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# In-situ Rate-Dependent Behavior of Finnish Silts by Flat Dilatometer and Piezocone Testing

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ABSTRACT: This study investigates the performance of flat dilatometer (DMT) and piezocone (CPTU) testing conducted at the silt-dominated site of Haistila, in western Finland, in the vicinity of the coastal city of Pori. Silty soils present unique challenges for site characterization due to their intermediate grain size and variable behavior, necessitating refined approaches to in-situ testing and interpretation. By performing DMT at varying rates, the research explores the sensitivity of test results to rate effects, highlighting implications for soil classification and the determination of engineering properties. Comparative analysis of DMT and CPTU data provides insights into the reliability and complementarity of these testing methods in silt deposits. Emphasis is placed on correlations between derived parameters, such as soil type indices and drainage interpretation, to better understand the influence of rate dependency on engineering assessments. The findings contribute to enhanced methodologies for geotechnical site investigations in silty soils, supporting improved accuracy in characterizing mechanical behavior and informing design decisions for infrastructure projects in similar geological settings.

KEYWORDS: silts, rate effects, flat dilatometer, piezocone, in-situ 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 interpretation difficult using existing approaches developed for standard sands or clays (e.g., Schnaid et al. 2004). In this respect, during the last decades different authors developed in-depth studies to evaluate the effect of partial drainage on these "intermediate soils" using piezocone (CPTU) and flat dilatometer (DMT) tests at standard and non-standard CPTU/DMT penetration rates and DMT membrane pressurization rates (e.g., Tonni & Gottardi 2010, Randolph & Hope 2004, Schnaid et al. 2016, Monaco et al. 2024). These preliminary findings underline the importance of assessing the drainage conditions measuring the pore pressures and performing dissipation tests in order to provide more realistic estimates of the geotechnical properties.

In Finland, extensive research has been done on the determination and modelling of clay parameters from seismic and standard piezocone as well as from laboratory and field vane testing (e.g., Di Buò et al. 2018, Selänpää et al. 2017, Selänpää et al. 2018, D'Ignazio et al. 2022, Di Buò et al. 2020). However, research on silt testing and modelling is limited. In Finland, the determination of design parameters for silts is often based on tabulated values suggested in the national guidelines, 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. The estimates are often conservative and not fully aiming to 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 properties of silty soils by means of piezocone and laboratory testing, and to develop correlations specific to Finnish silts, supported by artificial intelligence-based tools for modelling layers in stratified deposits and enhance the definition of engineering properties. Some initial results of FINCONE II have been presented in Pöyry et al. (2024) in relation to sampling issues in silty soils.

Preliminary in-situ and laboratory test results from a FINCONE II silt test site at Haistila in western Finland are presented in Amoroso et al. (2025). That study compared seismic piezocone SCPTU and Medusa SDMT at standard rates with laboratory oedometer and classification tests. This paper focuses on the DMT performance at varying penetration rates, exploring the sensitivity of test results to rate effects and highlighting implications for soil classification and the determination of engineering properties of silt. Note that the Haistila site is characterized by a relatively homogeneous soil profile, making it a suitable location for testing and comparing different in-situ investigation methods.

## 2 GEOTECHNICAL TESTING PROGRAM

### 2.1 *In-situ testing equipment*

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 (Marchetti & Monaco 2018, Marchetti et al. 2019). 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 (Marchetti 1980, Marchetti et al. 2001) 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 behavior of intermediate soils.

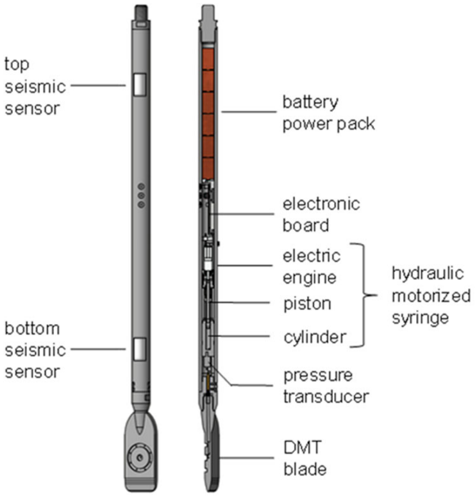

Figure 1. Medusa SDMT equipment.

The seismic piezocone (SCPTU) adopted in this study is characterized by 60° apex angle, 10 cm$^2$ base and 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 electronic 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 for $u_2$ (0.0015%). The high accuracy is the result of the embedded sensors type 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 Wheatstone bridge configuration. The piezocone is further equipped with a seismic module, which allows the measurement of the shear wave velocity.

