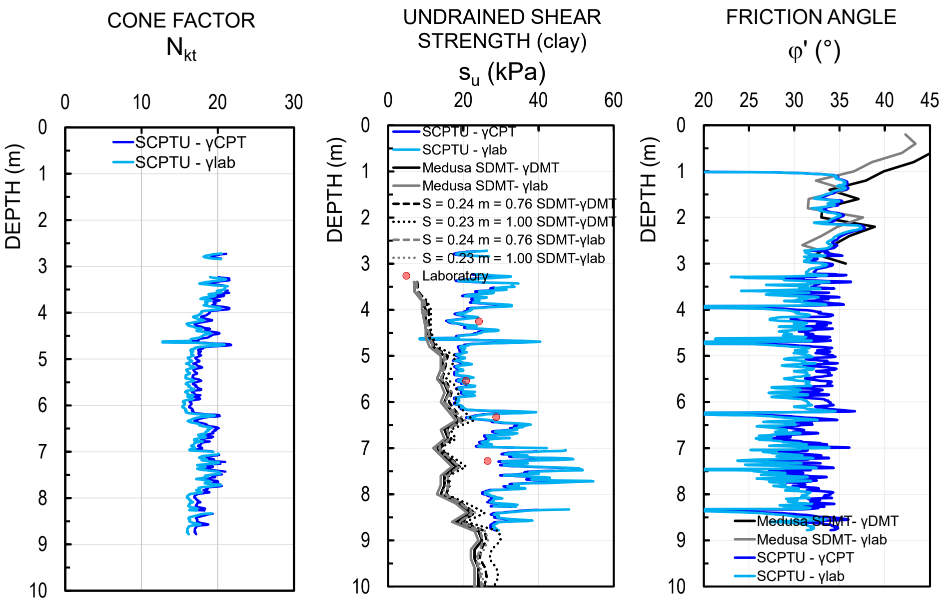

Figure 8. Comparison of shear strength parameters using SCPTU, Medusa SDMT, and laboratory tests.

Finally, Figure 8 includes the friction angle (*φ'*) profiles obtained from SCPTU according to [49] and from Medusa SDMT in cohesionless soils ($I_D > 1.8$) according to Marchetti [57]. In sands and silty sands, the comparison of the two in situ tests provides a good agreement. Finnish design guidelines [36] suggest $\varphi' = 28–32°$ for loose to dense coarse silt, in the absence of site-specific laboratory data. The preliminary interpretation suggests potentially larger values of *φ'*, potentially affecting geotechnical design. Triaxial testing of Haistila silt, which is planned in the future, shall be used to validate such interpretation and/or to develop site-specific correlations.

Figure 9 provides a preliminary estimation of the hydraulic conductivity and of the consolidation coefficient in the vertical direction (k_v and c_v) using the I_c from SCPTU data according to Robertson [58]. The use of the logarithmic scale on the x-axis enhances the difference between the k_h (or c_h) profiles obtained using γ_{CPT} and γ_{lab}, although the variability is minimal. Figure 9 also plots the hydraulic conductivity and the consolidation coefficient in the horizontal direction k_h and c_h, estimated from the Medusa SDMT dissipation tests according to the DMTA interpretation method proposed by Marchetti and Totani [59]. Finally, the k_v and c_v data are reported in Figure 9 from oedometer tests. Discrepancies, highlighted by the logarithmic scale, are visible in Figure 9 comparing the k_v and c_v profiles from the laboratory and from the SCPTU. However, this difference is not unexpected since the estimation by SCPTU is associated with in situ test correlations and not dissipation tests that are generally considered more reliable. Finally, the laboratory data (k_v and c_v) and the Medusa SDMT (k_h and c_h) provide values generally in the same order of magnitude, with $c_h > c_v$ and $k_h > k_v$. As deeply discussed in the literature, this aspect can be possibly related to the anisotropy of the soil deposits, easily reaching values of the ratio $c_h / c_v \approx 5–10$ (e.g., [59,60]).

Figure 10 provides the profiles of the constrained modulus (M) at σ'_{v0} obtained from the SCPTU ([30]), the Medusa SDMT ([49]), and oedometer tests. The in situ and laboratory tests are in good agreement in the entire layer of the silt mixture. As already observed for the s_u profile, the M profile from SCPTU and Medusa SDMT is not sensitive to the selection of the unit weight.

