Cone Penetration Testing 2022 – Gottardi & Tonni (eds)

Fincone: A study on the use of CPT in soft sensitive clays

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ABSTRACT: The paper presents the results of a recent study on the application of CPTU on soft sensitive Finnish clays. An extensive field and laboratory investigation program was carried out, including 9 test sites of which 5 were studied in more detail. In each of the test sites, a minimum of 4 CPTU soundings, 2-3 field vane test with a new type of down hole vane, sampling with a newly developed large diameter tube sampler and an extensive laboratory investigation program were carried out. Transformation models were developed to estimate the undrained shear strength, preconsolidation stress, and constrained modulus for the over consolidated region. In addition, new information about anisotropy of Finnish clays were obtained. In general, the CPTU tests proved to be very reliable with very good repeatability. However, the measurement of sleeve friction proved to be somewhat problematic for the very soft and sensitive clays studied.

1 INTRODUCTION

Until 2010, the use of CPTU had not gained wide popularity in Finland. Attempts made in the 90's to assess the undrained shear strength of Finnish soft clays with the CPTU had not been very successful mainly due to accuracy problems related to the low undrained shear strength (s_u)values for both the CPTU and the field vane tests used as reference. As the problems with the field vane test became clearer (Mansikkamäki, 2015), a need to find better solutions became obvious.

Based on this background Research Centre Terra at Tampere University started together with the Finnish Transport Agency a comprehensive study to establish reliable correlations to estimate s_u and preconsolidation stress (σ'_p) of soft clays, and to promote the use of CPTU in Finland. To achieve these goals, an extensive field and laboratory investigation program was carried out at 9 test sites. This paper gives an overview of the project, describing the test sites, field, and laboratory work executed, and the correlations and other results found during the study.

2 TESTING PROGRAMME

The CPTU tests included tests with two different probes, i.e., a sensitive cone and a high-capacity cone with a maximum cone resistance of 7.5 MPa and 75 MPa respectively. Both cone types have a standard 60° apex tip, with a cross-sectional area (A_c) of 10 cm^2 and a sleeve area (A_s) of 150 cm^2. The filter element for measuring the pore-water pressure is located at the shoulder, above the cone tip (u_2).

In addition, seismic and resistivity modules were used. A minimum of 4 soundings were performed at each site. In addition to CPTU tests, field vane tests were carried out with a new type of down hole vane, characterized by measuring system and torque motor located right above the vane, to overcome problems related to rod friction (Selänpää et al. 2018). Comparative test with standard type of up-hole devices were carried out at some of the sites.

To ensure high quality undisturbed samples for the laboratory tests, a new sampler was developed (Di Buò et al. 2019). The sample resembles the SGI type of Laval sampler, with a cutting wire and possibility to feed air/water to avoid suction during withdrawing.