## 2.2 *Site investigation program*

The Medusa SDMT testing program at Haistila included one Medusa SDMT sounding carried out using the standard procedure (i.e., penetration rate: 20 mm/s; time to *A*, *B* readings: 15 s), and four Medusa DMT soundings performed adopting penetration rates slower (~ 4-5 mm/s) or faster (~ 67 mm/s) than the standard, combined with membrane pressurization rates slower (~ 7.5 s) or faster (~ 30 s) than the standard (Table 1). Medusa DMTA dissipation tests were also carried out in each sounding 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 the proximity of the SCPTU test performed only at standard penetration rate.

Table 1. Summary of Medusa SDMT tests at Haistila.

| Sounding ID | Test type | Penetration rate (mm/s) | Time to *A*-reading (s) | Time to *B*-reading (s) |
|---|---|---|---|---|
| DMT010 | standard (baseline) | 20 | 15 | 15 |
| DMT020 | slow rate | 4.7 | 15 | 15 |
| DMT030 | fast rate | 66.7 | 15 | 15 |
| DMT040 | slow rate/ slow press | 4.3 | 30 | 30 |
| DMT050 | fast rate/ fast press | 66.7 | 7.5 | 7.5 |

The preliminary laboratory test results at Haistila test site presented in this study include index tests and particle size distribution. An extensive laboratory testing campaign is still ongoing, including detailed study of the testing site.

## 3 RESULTS AND DISCUSSIONS

Table 2 summarizes measured index properties and particle size distribution parameters at Haistila. The soil particle distribution identifies fine-grained material, mostly recognizable as silt since the clay fraction (particle size < 0.002 mm) is less than 7% and the sand content (particle size > 0.063 mm) is generally less than 6% (the only exception is within the shallow layer where the sand is present with a percentage of 27%). The bulk unit weight is in the range $\gamma$ = 15.6-18.5 kN/m$^3$, with the highest values measured in the shallow and bottom fine-grained layers. The unit weight trend is in line with the measured natural water content *w*, showing the lowest value (34%) close to 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 13-24%, with a lowest value measured at the shallowest sample depth (*PI* = 3%).

Table 2. Summary of available laboratory test results.

| Sample depth (m) | Fines (%) | Clay (%) | *PL* (%) | *LL* (%) | *PI* (%) | *w* (%) | $\gamma$ (kN/m$^3$) |
|---|---|---|---|---|---|---|---|
| 2.66-2.76 | 73 | 0 | 28 | 31 | 3 | 34.5 | 18.5 |
| 3.73 | - | - | - | - | - | 45.0 | 17.0 |
| 4.24-4.33 | 94 | 2 | 32 | 45 | 13 | 41.8 | 17.1 |
| 5.47-5.96 | 99 | 4 | 33 | 57 | 24 | 63.7 | 15.6 |
| 6.34-6.80 | - | - | 29 | 45 | 16 | 53.9 | 16.2 |
| 7.29 | 94 | 7 | - | - | - | 39.7 | 18 |