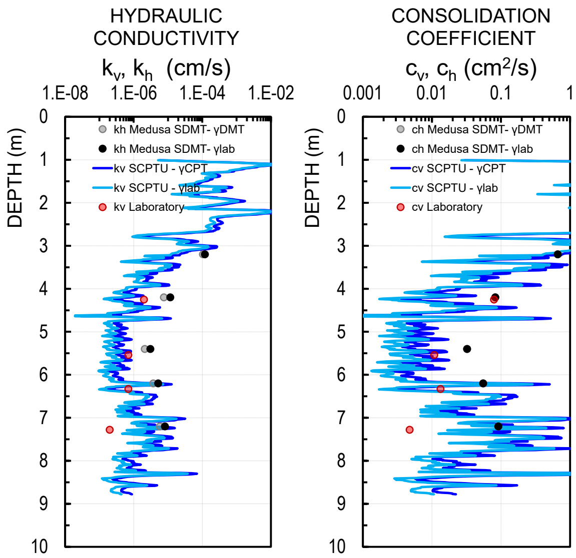

Figure 9. Comparison of hydraulic conductivity and consolidation coefficient using SCPTU, Medusa SDMT, and laboratory tests.

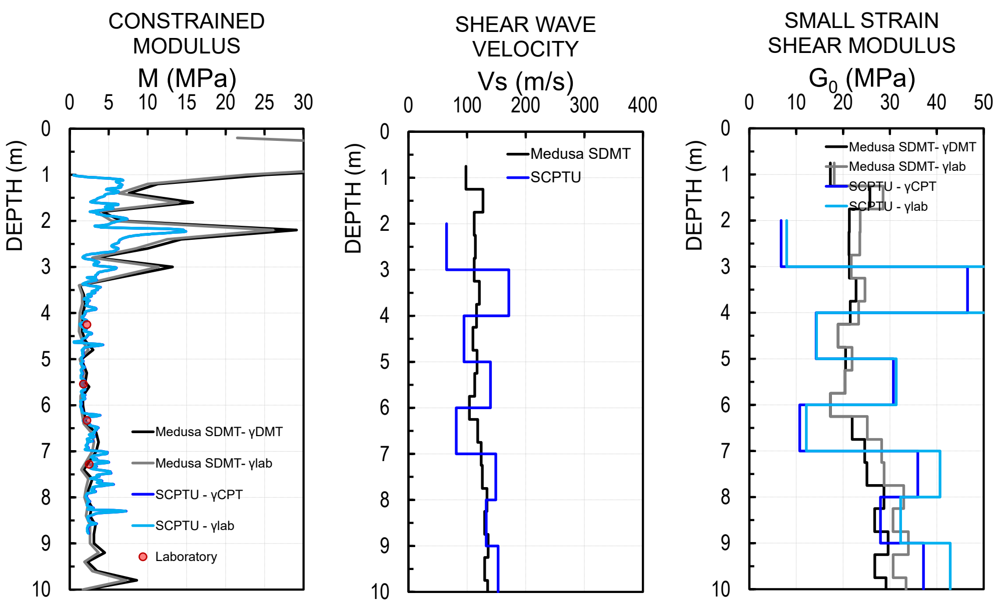

Figure 10. Comparison of stiffness parameters and shear wave velocity using SCPTU, Medusa SDMT, and laboratory tests.

Figure 10 also reports the measurements of the shear wave velocity (V_s) and small-strain shear modulus (G_0, obtained from V_s through the theory of elasticity) from SCPTU and Medusa SDMT. An example of seismograms acquired and interpreted by Medusa SDMT and SCPTU is reported in Figure 11. Significant discrepancies are visible by comparing the two profiles. Both tests were performed using the downhole configuration, in which the wave source is located at the ground surface, and the receivers are located at depth in the seismic module of the probe. At the Haistila site, the Medusa SDMT acquired the S-waves every 0.5 m depth using two geophones, spaced 0.5 m, and the seismograms were interpreted using a "true-interval" approach using a cross-correlation algorithm

(Figure 11a). The SCPTU measurements were conducted at every 1.0 m intervals. The seismic module of the CPTU contained a single geophone used as the receiver of the seismic waves. In this "pseudo interval" measuring system (Campanella and Stewart [45]), the travel time at depth interval [*a*-*b*] was measured by comparing the two detected waves at depths *a* and *b*, as the received waves at depths 5.0 and 6.0 m illustrated in Figure 11b. Accordingly, the time lag between the succeeding received signals and the travel distance was used to calculate the shear wave velocity, V_s. The notable difference between the V_s profiles from Medusa SDMT and SCPTU in Figure 10, and the derived G_0 profiles, is most probably due to the different interpretation method adopted in relation to the 1-receiver (SCPTU) or 2-receiver (SDMT) configuration. A detailed discussion on this point is provided in the following section. Estimation of the shear wave velocity can also be performed using the preconsolidation stress according to the correlation proposed in Finnish soil deposits by [21].

