Preliminary results from a study aiming to improve ground investigation data

B. Di Buò
Tampere University of Technology, Finland, bruno.dibuo@tut.fi

M. D'Ignazio, J. Selänpää, T. Länsivaara
Tampere University of Technology, Finland

ABSTRACT
Site investigation and assessment of soil strength and deformation properties represent a crucial aspect for a safe and cost-effective design. A proper plan of laboratory and in-situ tests can provide a deep knowledge of soil behaviour. In-situ tests are becoming increasingly important in practice as, besides being cost-time effective, soil disturbance due to sampling is avoided. However, laboratory tests provide very versatile possibilities to test soil samples under various stress conditions, while in-situ testing involves more complex boundary conditions and low control over stress path.
Both field and laboratory investigations are under constant development. This paper presents some preliminary results of an ongoing study conducted at Tampere University of Technology aimed to improve the quality of ground investigation data. A new field vane has been taken into use where the rotation and torque moment are measured right above the vane. In addition, a sensitive CPTu probe is used with the possibility to connect resistivity and seismic cones into the probe. For the verification of the field investigations laboratory test are done. During the last decades many investigations have pointed out that block sampling is needed to obtain high quality undisturbed soil samples. Comparisons between results from traditional ST2 50 mm sampler and a new 132 mm Laval type piston sampler are shown. The quality of soil samples is investigated considering the strain required to reach preconsolidation pressure in oedometer test.

Keywords: soil investigation; in-situ testing; soft clay; piezocone; undrained shear strength.

1 INTRODUCTION

Site investigation plays an important role in civil engineering design. Both field and laboratory tests should be planned according to the level of knowledge required by the project. In Finland, field vane test is widely used for the determination of undrained shear strength of soft clays. Recent research studies conducted at Tampere University of Technology (Mansikkamäki 2015, D'Ignazio et. al. 2015) showed that field vane test is affected by uncertainties due to limitations of the apparatus, test procedure and some special soil conditions. The measurement of torque at the ground surface seems to be the greatest source of error, especially if casing is not used.

Unlike field vane test, piezocone test (CPTu) is not of common use in Finland. Among all the advantages, CPTu is particularly known for being an efficient and economical tool for soil investigation. Continuous (with depth) and independent information can be obtained from a single sounding. As the CPTu test is rather fast to perform, a much larger part of a site can be investigated compared to e.g. field vane test in the same time frame. Also much more versatile results can be obtained. Various correlations can be used to evaluate, for instance, the soil shear strength from the cone tip resistance, based on the soil type (e.g. Robertson and Campanella, 1983; Larsson and Mulabdic, 1991). However,

more difficulties are encountered in the determination of deformation properties based on CPTu data.
The use of piezocone can be further extended since additional sensors can be installed into the cone (Powell, 2010). Of special interest are the seismic and the resistivity modules added to an ordinary CPTu probe chassis. Such modules give the possibility to measure shear wave velocity and electric conductivity of the soil.
Due to the enormous potentiality of CPTu testing device, TUT has purchased a piezocone equipped with seismic and resistivity cone. In order to ensure accurate measurements in the very soft and sensitive Finnish clays, an extra sensitive cone with high accuracy is used. Also, a new type of vane tester has been taken into use. Its main advantage is that the rod friction is eliminated from the measurement, as the torque moment is measured right above the vane. Both equipments are integrated into a fully equipped crawler rig.
In parallel with the development of in-situ testing, a new 132 mm Laval type tube sampler has been designed by Tampere University of Technology to obtain high quality samples for laboratory testing.
The main objective of the research project is to create a database of high quality field and laboratory test results from different sites in Finland. This database will then be used to develop and verify correlations to evaluate CPTu data.
In this paper, field and laboratory data obtained from three sites is shown and discussed. Furthermore, disturbance induced by soil sampling is evaluated by comparing test results from block and piston samples.

2 EQUIPMENT AND TEST PROCEDURE

The new CPTu equipment that Tampere University of Technology has recently purchased from van den Berg consists of:

1) Pushing system installed on tracked CPT truck
2) Cone penetrometers
3) Seismic cone
4) Resistivity cone
5) Field vane apparatus
6) Data acquisition system

The penetrometer consists of a standard 60º cone, with 10 cm^2 base area and a 150 cm^2 surface area of the friction sleeve located above the cone. Excess pore pressure is measured right above the cone.
In order to get relevant information from each test site, two different cone types, with different capacities, have been used. 1) A high capacity cone with capacity of 75 MPa and 2) a lower capacity cone (hereinafter referred to as “sensitive” cone) with capacity of 7.5 MPa. As Finnish clays are very soft, the sensitive cone appears to be the most suitable for assessing tip resistance and sleeve friction. The differences between results from the two cones have so far been quite small.
Initial pre-drilling has been performed at all sites in the dry crust layer in order to avoid possible loss of saturation. The penetrometer has been then placed into the hole filled with water to ensure the temperature balancing. A successful saturation of the filter stones is very important not only for the penetration part of the test, but also for the quality of the dissipation tests. Dissipation tests are performed to evaluate the decay of pore water pressure with time at a given depth and, therefore, the equilibrium pore pressure. Results from such test are exploited to estimate the groundwater table position.
The rate of penetration of the piezocone test is 20 mm/s according to the European Standards (EN ISO 22476-1-2012). However, tests at faster and lower speed have also been performed and results are shown and discussed later.
In addition to the standard CPTu tests, resistivity and seismic tests have been also performed. The seismic cone provides additional information on shear wave velocities, thus avoiding separate downhole or cross-hole testing. Both shear and compression wave velocities can be measured and, therefore, small strain stiffness assessed.
For detailed profiling of each site, CPTu with resistivity cone has been also carried out. The conductivity method is generally used for environmental purposes, e.g. the evaluation

of contamination and corrosive potential of the soil using the electrical resistivity (see e.g. Lunne et al., 1997b). Recently, a study has been conducted to map quick clay areas using electrical resistivity measurements (Solberg et al, 2008). One important aspect to be studied in future is whether the electrical conductivity can be linked to the natural water content, which is known to correlate with deformation properties (e.g. Janbu, 1998).