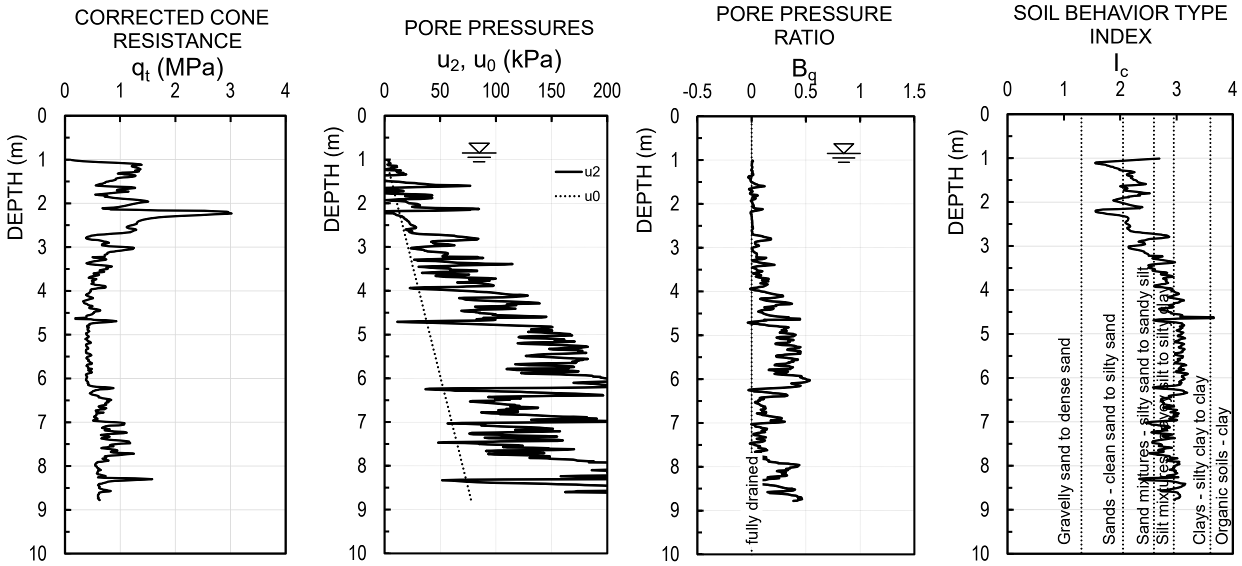

Figure 2. In situ CPTU measurements, drainage and soil type interpretation.

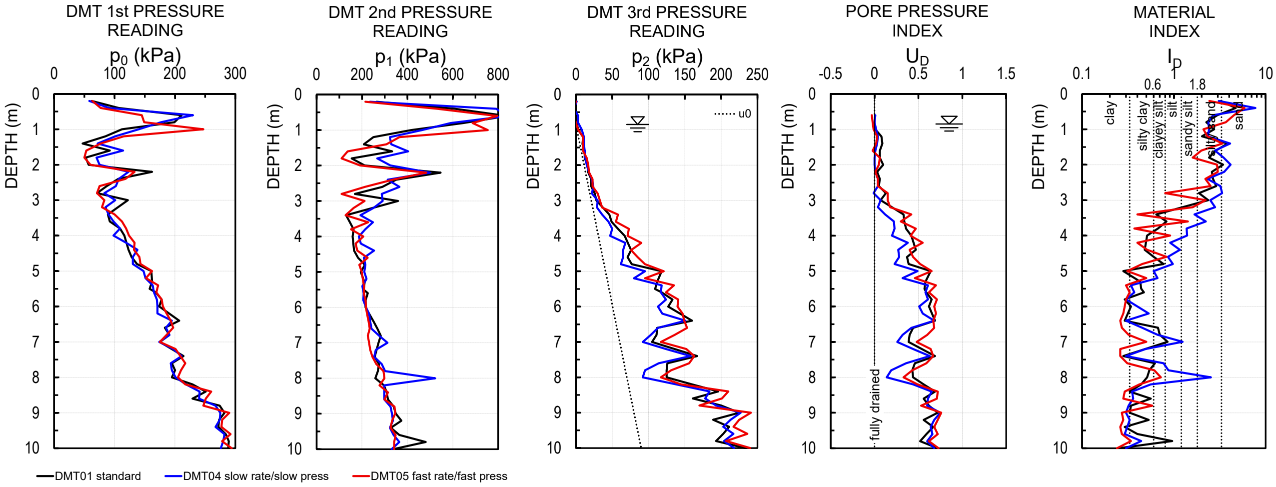

Figure 3. Medusa SDMT measurements recorded with variable penetration and pressurization rates at Haistila site.

Figures 2 and 3 summarize the results of the basic measurements acquired in-situ by both SCPTU and Medusa SDMT and the related interpretation for the drainage conditions and soil type at the Haistila site.

Figure 2 provides these CPTU results at standard rate: the corrected cone resistance ($q_t$), the pore pressure ($u_2$) compared with the hydrostatic pore water pressure ($u_0$), the pore pressure ratio ($B_q$) and the soil behavior type index ($I_c$) according to Robertson (2016). Figure 3 plots the Medusa SDMT results at standard and variable penetration/pressurization rates: 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 Marchetti (1980) and Marchetti et al. (2001). At standard penetration rates (black profiles in Figures 2 and 3) both $I_c$ and $I_D$ profiles, as 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 deep. $B_q$ 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 & Souza (2024): the sands and silty sands behave 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 towards an undrained behavior up to 6.5 m, and in the bottom layer the SCPTU and Medusa SDMT interpretation have some discrepancy in terms of drainage, probably in relation to some lithological variability. The ground water 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.