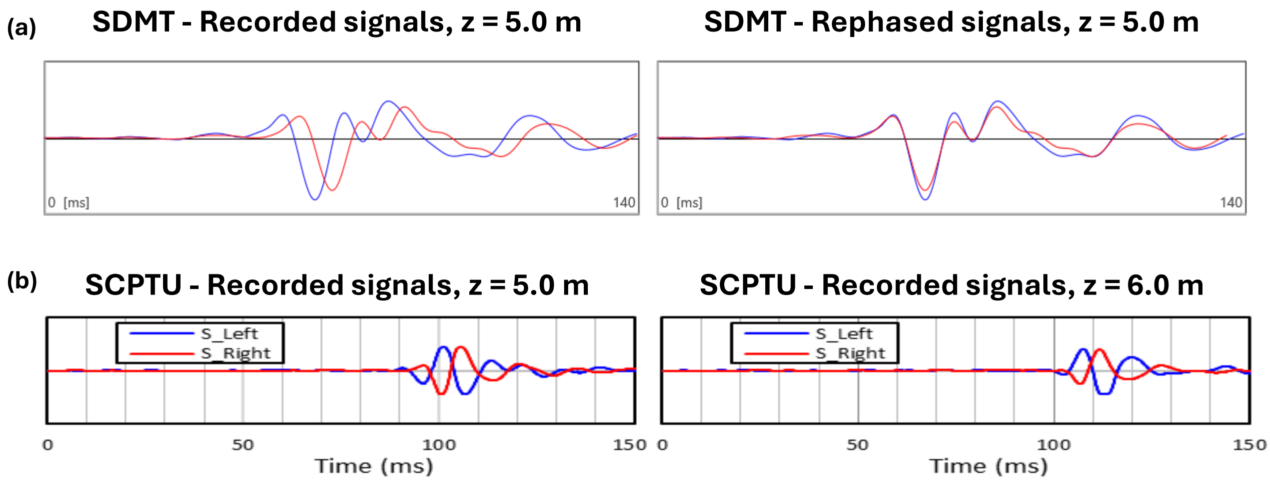

Figure 11. Seismograms from the in situ tests at Haistila site: (a) Recorded and rephased signals at 5 m depth from Medusa SDMT; (b) recorded signals at 5 and 6 m depth from SCPTU.

5. Discussion

The comparison between SCPTU and Medusa SDMT results at the Haistila test site demonstrates both the potential and the current limitations of in situ testing in Finnish silty soils. While the two methods provided a broadly consistent stratigraphic, behavioral characterization and working-strain modulus of the deposit, key differences emerged in interpreted parameters, particularly those linked to stress history and shear strength, largely due to the absence of site-specific SDMT correlations.

Both tests effectively identified the upper 3.5 m as sands and silty sands, underlain by a more cohesive silt mixture extending to 10 m depth. The interpretation of drainage conditions using B_q (SCPTU) and U_D (SDMT) reinforced the stratigraphic observations and indicated a shift from drained to undrained behavior with depth. However, minor discrepancies near the base of the profile suggest the presence of lithological heterogeneity.

In terms of stress history, SCPTU results (OCR, σ'_p) showed good agreement with CRS oedometer test data when using measured unit weights, while the SDMT tended to overestimate these parameters depending on whether laboratory or in situ γ-values were applied. This difference is likely a consequence of using empirical SDMT correlations developed outside Finland, highlighting the need for calibration to local sediment conditions. Similarly, the underestimation of the undrained shear strength by SDMT further highlights the influence of regional calibration, while SCPTU estimates aligned well with laboratory values. The DMT strength and stress history correlations have been deeply validated all over the world in clay (e.g., Marchetti et al. [61]), while the Haistila soil deposits are composed mainly by silt. While the clay is generally undrained, the silt is an intermediate soil that can have a "sand-like" or "clay-like" behavior [9,10]. Therefore, considering that, for DMT, both *OCR* and s_u depend on K_D, and therefore on the first DMT pressure readings [49] acquired 15 s after the start of the pressurization, while for CPTU the same stress history and strength parameters are related to q_t, measured at the same instant of the penetration into the ground, the DMT interpretation of the Haistila silt may be influenced by the partial drainage of the first DMT reading, making the use of the available DMT correlations developed for clay unreliable.

The limited number of laboratory data points (i.e., four analyzed undisturbed samples) makes it difficult to estimate new correction factors for the interpretation of the stress history and strength SDMT parameters in Finnish silts, since the trend of the data is not clear. Also, considering that s_u from SDMT is obtained using the SHANSEP-based equation (1) according to [49], a first attempt has been made correcting s_u by applying the same correction factors used for the SCPTU at the Haistila site:

- $S = 0.24$ and $m = 0.76$ (black and gray dashed lines in Figure 8),
- $S = 0.23$ and $m = 1.00$ (black and gray dot lines in Figure 8).