DOI: 10.1201/9781003308829-70

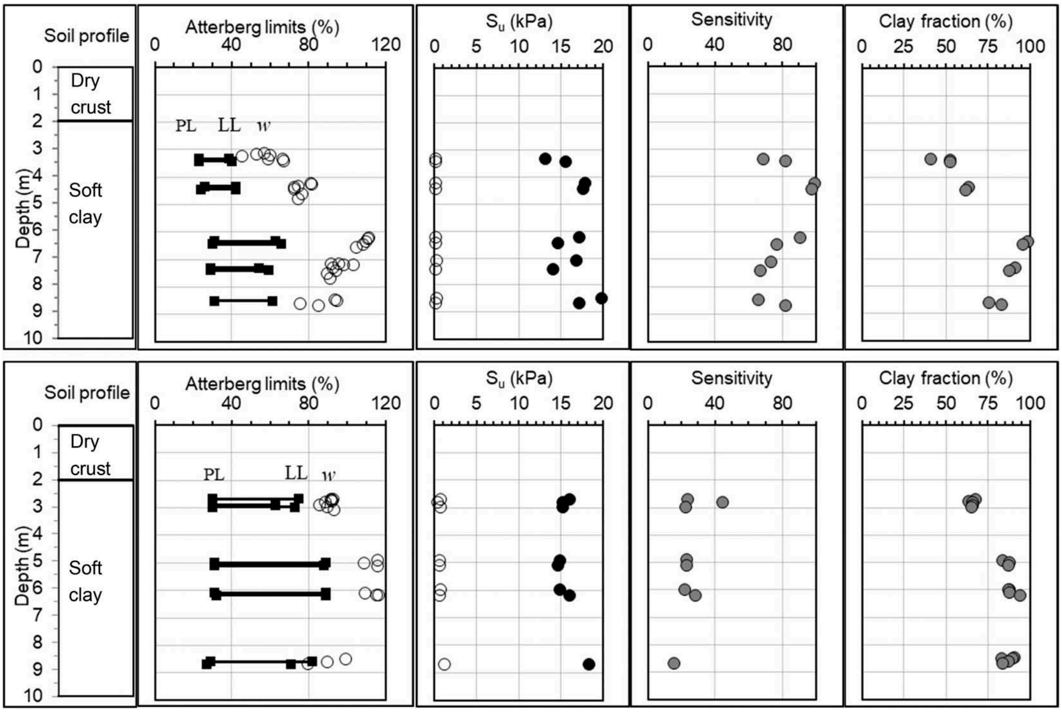

Figure 1. Index properties and undrained shear strength for Paimio (upper figure) and Sipoo (lower figure) test sites.

The sample is though somewhat smaller is size, having an internal diameter of 131 mm. Another difference is that the samples are stored in the sampling tubes that can be pressurized to keep the in-situ stress conditions.

The laboratory tests included classification tests, CRS oedometer tests, triaxial compression and extension tests and direct simple shear (DSS) tests. All tests have been conducted in accordance with appropriate standards when available.

3 TEST SITES

Field and laboratory investigations have been carried out altogether in 9 different sites, i.e., in Perniö, Masku, Paimio, Sipoo, Lempäälä, Murro, Kotka, Joensuu and Pohja. The five foremost have been the main testing sites in calibration of cone factors and are presented here in more detail.

The Perniö test site is located on the southwestern coast of Finland, about 140 km west of the city of Helsinki. The soil stratigraphy of the deposit includes a 1–1.5 m thick dry crust underlain by 8–9 m thick, soft clay layer; silt and stiff sandy layers can be found at a greater depth. The groundwater table is located at 1 m depth.

The Masku test site is located at the southwestern coast of Finland, near the city of Turku. The soil stratigraphy includes a 1.5 m thick weathered clay crust, followed by an 8 m thick, soft clay layer. The groundwater table is located at 1.2 m depth.

The Paimio test site is also located close to the city of Turku. The stratigraphy consists of a 2 m thick clay crust overlaying an 8 m thick, soft clay layer. The groundwater table is located at 0.8 m depth.

The Sipoo site is situated 30 km north of the city of Helsinki. The deposit consists of a homogeneous soft clay layer between 2 and 9 m depth and a - 2 m thick dry crust layer. The groundwater table is located at 1 m depth.

The Lempäälä test site is located close to the city of Tampere. The soil stratigraphy consists of a 1–1.5 m thick dry crust layer, followed by 1–1.5 m of organic soil underlain by a soft sensitive low-plastic clay layer. The groundwater table is located at 0.6 m depth.

All sites are characterized by low s_u values and high water content (*w*), usually above the liquid limit (*LL*). The clays are thus very sensitive and their remolded shear strength values obtained by the fall cone test are generally below 0.5 kPa for Perniö, Paimio and Lempäälä sites, and close to unity for Sipoo and Masku sites.

The index properties and the intact (black) and remolded (white) undrained shear strength obtained from the fall cone test, of the clays for Paimio representing highest sensitivity (S_t) and Sipoo representing lowest S_t are presented in Figure 1. Typically for the clays with lower plasticity index *PI*, the *w* is much higher than the *LL*, resulting in high liquidity index (*LI*), which correlates strongly with S_t.