To assess the combined effects of both variable penetration and pressurization rates, only the results obtained from the standard "baseline" DMT01 (black line) compared with the "slowest" DMT04 (slow rate/slow press, blue line) and the "fastest" DMT05 (fast rate/fast press, red line) are shown in Figure 3. The comparison of the three soundings highlights that:

- intermediate soils appear more clearly identifiable between 3.5 and 8.5 m depth, while the shallow layer (from 0 to 3.5 m) behaves more like a sandy deposit (i.e., drained layer) and the bottom layer (from 8.5 to 10 m) performs more like a clayey soil (i.e., undrained layer) independently from the penetration and pressurization rates;
- focusing on the silty mixture, generally $p_0$ is similar for all tests, while $p_1$ and $p_2$ (even better) show differences in relation to the rate of penetration and pressurization. This behavior is even more emphasized by $U_D$ and $I_D$. Generally, the "fastest" test results indicate more undrained behavior than the "standard" test, and the "standard" test results more undrained than the "slowest" tests. The identified trend appears similar to the

performance of another test site composed by intermediate deposits and located in Bondeno, Italy (Monaco et al. 2021), where data on *PI* and clay fraction are comparable to Haistila while the fines content can reduce even up to 80 % (Amoroso et al. 2022, Minarelli et al. 2024) and the soil type according to $I_D$ can vary from silt to sandy silt to silty sands. However, this last aspect differs from the Haistila site where $I_D$ provides a soil type interpretation mostly as clays for the "fastest" test, as silts and clays for the "standard" test and as silts for the "slowest" test.

## 4 CONCLUSIONS

This study presents the first comparative assessment of SCPTU and Medusa SDMT testing at a coastal silt site in Finland, exploring the sensitivity of test results to rate effects.

In terms of stratigraphy and drainage at standard penetration rate (i.e., 20 mm/s) both in-situ methods consistently identified key soil layers and captured the progression from drained sands to undrained silts, offering a robust stratigraphic interpretation.

The combined effects of variable penetration and pressurization rates recorded by the Medusa SDMT measurements allowed properly identification of the depth interval of intermediate soils and detection of different drainage conditions. In this respect, the presented results reinforce using the pore pressure index $U_D$ to distinguish drained, undrained, or partially drained soil behavior, and the material index $I_D$ as an indicator of soil type which broadly reflects some "soil behavior type", including "sand-like" or "clay-like" behavior of intermediate soils.

These preliminary findings corroborate the approach already adopted in other recent studies (e.g. Monaco et al. 2021, Monaco et al. 2024) for the in-depth analysis of intermediate soil behavior, supporting the use of these advanced test procedures (i.e., variable penetration and pressurization rates) for the study of these soils. However, the implementation of this information with extensive laboratory testing would better enhance the understanding of the mechanical and hydraulic behavior of the silty deposits.

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## 6 REFERENCES

Amoroso, S., Farhadi, M., D'Ignazio, M., Monaco, P., Marchetti, D., and Länsivaara, T. 2025. Comparing seismic piezocone and seismic dilatometer test results for the characterization of a coastal silt deposit from Finland. *AIMS Geosciences*, https://doi.org/10.3934/geosci.2025036

Amoroso, S., García Martínez, M.F., Monaco, P., Tonni, L., Gottardi, G., Rollins, K.M., Minarelli, L., Marchetti, D., and Wissmann, K. 2022. Comparative study of CPTU and SDMT in liquefaction prone silty sands with ground improvement. *Journal of Geotechnical and Geoenvironmental Engineering* 148 (6), 04022038, https://doi.org/10.1061/(ASCE)GT.1943-5606.0002801

Benoît, J., and Souza, B. 2024. Comparison of pore pressure parameters from piezocone and dilatometer. *Proc. 7th International Conference on Geotechnical and Geophysical Site Characterization*, Barcelona, Spain, 1510-1516, https://doi.org/10.23967/isc.2024.211

Di Buò, B., D'Ignazio, M., Selänpää, J., Länsivaara, T., and Mayne, P. W. 2020. Yield stress evaluation of Finnish clays based on analytical piezocone penetration test (CPTu) models. *Canadian Geotechnical Journal* 57(11), 1623-1638.

Di Buò, B., Selänpää, J., Länsivaara, T., and D'Ignazio, M. 2018. Evaluation of existing CPTu-based correlations for the deformation properties of Finnish soft clays. *Proc. Cone Penetration Testing 2018*, Delft, The Netherlands, 185-191.