Field vane test has been also performed at each test site with the new equipment. Such a test provides a continuous strength – rotation profile, revealing nicely the nature of the failure behavior. However, vane testing is often affected by uncertainties related to test procedure and disturbance caused by vane insertion and soil conditions, as also pointed out by Chandler (1988). Therefore, field vane measurements have been taken three times for all the test sites.

Results from field vane tests are later discussed and exploited to evaluate the undrained shear strength from CPTu test results.

Besides in-situ tests, laboratory tests have been performed in parallel. Sampling has been done using a new open-drive block sampler designed by the geotechnical group at TUT. At the same time, a piston sampler has been used in order to compare the quality of the test results.

Open-drive samplers consist of a tube which is open at its lower end, while in piston drive samplers the movable piston is located within the sampler tube. Piston samplers can be pushed through the soil to the desired sampling level, while open-drive samplers will admit soil as soon as they are brought into contact with, for example, the bottom of a borehole (Clayton et al. 1982).

The newly-built sampler is a small-scaled copy of the SGI type Laval open-drive block sampler (Larsson 2011). However, few changes have been made. The soil is stored in the same tube used during sampling, unlike the Swedish sampler type from which the soil is extruded in the field. This was chosen to avoid unnecessary handling of the sample and to avoid the reduction of lateral stress during sample storage.

Moreover, a cutting wire system is used prior to sampler withdrawal to isolate the soil sample. Air feeding is used to prevent suction at the cutting end.

3 DESCRIPTION OF THE TEST SITES

The investigation has been conducted so far at three different sites in the marine clay area of the South-West region of Finland. The study is mainly oriented to the evaluation of undrained shear strengh. In this section, the three test sites are described and index properties (liquid limit, *LL*, plastic limit, *PL* and natural water content, w_n), unit weight (γ) and sensitivity (S_t) are shown. Sensitivity is defined as the ratio between the intact (s_u) and the remolded undrained shear strength (s_u^{rem}), both determined from the Fall Cone test (CEN ISO/TS 17892-6 (CEN, 2004b)). From the Fall Cone test, liquid limit was also determined. Plastic limits were determined according to the standard plastic limit test (CEN ISO/TS 17892-12 (CEN, 2004c)).

3.1 Perniö test site

The Perniö test site is located on the South-West coast of Finland, near the town of Salo. A full-scale embankment failure experiment was conducted in 2009 gathering extensively amount of data which have been used for embankment stability evaluation and assessment of new soil models (Lehtonen et al., 2015).

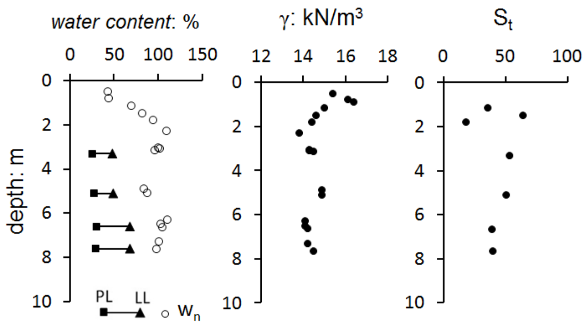

Figure 1 Properties of Perniö clay.

The site is located next to the coastal railway track connecting the cities of Helsinki and Turku. The stratigraphy consists of a 1-1.5 m thick weathered clay crust layer followed by a 8–9 m thick soft clay layer overlaying silty and stiff sandy layers located at greater depths. Natural water content ranges from 60% to 120%, while it is lower than 50% in the dry crust. Unit weight is 15-17 kN/m^3 in the upper part and 14-15 kN/m^3 in the lower soft clay. Sensitivity (S_t) varies between 20 and 60. The piezometric level is located at 0.63 m from the ground surface according to the dissipation test. Some of the properties of Perniö clay are summarized in Figure 1.

3.2 *Lempäälä test site*

The site is located in the South-West region of Finland next to the railway track between Tampere and Helsinki.

The stratigraphy consists of a 1.5 m thick layer of weathered clay crust, 1–1.5 m thick layer of organic soil over a 6-7 m thick soft sensitive clay deposit. The top 4-5 m are characterized by high natural water content, between 100% and 150%, thus suggesting the presence of organic material. Below 4 m, the interval of variation of w_n is restricted to 70-80%. Measured unit weight is lower than 14 kN/m^3 in the upper part, increasing up to about 15 kN/m^3 at greater depths. Sensitivity seems to increase with depth, from 10 to 33 at about 7.5 m depth. From the dissipation test performed at 4.8 m depth, the piezometric level seems located at the ground surface, while the groundwater table is located below the dry crust layer. Properties of Lempäälä clay are shown in Figure 2.

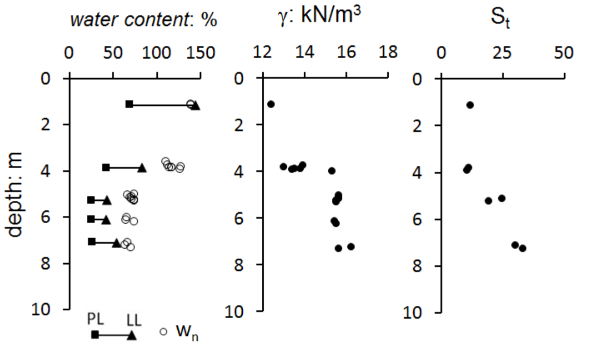

Figure 2 Properties of Lempäala clay.