4 QUALITY OF DATA

In general, the repeatability of the CPTU tests was found very good. As an example, the coefficient of variation (*COV*) values for corrected cone tip resistances and pore pressure measurements varied between 0.026 – 0.060 and 0.023 – 0.106 respectively between different sites (Knuuti & Länsivaara 2019 a, b). However, for the sleeve friction measurements, the resolution was too low for the very soft sensitive clay sites, in which the measured values generally were below 5 kPa (*COV* values in the range 0.15 -0.30). In Figure 2 results from four tests carried out using the sensitive cone and one with the high-capacity cone are presented from Paimio test site. As can be seen, the four corrected tip resistance measurements are very similar, while the one using the high-capacity cone is giving somewhat lower values. This observation was generally made in all test sites. It should be noted that the high-capacity cone had not been calibrated especially to low values. The too low resolution is clearly visible on the sleeve friction graph.

While the pore pressure measurements for the two types of cones were performed with same kind on transducers having the same accuracy, the minor differences that can be seen between the different pore pressure measurements are related to the preparation works and actual measurements, not to the equipment.

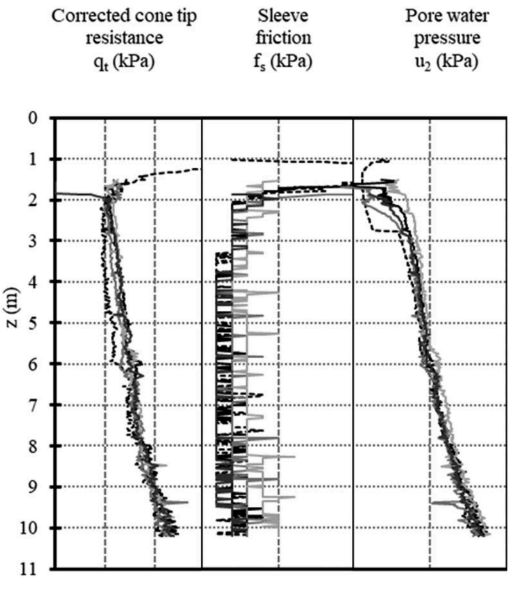

Figure 2. CPTU results from Paimio test site. Results from four sensitive cone measurements are presented with solid lines, while the results from one high-capacity cone measurement are given by a black dotted line.

The new down-hole field vane device showed better consistency and repeatability than traditional up-hole devices. The *COV* values for the down hole field vane test varied in between 0.04 and 0.23 between different sites, with an average of 0.14 for 88 tests. When the tests are performed with care, and casing is used for the up-hole device, the two methods gave very similar results for intact clay, although there was a slight tendency to higher values for the down-hole devise. However, for the remolded undrained shear strength the down-hole device clearly yielded lower values, closer to values obtained with the fall-cone.

The quality of the undisturbed soil samples was mainly evaluated based on the criteria proposed by Lunne et al. (1997). Accordingly, sample quality is classified as “very good to excellent”, “good to fair”, “poor”, and “very poor”. In Figure 3 the sample quality found for CRS oedometer tests are presented as change of void ratio versus depth. The same sampler types are indicated by equal marker shapes while different shades are used for the various sites. As can be seen, most of the samples fall into categories “very good to excellent” and “good to fair”. The poor results for the TUT sampler at Lempäälä site is explained by it being the first site where the new sampler was tested, and all procedures were not in order at the beginning. However, as the procedures were optimized mostly “very good to excellent” quality samples were obtained. Results from laboratory test obtained from samples classified as poor or very poor have not been used in the calibrations. As reported by Di Buò et al. (2019), the sample quality did not suffer from a storage time of two years.