D'Ignazio, M., Di Buò, B., Länsivaara, T., L'Heureux, J.S., Paniagua, P., and Selänpää, J. 2022. Piezocone testing in Nordic soft clays: Comparison of high-quality databases. *Cone Penetration Testing 2022*, Bologna, Italy, 356-362.

Marchetti, S. 1980. In situ tests by flat dilatometer. *Journal of Geotechnical Engineering Division* 106(GT3), 299-321.

Marchetti, S., and Monaco, P. 2018. Recent improvements in the use, interpretation, and applications of DMT and SDMT in practice. *Geotechnical Testing Journal* 41, 837-850.

Marchetti, D., Monaco, P., Amoroso, S., and Minarelli, L. 2019. In situ tests by Medusa DMT. *Proc. XVII European Conference on Soil Mechanics and Geotechnical Engineering*, Reykjavik, Iceland, https://doi.org/10.32075/17ECSMGE-2019-0657

Marchetti, S., Monaco, P., Totani, G., and Calabrese, M. 2001. The flat dilatometer test (DMT) in soil investigations – A report by the ISSMGE Committee TC16. *Proc. International Conference on Insitu Measurement of Soil Properties and Case Histories*, 95-131, reprinted in *Proc. 2nd International Conference on Flat Dilatometer*, 2006, 7-48.

Minarelli, L, Fontana, F., Lugli S., Rollins, K.M., Stefani, M., Tonni, L., and Amoroso, S. 2024. Sediment stacking pattern effect on sand liquefaction inferred from full-scale experiments in the Emilia alluvial plain (Italy). *Engineering Geology* 341, 107735, https://doi.org/10.1016/j.enggeo.2024.107735

Monaco, P., Amoroso, S., Chiaradonna, A., Marchetti, D., Le, T.M.H., and L'Heureux, J.S. 2024. Characterization of intermediate soils by innovative in-situ testing procedures using Medusa DMT. *Proc. XVIII European Conference on Soil Mechanics and Geotechnical Engineering*, Lisbon, Portugal, 679-682, https://doi.org/10.1201/9781003431749-109

Monaco, P., Tonni, L., Amoroso, S., Martinez, M.F., Gottardi, G., Marchetti, D., and Minarelli, L. 2021. Use of Medusa DMT in alluvial silty sediments of the Po river valley. *Proc. 6th International Conference on Geotechnical and Geophysical Site Characterization*, Budapest, Hungary, https://doi.org/10.53243/ISC2020-424

Pöyry, E., Farhadi, M.S., Haikola, M., and Länsivaara, T. 2024. Soil plugging in small diameter tube samplers in silty soils. *Proc. XVIII European Conference on Soil Mechanics and Geotechnical Engineering*, Lisbon, Portugal, 745-749.

Randolph, M., and Hope, S. 2004. Effect of cone velocity on cone resistance and excess pore pressures. *Proc. IS Osaka - Engineering Practice and Performance of Soft Deposits*, Osaka, Japan, 147-152.

Robertson, P.K. 2016. Cone penetration test (CPT)-based soil behaviour type (SBT) classification system — An update. *Canadian Geotechnical Journal* 53, 1910-1927.

Schnaid, F., Lehane, B.M., and Fahey, M. 2004. In situ test characterisation on geomaterials. *Proc. 2nd International Conference on Site Characterization*, Porto, Portugal, 49-74.

Schnaid, F., Odebrecht, E., Sosnoski, J., and Robertson, P.K. 2016. Effects of test procedure on flat dilatometer test (DMT) results in intermediate soils. *Canadian Geotechnical Journal* 53, 1270-1280, https://doi.org/10.1139/cgj-2015-0463

Selänpää, J., Di Buò, B., Haikola, M., Länsivaara, T., and D'Ignazio, M. 2018. Evaluation of existing CPTu-based correlations for the undrained shear strength of soft Finnish clays. *Proc. Cone Penetration Testing 2018*, Delft, The Netherlands, 571-577.

Selänpää, J., Di Buò, B., Länsivaara, T., and D'Ignazio, M. 2017. Problems related to field vane testing in soft soil conditions and improved reliability of measurements using an innovative field vane device. In *Landslides in Sensitive Clays: From Research to Implementation*, 109-119. Cham: Springer International Publishing.

Tonni, L., and Gottardi, G. 2010. Interpretation of piezocone tests in Venetian silty soils and the issue of partial drainage. *Proc. Deep Foundations and Geotechnical In Situ Testing*, Reston, VA, 367-374.