3.3 *Masku test site*

The site is located on the South-West coast of Finland, near the city of Turku. The stratigraphy consists of 11 m thick soft clay deposit overlain by a 1.5 m thick weathered clay crust layer. Below 12 m, a stiffer clay layer is encountered. The piezometric level is located at the ground surface, according to the dissipation tests.

From a few available data points, natural water content seems to increase from 90% at 3 m depth up to about 110% at 5 m depth, decreasing to about 95% at 8 m depth. Unit weight, in accordance with the natural water content, decreases from about 15 to 14 kN/m^3 at 5 m, increasing up to about 15 kN/m^3 at 8 m depth. Only one sensitivity measurement is currently available. At 3.15 m depth S_t = 21.5. Properties of Masku clay are reported in Figure 3.

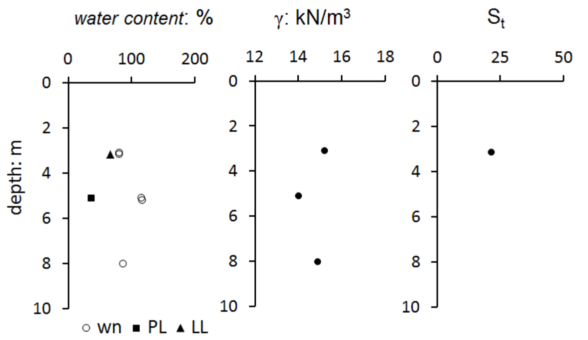

Figure 3 Properties of Masku clay.

4 PIEZOCONE TEST RESULTS

CPTu test results are available for each test site. In order to investigate the accuracy and repeatability of measurements, the tests have been repeated at different nearby points. Corrected cone resistance, friction ratio and pore pressure data are presented.

4.1 *CPTu parameters*

The measured cone resistance, q_c, needs to be corrected to account for "the unequal area effect" (see Lunne et al., 1997b). The area correction factor is equal to 0.75 for the piezocone used.

The corrected friction ratio is calculated from eq. (1):

$$R_f = f_t / q_T \times 100 \tag{1}$$

Where f_t is the sleeve friction corrected for pore pressure effects.

4.2 Test results

Preliminary results from Perniö, Lempäälä and Masku are shown in Figure 4, Figure 5 and Figure 6, respectively.

The piezocone was pushed up to 9 meters depth in Perniö and in Lempäälä, since the investigation was mainly focused on the soft clay layer. For Masku, measurements are available up to 15 m depth.

Consistency between measurements taken at different nearby points can be observed for all the three test sites, suggesting that good repeatability can be obtained using CPTu test. Moreover, the high capacity cone seems to provide fairly accurate results in the soft clay layers. However, some scatter in the results can be observed in the uppermost part of the deposit both in Perniö and Lempäälä, right below the dry crust.

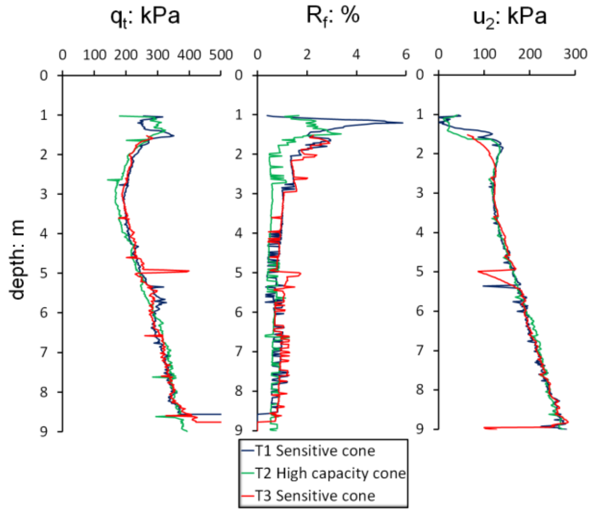

Figure 4 CPTu measurements at Perniö site.

The observable localized drops in pore water pressure in Figure 4 and Figure 5 are due to the fact that the cone penetration was stopped and a dissipation test performed.

While for cone resistance and pore pressure there seems to be a strong convergence of the measurement regardless of the cone capacity, Figure 4 and Figure 6 would suggest some discrepancy in terms of measured friction ratio. R_f estimated from the high capacity cone results lower than R_f from the sensitive cone in the top 4 m in Perniö. On the contrary, in Masku, R_f from high capacity cone is always higher than R_f from the sensitive cone. Further investigation is though needed for a better understanding of the phenomena.

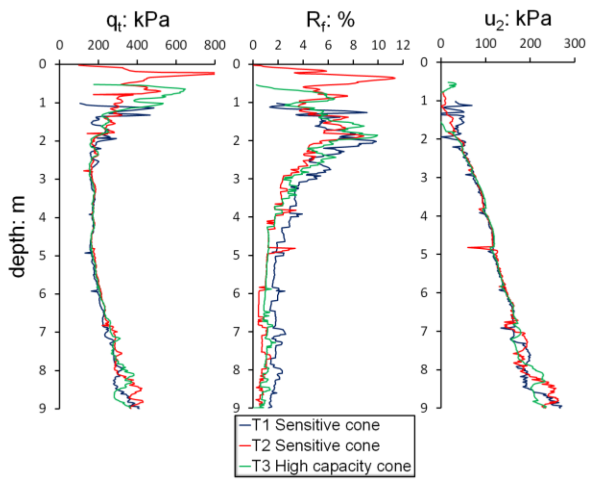

Figure 5 CPTu measurements at Lempäälä site.