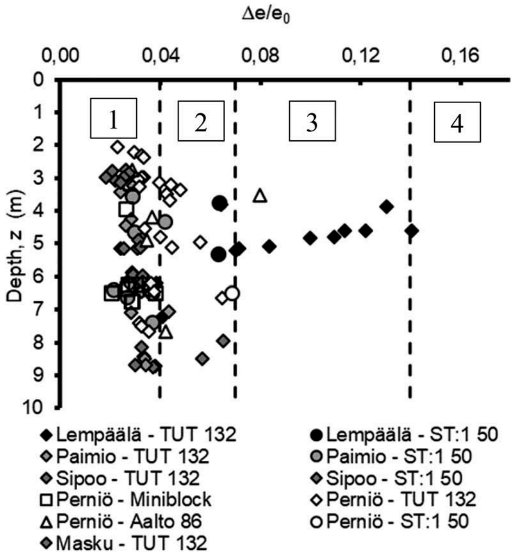

Figure 3. Sample quality according to the Lunne criteria (1997), 1 – very good to excellent, 2 – good to fair, 3 – poor, 4 -very poor.

5 TRANSFORMATION MODELS

5.1 *Evaluation based on SCE-CSSM*

Di Buò et al. (2020) and Di Buò (2020) studied the possibilities of the hybrid spherical cavity expansion – critical state soil mechanics (SCE-CSSM) framework by Mayne (1991) and Chen and Mayne (1994), and the modified SCE-CSSM solution (Agaiby 2018) for the determination of σ'_p /*OCR*. It can be concluded that for low sensitivity (*St*) clays both solutions gave a relatively good match, but as *St* increased the modified solutions preformed much better. Another general finding of the study is that the friction angel values needed in the solutions can be seen more as curve fitting values rather than true values. To get good correlation to laboratory based σ'_p values, the used friction angle values needed to be clearly higher than those observed in the laboratory.

Based on the above theoretical framework Di Buò et al. (2020) and Di Buò (2020) proposed simplified transformation models based on average operational values, calibrated those based on the entire data, and finally suggested five equations for evaluating σ'_p in Finnish clays. Out of those five the following two are herein suggested as the primary transformation models:

$$\sigma'_p = 0.28(q_t - \sigma_{vo}) \quad (1)$$

$$\sigma'_p = 0.39(u_2 - u_o) \quad (2)$$

The outcome of Eq. (1) and (2) are presented in Figure 4 in comparison to CRS oedometer based σ'_p values for Paimio and Sipoo test sites.

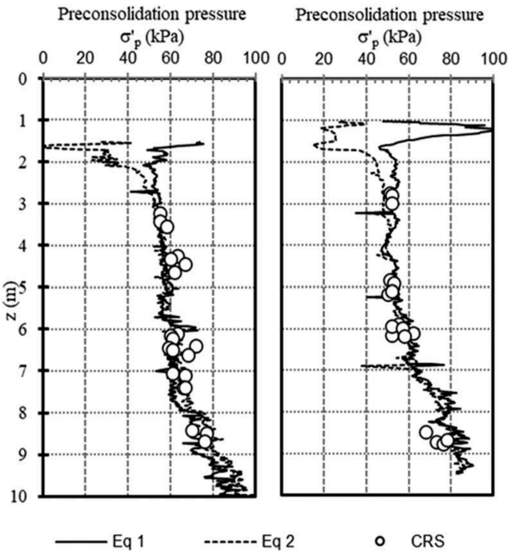

Figure 4. Values of σ'_p evaluated using Equations (1) and (2) in comparison to CRS test results.

It could further be noted, that for Equation (1), the low sensitivity clays indicated generally a lower multiplier than 0.28, while for high sensitivity clays a higher multiplier were generally found. All clays had an *OCR* generally below 2.