Limited improvement is visible from the additional tentative s_u profiles and, therefore, further calibration is necessary using a conspicuous number of laboratory data. Finally, significant discrepancies in shear wave velocity (V_s) between SCPTU and SDMT were notable and deserve further investigation, particularly as V_s is essential for small-strain stiffness estimation. The observed variability may be linked to differences in seismic receiver configuration (1-receiver for SCPTU and 2-receiver SDMT configuration) and signal processing techniques. As deeply discussed in the literature (e.g., McGillivray and Mayne [62]), the 1-receiver configuration for downhole tests has been long identified as problematic. The true-interval configuration using two receivers is very effective for the wave delay evaluation, because it relies on the same wave travelling to both receivers, as opposed to the pseudo-interval configuration in which two distinct waves are generated and recorded by a single receiver at different depths. Furthermore, the true-interval configuration is not affected by possible inaccuracies typical of the pseudo-interval configuration related to the "zero time" (trigger): in the true-interval configuration, the time origin is common to both wave traces independently of the trigger instant; in the pseudo-interval configuration, on the other hand, the difference between two subsequent first arrivals is usually very small and, therefore, their identification could vary among different operators, resulting in a magnification of the measurement error (e.g., Garofalo et al. [63]). In addition, the cross-correlation delay evaluation relies on the analysis of two waveforms rather than relying only on a single—subjectively selected—first arrival time on each wave trace (e.g., [64,65]). The typically observed repeatability of V_S measurements obtained by SDMT is remarkable (≈1%, i.e., a few m/s [44]). Estimates of hydraulic conductivity and consolidation coefficients from both in situ methods were broadly consistent with laboratory data, though small differences, visible in the logarithmic scale, likely reflect the anisotropic nature of the silty deposit.

6. Conclusions

This study presents the first comparative assessment of SCPTU and Medusa SDMT testing at a coastal silt site in Finland, and, for the first time, an application of SDMT in the country. SCPTU and Medusa SDMT provide a similar interpretation in terms of soil stratigraphy, drainage, constrained modulus, and hydraulic properties of the soil deposits, while some discrepancies can be noted for stress history and strength, probably due to the availability of regional correlations only for SCPTU. The use of 1-receiver configuration for SCPTU and 2-receivers configuration for Medusa SDMT marked the differences in data acquisition and interpretation for the shear wave velocity, enhancing the use of the true-interval configuration for future geophysical S-wave in-hole acquisition in Finland.

Due to the limited number of laboratory data to validate the available in situ testing correlations, the unclear trend of combined laboratory–Medusa SDMT data, and the intermediate behavior of the Haistila deposit, this paper cannot propose correction factors for stress history and strength parameters in Finnish silts, highlighting the need for further investigations.

Future research at the Haistila site will include an extensive laboratory testing program, including triaxial and bender element tests, to enhance the understanding of the mechanical and hydraulic behavior of Finnish silts. Moreover, an in-depth analysis of the Medusa SDMT tests performed at variable penetration and pressurization rates, as well as combined CPTU and SDMT soundings, will help identify depth intervals with differing drainage conditions in intermediate soils. Altogether, these data will support the development of site-specific correlations for both SCPTU and SDMT, providing a foundation for more accurate interpretation and confident application of in-situ testing methods in glacial and post-glacial silt environments.

From an industry perspective, this work demonstrates the growing potential to characterize silts more accurately using advanced in situ testing. As the geotechnical community moves toward better-informed and more site-specific interpretations, design practices can become more reliable, cost-efficient, and sustainable. By reducing reliance on overly conservative tabulated parameters and moving toward modern tools calibrated for local soils, the industry can improve both safety margins and material use in infrastructure development.

Author contributions

Sara Amoroso: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft; Mohammad Sadegh Farhadi: Conceptualization, Formal analysis, Investigation, Visualization, Writing—original draft; Marco D'Ignazio: Conceptualization, Formal analysis, Methodology, Visualization, Writing—original draft; Paola Monaco: Supervision, Validation, Writing—review & editing; Diego Marchetti: Investigation, Resources, Funding acquisition, Writing—review & editing; Tim Länsivaara: Supervision, Writing—review & editing.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of Interest

The Authors declare that they have no conflicts of interests with the data presented in this paper. Marco D'Ignazio and Tim Länsivaara are guest editors for AIMS Geosciences and were not involved in the editorial review or the decision to publish this article.

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