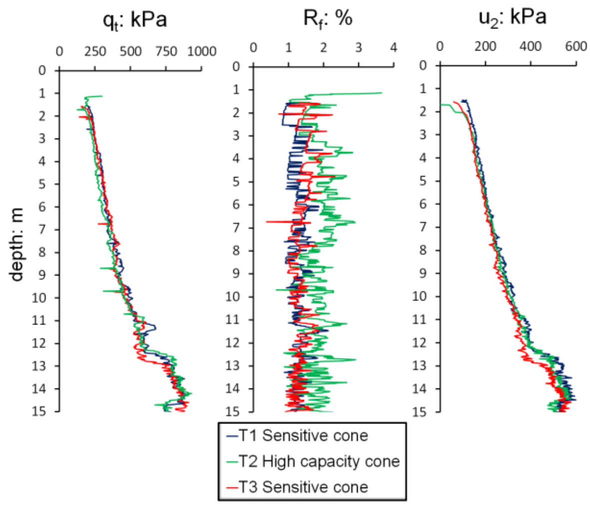

Figure 6 CPTu measurements at Masku site.

5 FIELD VANE TEST RESULTS

Field vane test results from Perniö, Lempäälä and Masku are shown in Figure 7, Figure 8 and Figure 9, respectively.

The vane used consists of four plates fixed at 90° with a length/width ratio of 2 (75 mm diameter, length of 150 mm and 2 mm thickness). Two different rotation speeds are used (EN ISO 22476-9-2014): 0.1°/sec for measuring the undisturbed peak shear strength and the residual strength (rotation of 90°), and 6°/sec for rotation >90°, to evaluate the remoulded shear strength. In particular, the remoulded strength is measured by rotating the vane 20 times at 6°/sec after reaching the 90° rotation.

The measured shear stress is plotted against the angle of rotation of the vane during shearing, up to 90°. For Masku, the vane rotation was stopped at 45°. A marked difference between pre-peak and post peak regime is visible from the test results. The softening (post-peak) regime is initiated with a sudden and dramatic loss of shear stress at very small strain (rotation < 5°). This would suggest that the clays object of study behave like brittle materials. Moreover, in Perniö there seems to be an increase in brittleness at greater depth, as the test performed at 7 m depth shows a more noticeable strength loss after peak than at 4.80 m depth. From previous oedometer test results (Länsivaara 2012) a higher structuration was found for samples taken from 6.5 m depth than for samples from shallower depths.

Nevertheless, even when using a more sophisticated vane, some disturbance always occurs. The new field vane used in the current research project is driven into the ground protected by a steel casing. The vane is eventually pushed down when the desired depth is reached and then rotated. Disturbance mainly affects peak strength, but it can also cause higher strain at peak, as shown in Figure 9. The amount of disturbance remains though hard to evaluate, and it may not be the same for each measurement. For this reason, field vane test is repeated at least once or twice for each depth.

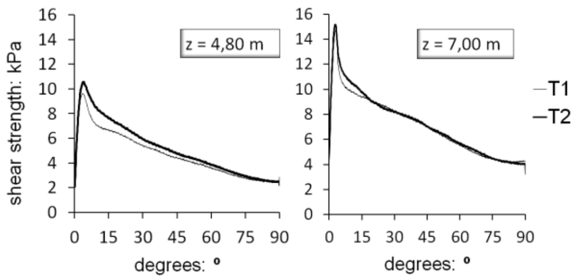

Figure 7 Field vane test in Perniö clay at different depths.

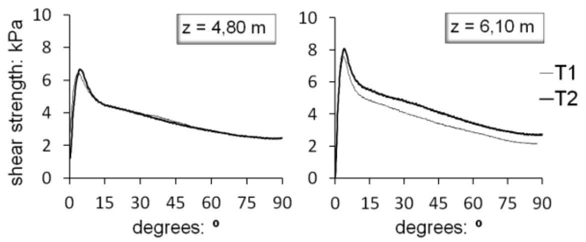

Figure 8 Field vane test in Lempäälä clay at different depths.

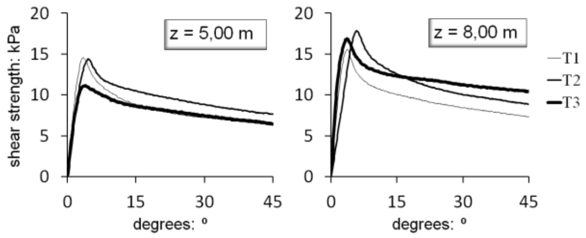

Figure 9 Field vane test in Masku clay at different depths.

6 DETERMINATION OF UNDRAINED SHEAR STRENGTH

6.1 Transformation models used

A preliminary evaluation of the undrained shear strength at the test sites is done by exploiting both piezocone and field vane measurements. Field vane data points are corrected based on plasticity according to the guidelines of Finnish Road Administration [eq. (2)]. Undrained shear strength (s_u) is evaluated from both cone tip resistance and pore pressure measurements according to the transformation models of eq. (3) and eq. (4), respectively.

$$\mu = \frac{1.5}{1 + W_L} \tag{2}$$

$$s_u = \frac{q_t - \sigma_{v0}}{N_{kt}} \tag{3}$$

$$s_u = \frac{u_2 - u_0}{N_{\Delta u}} \tag{4}$$

Where W_L is the liquid limit of the clay, q_t is the corrected cone resistance, σ_{v0} the total overburden vertical stress, u_2 the measured pore pressure, u_0 the hydrostatic pore pressure, N_{KT} the cone factor for q_t and $N_{\Delta u}$ the cone factor for $\Delta u = u_2 - u_0$.