5.2 *Evaluation based on index properties*

After discussing varies theories Selänpää (2021) studied the influence of index properties and pore pressure ratio (B_q) to the cone factors. The main goal was to determine the best practical transformation models for determination of undrained shear strength. Cone factors were determined in relation to different shearing modes (tests) for undrained (triaxial) compression ($s_{u\ comp}$), undrained (triaxial) extension ($s_{u\ ext}$), direct simple shear (DSS) (test) ($s_{u\ DSS}$), measured field vane ($s_{u\ FVmeas}$) and corrected field vane ($s_{u\ FVcorr}$) undrained shear strength. Field vane measurements were corrected as a function of liquid limit according to Helenelund (1977). In general, it can be concluded that best correlations were found for $s_{u\ comp}$ as the triaxial compression test revealed to be the most reliable test with lowest scatter. For the $s_{u\ FVcorr}$ Selänpää suggested that the N_{kt} and $N_{\Delta u}$ cone factors would depend on *PI* and the N_{ke} cone factor on *Bq*. The two previous proposed $s_{u\ FV\ corr}$ equations are as follows:

$$s_{u\ FV\ corr} = \frac{(q_t - \sigma_{vo})}{0.126 \cdot PI + 11.793} \quad (3)$$

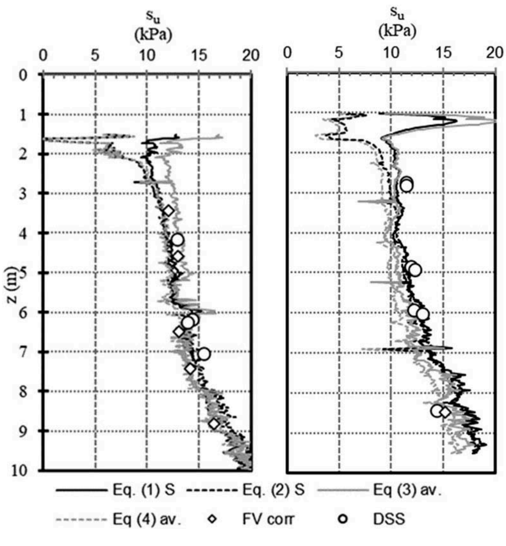

Figure 5. Values of s_u evaluated using Equations (3) and (4) and (1) and (2) applying the SHANSEP approach in comparison to field vane and DSS test results for Paimio (left) and Sipoo (right) test sites.

$$s_{u\,FV\,corr} = \frac{(u_2 - u_o)}{0.064 \cdot PI + 10.279} \tag{4}$$

In Figure 5 the results of Equations (3) and (4) are compared with $s_{u\ FVcorr}$ and $s_{u\ DSS}$ data for Paimio and Sipoo test sites using average *PI* values. To compare the different approaches by Di Buò (2020) and Selänpää (2021), values determined using Equations (1) and (2) applying the SHANSEP to estimate s_u is applied. Accordingly, s_u can be determined from:

$$s_u = \mathrm{S} \cdot \sigma'_{vo} \cdot OCR^m \tag{5}$$

For the parameters *S* and *m* values reported by D'Ignazio et al. (2016) with S = 0.244 and m = 0.763, are used.

For the Sipoo test site, only one good quality field vane test was achieved, so the comparison is primarily to DSS test results. As can be seen from Figure 5, all equations performed quite well for the Paimio site. For the Sipoo test sites, the estimation is also good, although some minor underprediction might be indicated by the $s_{u\ DSS}$ values in the upper part.

6 SOME OTHER FINDINGS

6.1 *SBT charts*

For all test sites the soil behaviour type (SBT) was evaluated based on the normalized SBT charts by Robertson (1990). A general finding was that although the clays were in general sensitive, the classification charts indicated them with very few exceptions as clays, rather than sensitive clays. For the chart based on the normalized friction ratio this can at least partly be explained by the low accuracy of the sleeve friction measurements as discussed before. However, neither the chart based on the normalized porewater ratio succeeded in identifying the sensitive clay layer while the values in practise never plotted on the zone for sensitive clays. The SBT charts for Paimio site, with a high sensitivity of the clay (S_t = 60…100%) is presented in Figure 6 (Di Buò, 2020).

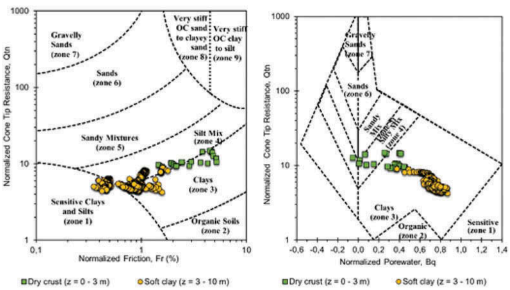

Figure 6. Soil behavior type (SBT) according to Robertson (1990) for the sensitive Paimio clay (Di Buò, 2020).

6.2 *Anisotropy of su*

The anisotropy of s_u for Finnish clays was studied systematically for the first time. The anisotropy ratios were determined by comparing the peak undrained strength values of respective tests corresponding to the different shear modes, irrespective of the shear strain values (Selänpää 2021). The ratio $s_{u\ ext}/s_{u\ comp}$ varied between 0.52-0.70, with a slight tendency to increase with plasticity and/or water content. The average value for the ratio is 0.615. Similarly, the ratio $s_{u\ DSS}/s_{u\ comp}$ varied between 0.56-0.72, with a slight tendency to increase with water content. The average value for the ratio is 0.64. What is notable is the very small difference between $s_{u\ ext}$ and $s_{u\ DSS}$ values.

6.3 *Constrained modulus for OC region*

Di Buò et al. (2018) and Di Buò (2020) evaluated different approaches to determine the constrained modulus M_0 for the overconsolidated region. As the value for M_0 is quite sensitive to sample quality, the correlations generally showed a rather high scatter. However, a simple approach relying on the relatively accurate determination of σ'_p proved to provide a pragmatic solution giving consistent values. The σ'_p for high quality samples of soft Finnish clays is reached approximately at a vertical strain of 4%. Therefore, the value of M_0 can be evaluated by firstly using transformation models as in Equations (1) and (2) to evaluate the σ'_p, and then divide the σ'_p value with 0.04 to obtain the M_0. As example such an approach for the pore pressure based Equation (2) yielded a *COV* value of 0.21 between CRS and CPTU based M_0 values.

6.4 *Additional modules*

In all test sites investigations were also conducted using two additional modules connected directly behind the cone, namely the seismic (S) and resistivity (R) modules. In general, two tests were performed for each site using both modules, showing good repeatability.

The shear wave velocity values varied between 40-110 m/s. The measured electrical conductivity values ranged from about 50 up to 300 mS/m, correlating highly with pore water salinity.

7 CONCLUSIONS AND FUTURE DEVELOPMENTS

In the FINCONE project the application of CPTU was studied for soft sensitive Finnish clays. Comprehensive testing, including high quality sampling, extensive laboratory program and down hole field vane in addition to the CPTU was performed altogether on 9 test sites, of which 5 were studied in more detail. Based on the achieved database transformation models were developed to evaluate σ'_p, s_u and M_0. Moreover, information about the anisotropy of Finnish clays were achieved for the first time. In addition, shear wave velocity and resistivity data were obtained from the S- and R-modules of the used CPTU equipment.

The CPTU data proved to be very reliable with good repeatability. However, the sleeve friction measurements suffered from too low resolution for the very low values. Some doubts were also raised about their accuracy. The resulting transformation models proved to work well for studied soft clays. It should though be noted that the clays are rather similar in nature, with low OCR and generally high water and clay content.

In the future, the aim is to broaden the range of studied soils to silty soils and fine sands and develop further transformation models for them. In addition, CPTU based soil characterization as well as determination of deformation properties for the normally consolidated will be studied. Some early results of the former are also presented in this conference (Farhadi et al. 2022).

ACKNOWLEDGEMENTS

The guidance of late Professor Rolf Sandven in the early phases of the project is highly acknowledged and remembered with warmth.

The guidance of Professor Paul Mayne and his warm hospitality during the visiting periods for the second and third author contributed highly to their studies and is very much acknowledged.