To evaluate the cone factors, different equations have been tested. As non of them gave a superior fit, the cone factors presented in this study have been determined by fitting the results to undrained shear strength values obtained from the new vane test. A range of cone factors is given for each site, since a single value of N_{kt} or $N\Delta_u$, could not cover the entire variation with depth. In order to obtain the best fit to the vane results, the soil has been divided into layers with assigned cone factors based on variability of other properties. Such variability might depend on e.g. index parameters, such as the liquid limit (Larsson and Mulabdic, 1991).

6.2 Results

As the scatter in the field vane data points is quite low, the estimation of cone factors (N_{kt} and $N_{\Delta u}$) for Perniö clay appears to be fairly reliable (Figure 10). Further investigation is though needed in the top 3 m, where field vane data disagree with the cone measurements. Such deviation may be due to soil disturbance caused by the insertion of the vane into the soil right below the dry crust layer. Above 2 m depth the soil is stiffer and more over consolidated. As suggested by Karlsrud et al. (2005), over consolidation might affect cone factor values. Therefore, using $N_{\Delta u}$ for estimation of undrained shear strength would not seem appropriate in over consolidated soils, unless dependence of $N_{\Delta u}$ on OCR is studied.

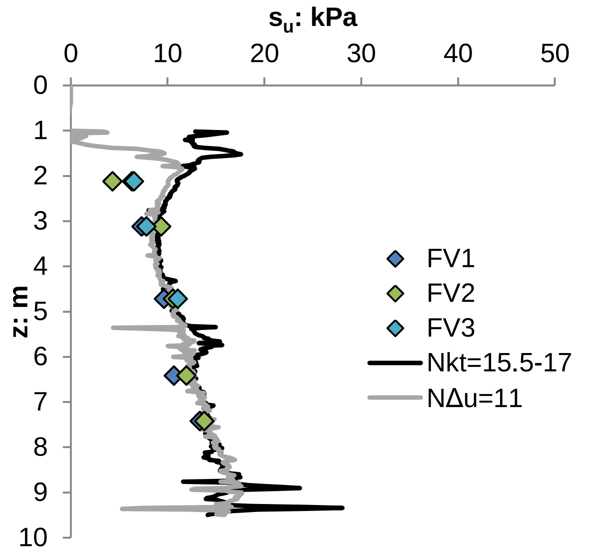

Figure 10 Undrained shear strength of Perniö clay from field test results.

The undrained shear strength at Lempäälä site can be satisfactorily assessed by using N_{kt} varying from 13 to 15 (Figure 11). However, using $N_{\Delta u}$ would lead to a severe underestimation of s_u in the top 4.5 m. One possible reason could be the presence of organic material in the upper 4-5 m (as discussed in section 3.2), besides a clearly high over consolidation, causing low excess pore pressure during cone penetration. On the other hand, N_{kt} values used seem to give a good estimate of s_u of the organic layers. These aspects need though more thorough investigation in the future.

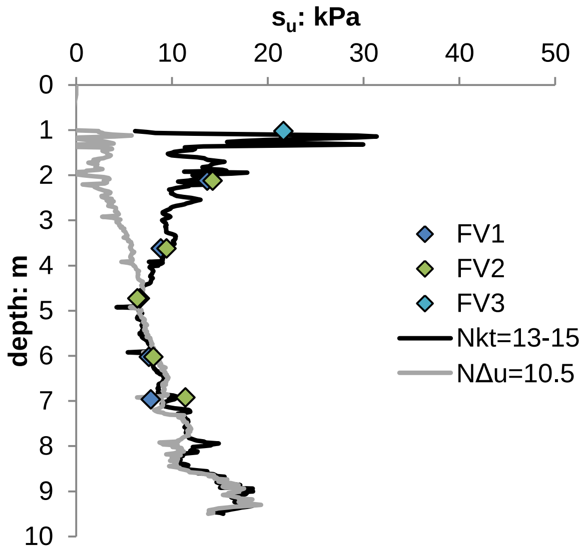

Figure 11 Undrained shear strength of Lempäälä clay from field test results.

Field vane test results from Masku show the highest scatter among the three test sites (Figure 12). In this regard, mineralogy and geological conditions at the test site may have affected the performance of the tests. As suggested by the q_t profile with depth, there seems to be noticeable layering, which may have caused variation of the peak strengths.

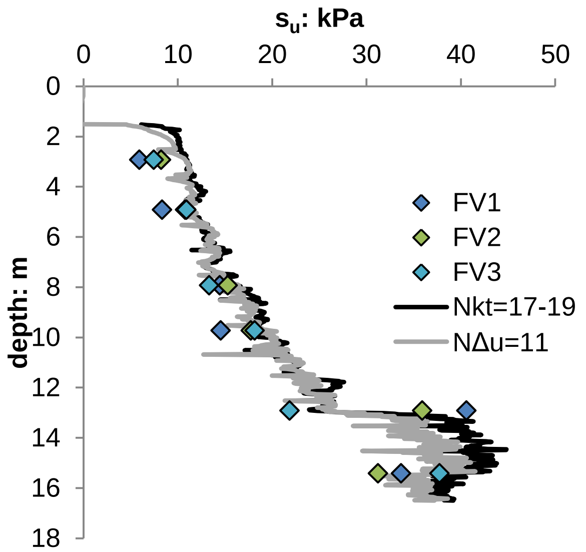

Figure 12 Undrained shear strength of Masku clay from field test results.