The financial support of the Finnish Transport Agency and Tampere University is highly appreciated in carrying out the study.

REFERENCES

Agaiby, S. 2018. Advancements in the interpretation of seismic piezocone tests in clays and other geomaterials. Doctoral dissertation, School of Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta.

Chen, B.S., and Mayne, P.W. 1994. Profiling the overconsolidation ratio of clays by piezocone tests. Rep. No. GIT-CEEGEO-94, 1

Di Buò, B. 2020. Evaluation of the Preconsolidation Stress and Deformation Characteristics of Finnish Clays based on Piezocone Testing. PhD Thesis, Tampere University, Tampere, Finland. ISBN 978-952-03-1468-2

Di Buò, B., D'Ignazio, M., Selänpää, J., Länsivaara, T. & Mayne, P. W., 2020. Yield stress evaluation of Finnish clays based on analytical piezocone penetration test (CPTU) models. In: Canadian Geotechnical Journal. 57, 11, p. 1623–1638 16 p.

Di Buò, B., Selänpää, J., Länsivaara, T., & D'Ignazio, M. 2018. Evaluation of existing CPTu-based correlations for the deformation properties of Finnish soft clays. In Cone Penetration Testing 2018 (pp. 185–191). CRC Press.

Di Buò, B., Selänpää, J., Länsivaara, T., and D'Ignazio, M. 2019. Evaluation of sample quality from different sampling methods in Finnish soft sensitive clays. Canadian Geotechnical Journal, 56(8): 1154–1168.

D'Ignazio, M., Phoon, K.K., Tan, S.A., & Länsivaara, T.T. 2016. Correlations for undrained shear strength of Finnish soft clays. Canadian Geotechnical Journal, 53(10), 1628–1645.

Farhadi, M.S, Länsivaara, T. & Tonni, L. 2022 a). Application of integrated Game Theory-optimization subground stratification (-IGTOSS) model to Venetian Lagoon deposits. Submitted. CPT22. Bologna.

Farhadi, M.S, Länsivaara, T. L'Heureux, J.S & Lunne, T. 2022 b). Application of two novel CPTu subground stratification models. Submitted. CPT22. Bologna.

Helenelund, K. V. 1977. Methods for reducing undrained shear strength of soft clay. In Swedish Geotechnical Institute, Proceedings (No. Report No. 3 Proceeding).

Knuuti, M. & Länsivaara, T. 2019 a). Variation of Measured CPTu Data. Proceedings of the 7th International Symposium on Geotechnical Safety and Risk (ISGSR). Ching, J., Li, D-Q. & Zhang, J. (eds.). Singapore: p. 164–169 6 p.

Knuuti, M. & Länsivaara, T. 2019 b). Variation of CPTu-based transformation models for undrained shear strength of Finnish clays. In: Georisk. 13, 4, p. 262–270 9 p.

Lunne, T., Berre, T., and Strandvik, S. 1997. Sample disturbance effects in soft low plastic Norwegian clay. In Symposium on Recent Developments in Soil and Pavement Mechanics.

Mansikkamäki, J. 2015. Effective stress finite element stability analysis of an old railway embankment on soft clay. PhD thesis, Department of Civil Engineering, Tampere University of Technology, Tampere, Finland.

Mayne, P.W. 1991. Determination of OCR in clays by piezocone tests using cavity expansion and critical state concepts. Soils and foundations, 31(2): 65–76.

Robertson, P.K. 1990. Soil classification using the cone penetration test. Canadian Geotechnical Journal, 27(1), 151–158.

Selänpää, J., Di Buò, B., Haikola, M., Länsivaara, T., & D'Ignazio, M. 2018. Evaluation of existing CPTu-based correlations for the undrained shear strength of soft Finnish clays. In Cone Penetration Testing 2018 (pp. xxx–xxx). CRC Press.

Selänpää, J. 2021. Derivation of CPTu cone factors for undrained shear strength and OCR in Finnish clays. PhD Thesis, Tampere University, Tampere, Finland.