The cone factor N_{kt} resulted higher than in the other two test sites (N_{kt}=17-19 versus N_{kt}

ranging from 13 to 17). Nevertheless, s_u predicted by $N_{\Delta u}$ is consistent with the shear strength obtained using N_{kt}.

7 RESISTIVITY AND SEISMIC TESTS

7.1 Electrical conductivity

The resistivity module is embedded in the cone. It consists of four electrodes and a temperature sensor and it provides a measure of the electrical conductivity and temperature with depth.

Figure 13 shows the conductivity data from the three test sites. To avoid loss of saturation, 1 m pre-drilling was made. In the upper layer some fluctuations in the measurements can be observed, mainly due to the partial saturation of the upper clay. On the other hand, high data quality and repeatability is observed in the lower soft clay.

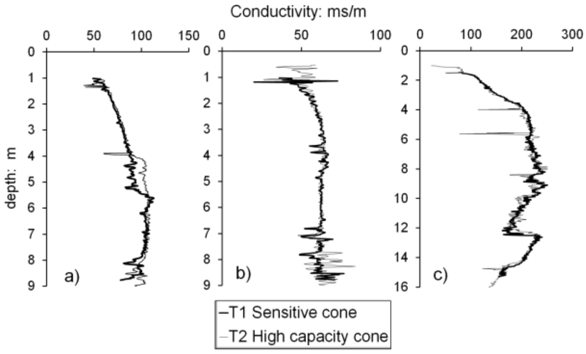

Figure 13 Electrical conductivity at a) Perniö, b) Lempäälä, c) Masku.

7.2 Seismic parameters

The shear wave velocity (V_s) profile with depth can for example be used to evaluate the maximum shear modulus (G_0 or G_{max}) as shown by eq. (5).

$$G_0 = \rho V_S^2 \quad (5)$$

Where ρ is the soil mass density.

Seismic cone consists of a piezocone unit with a receiver placed right above it. Extra equipment is needed, such as oscilloscope and impulse source. The source consists of a steel beam pressed against the ground by the weight of the CPT vehicle. The shear wave is generated by hitting the beam with the hammer in different directions in order to create compression and shear waves. The test has been repeated at 1 m intervals. During the pause in penetration, waves are generated and their intensity is measured from the time required to reach the seismometer. Seismic cone test results from the test sites are shown in Figure 14. Good repeatibility is obtained at Masku site (Figure 14c), while a moderate scatter in the data can be observed at Perniö (Figure 14a). Further investigation is required to evaluate factors affecting the measurements. In-situ bender element test has also been performed and data is compared with those obatined from the seismic test. In order to investigate the disturbance induced by transportation and storage, bender element test is repeated at different times as an indicator of sample quality. However, the study is still ongoing and results will be shown in a later publication.

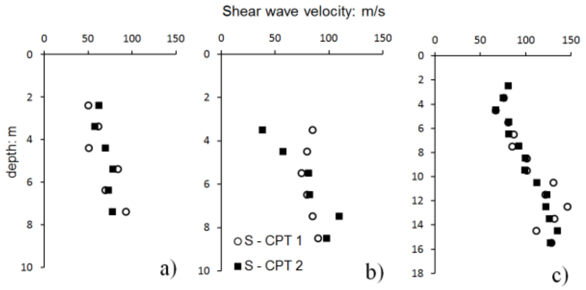

Figure 14 Shear wave velocity at a) Perniö, b) Lempäälä, c) Masku.

8 TESTS AT DIFFERENT RATES

According to the European Standard ISO 22476-1-2012, the rate of penetration for a CPT test is 20 mm/s ± 2 mm/s. A study conducted by Danziger et al. (1997) has shown that rate effects are visible when the rate of penetration deviates from the standard.

By varying the rate of penetration during a CPT test it may be possible to simulate undrained, partially drained or fully drained conditions for a particular soil, especially for intermediate soils such silts (Lunne et al., 1997b). However, since the investigation is conducted mainly in soft clay deposits, the penetration is considered fully undrained for all the different tests. Bemben and Myers (1974) conducted a study on the influence of penetration rate in a lightly overconsolidated

varved clay using speeds between 0.2 mm/s and 200 mm/s. The minimum value of cone resistance was obtained at 2 mm/s.
The influence of penetration rate has been investigated at Masku test site. Results are shown in Figure 15.
It can be noticed that an increase in cone resistance is obtained by increasing the penetration rate. Accordingly, the test performed at lower speed (0.5 cm/s) shows lower values of tip resistance. However, pore pressures do not seem to be affected by the speed of penetration. In addition, it appears difficult to detect marked differences from the measured friction ratios.
For a better understanding of the influence of penetration speed, collected data will be elaborated in the near future. Preliminary results clearly show that viscous effects and water drainage at different penetration rates may affect the measurements.

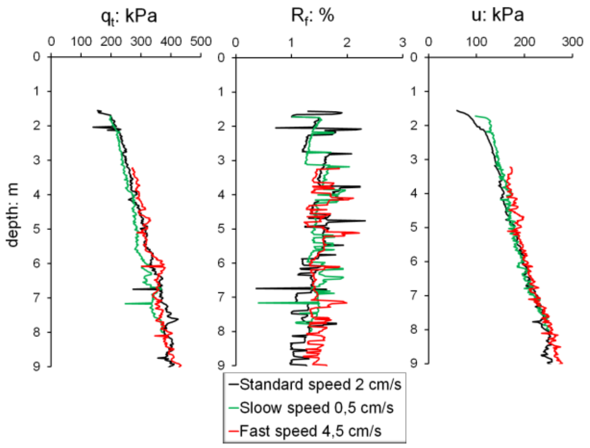

Figure 15 CPTu measurements at different penetration rates at Masku test site.

9 LABORATORY TEST RESULTS

Laboratory tests on undisturbed specimens obtained from both tube and piston samplers have been carried out. Piston samples from Masku are not available at present.
Preliminary results from CRS (constant rate of strain) oedometer tests from the test sites at different depths are shown in Figures 16-18, where the main effective vertical stress is plotted against the total vertical strain.
A standard test procedure has been adopted for sample trimming and preparation.
Therefore the quality of the test results would be mainly affected by the sampling procedure.
CRS-oedometer test results from Perniö clearly show that piston samples do not provide a distinct value of preconsolidation pressure (σ'_p). On the contrary, clearer transition from the over consolidated to the normally consolidated state can be observed from the block samples. Piston and block samples from Lempäälä show, instead, comparable values of σ'_p. CRS tests from Masku show a net change in stiffness beyond the preconsolidation stress.

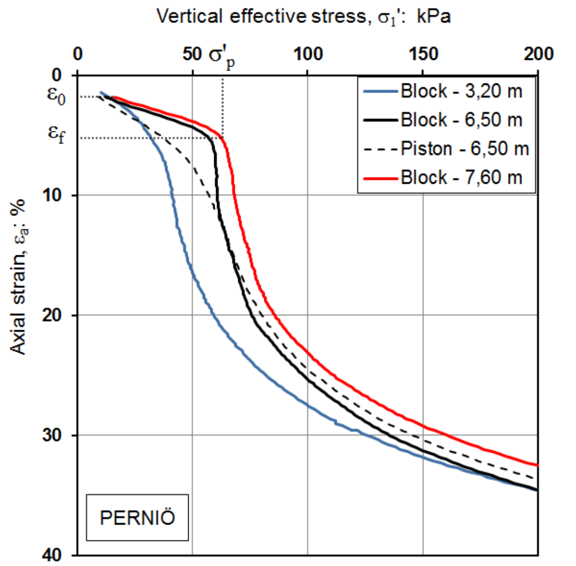

Figure 16 CRS tests on block and piston samples of Perniö clay.

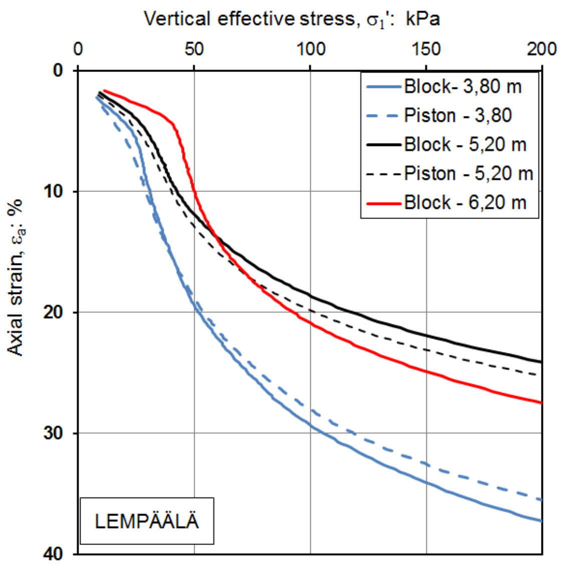

Figure 17 CRS tests on block and piston samples of Lempäälä clay.

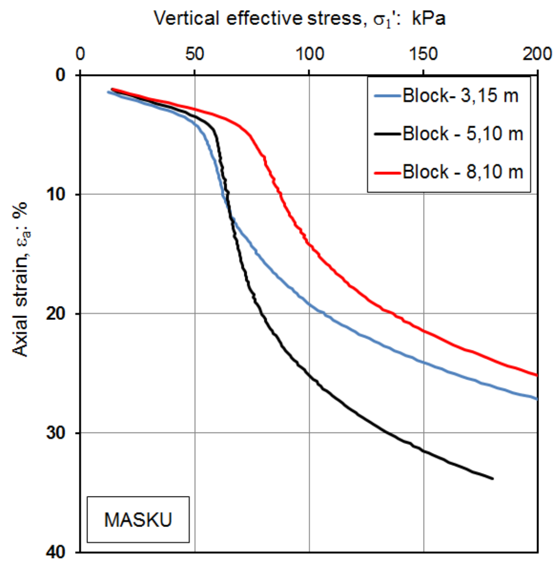

Figure 18 CRS tests on block samples of Masku clay.

The sample quality of CRS oedometer tests has been investigated using the method proposed by Lunne et al. (1997a), and results are shown in Figure 19. The increment of vertical strain (ε_p) needed to reach preconsolidation pressure is plotted against the water content. ε_p is the difference between ε_f and ε_0, as defined in Figure 16.

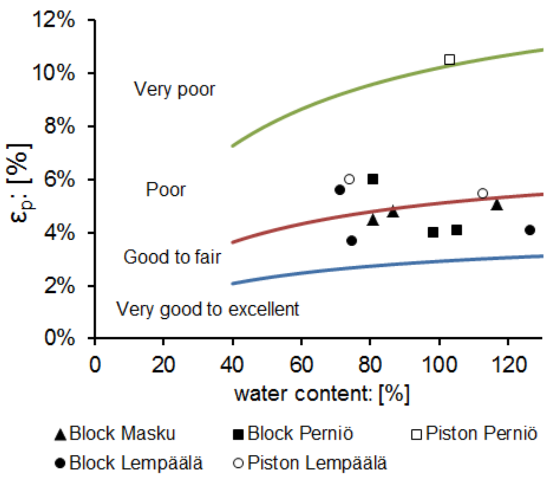

Figure 19 Vertical strain at preconsolidation pressure from CRS oedometer tests compared to the limits of disturbance categories by Lunne et al. (1997a).

According to the boundary lines suggested by Lunne et al. (1997a), the quality of the tested specimens trimmed from the block samples seems reasonably good. Conversely, those obtained from the piston sampler are generally characterised by lower quality. It must be also mentioned that preconsolidation pressure could not be observed for the majority of the piston samples. Therefore, data points could not be reported in Fig. 19. In order to evaluate the impact of sampling procedure on the quality of the test results, further investigation is though needed. The influence of soil structure and mineralogy should be also addressed in the future.

10 CONCLUSIONS

Tampere University of Technology has been carrying out a research project on the calibration of CPTu test in Finnish clays. The main goal is to create a database of clay parameters from high quality in-situ and laboratory tests and derive transformation models for strength and deformation properties.

In this study, some preliminary test results from three test sites from Finland are presented and discussed.

Piezocone test results are compared to field vane test results obtained using an innovative in-situ vane tester. Cone factors for undrained shear strength are hence evaluated.

The piezocone used includes also seismic and resistivity modules. Moreover, penetration tests performed at different rates showed a positive trend between measured cone resistance and test speed.

The quality of the specimens taken from block and piston samples is assessed based on the vertical strain needed to reach the preconsolidation pressure in oedometer tests. CRS oedometer tests on block samples from the test sites suggest that sample quality is generally higher than the quality obtainable from a piston sampler.

11 REFERENCES

Bemben, S.M. and Myers, H.J. (1974). The influence of rate of penetration on static cone resistance in Connecticut River Valley varved clay. In Proceedings of the European Symposium on Penetration Testing, ESOPT, Stockholm, Vol. 2(2), 33-43.

CEN, (2004b) ISO/TS 17892-6: Geotechnical investigation and testing. Laboratory testing of soil. Part 6: Fall cone test. Brussels, Belgium: CEN.

CEN, (2004c) ISO/TS 17892-12: Geotechnical investigation and testing. Laboratory testing of soil. Part 12: Determination of Atterberg limits. Brussels, Belgium: CEN.

Chandler, R. J. (1988). The in-situ measurement of the undrained shear strength of clays using the field vane. In Vane shear strength testing in soils: field and laboratory studies, 13-44.

Clayton, C. R., Simons, N. E., & Matthews, M. C. (1982). Site investigation.

Danziger, F. A. B., Almeida, M. S. S., & Sills, G. C. (1997). The significance of the strain path analysis in the interpretation of piezocone dissipation data. Geotechnique, 47(5), 901-914.

D'Ignazio, M., Di Buò, B., & Länsivaara, T. (2015). A study on the behaviour of the weathered crust in the Perniö failure test. In Proceedings of the XVI European Conference on Soil Mechanich and Geotechnical Engineering, XVI ECSMGE, Edinburgh, Scotland, ICE Publishing, 3639-3644.

ISO. 2012. Geotechnical investigation and testing - field testing - part 1: Electrical cone and piezocone penetration test. ISO 22476-1. 2012.

ISO. 2014. Geotechnical investigation and testing - field testing - part 9: Field vane testing. ISO 22476-9. 2014.

Janbu, N. (1998). Sediment deformation. Bulletin 35. Norwegian University of Science and Technology.

Karlsrud, K., Lunne, T., Kort, D. A., & Strandvik, S. (2005). CPTU correlations for clays. In Proceedings of the international conference on soil mechanics and geotechnical engineering, Vol. 16(2), AA Balkema.

Larsson, R. (2011). Metodbeskrivning för SGI:s 200 mm diameter 'blockprovtagare'-Ostörd provtagning i finkornig jord (In Swedish) Swedish Geotechnical Institute, SGI. Göta River Commission. GÄU. Subreport 33. Linköping.

Larsson, R., & Mulabdic, M. (1991). Piezocone tests in clay. Swedish Geotechnical Institute, Linköping, Sweden. Report No. 42

Lehtonen, V. J., Meehan, C. L., Länsivaara, T. T., & Mansikkamäki, J. N. (2015). Full-scale embankment failure test under simulated train loading. *Géotechnique*, 1-14. doi:10.1680/jgeot.14.P.100

Lunne, T., Berre, T., & Strandvik, S. (1997a). Sample disturbance effects in soft low plastic Norwegian clay. In Proceeding of the International Symposium on Recent Developments in Soil and Pavement Mechanics. Rio De Janeiro, Brazil, 81-102.

Lunne, T., Robertson, P. K., & Powell, J. J. M. (1997b). Cone Penetration Testing in Geotechnical Practice, Blackie Academic and Professional, London.

Länsivaara, T. (2012). Some aspects on creep and primary deformation properties of soft sensitive Scandinavian clays. In Proceedings of the 16th Nordic geotechnical meeting, NGM, 9-12 May 2012, Copenhagen, Denmark. pp. 397-404.

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

Powell, J. J. M. (2010). Session Report 1: CPT Equipment & Procedures. In Proceeding of the 2nd International Symposium on Cone Penetration Testing, CPT'10, California 2010.

Robertson, P. K., & Campanella, R. G. (1983). Interpretation of cone penetration tests. Part II: Clay. Canadian Geotechnical Journal, 20(4), 734-745.

Solberg, Inger-Lise; Ronning, Jan Steinar; Dalsegg, Einar; Hansen, Louise; Rokoengen, Kare; Sandven, Rolf (2008). Resistivity measurements as a tool for outlining quick-clay extent and valley-fill stratigraphy: a feasibility study from Buvika, central Norway. Canadian Geotechnical Journal 45, (2), pp210-225, 2008/02