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Evaluation of sample quality from different sampling methods in Finnish soft sensitive clays

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ABSTRACT

The determination of reliable geotechnical parameters from laboratory testing is highly dependent on sample quality. Over the past decades, undisturbed sampling of soft sensitive clays has been performed using various apparatuses and procedures. This paper outlines details of the design and performance of a new Laval type tube sampler employed for the investigation of five soft clay sites located in Finland. The investigation was conducted using the new tube sampler and two different piston samplers. The sample quality is evaluated based on the recompression volume during reconsolidation to the *in situ* effective stress in constant-rate-of-strain (CRS) oedometer tests. Test results show that tube samples are generally characterized by higher quality, especially in low plastic clays. In particular, the quality of piston samples is highly affected by the apparatus condition and sampling operations. Furthermore, the influence of storage time on tube samples is investigated. In order to guarantee a proper confinement, and thus reducing swelling, a pressurized system is applied to the tube samples obtained in two soft clay sites. Results demonstrate that the sample quality is not significantly affected by storage time as long as the soil is properly stored into the tube.

Key words: consolidation; sampling; soft clays; sample quality; storage time, disturbance

INTRODUCTION

The importance of sample quality in the determination of strength and deformation properties of soft sensitive clays has been extensively documented (e.g., Hvorslev 1949; Lunne et al. 2006; Karlsrud and Hernandez–Martinez 2013; Karlsson et al. 2016; Mataic 2016). Conclusions from these studies highlight the difficulties encountered while retrieving undisturbed samples using different sampling techniques, pointing out the implications in terms of measured soil properties from laboratory testing. The most commonly-employed sampler in Finnish geotechnical practice is the stationary piston sampler ST:1 with 50 mm diameter inner tube (Kallstenius 1971). The main reason for using such a sampling technique is its cost-effectiveness. Other types of piston samplers have been used mainly for research purposes, such as the NGI 54 mm diameter (Berre et. al. 1969; Lunne et al. 2006) and the Aalto 86 mm diameter piston samplers (Mataic 2016). The aim was to evaluate possible improvements of piston sample quality by collecting larger specimens. These studies revealed that piston samples often result in low quality, especially in highly sensitive clays (e.g. Lunne et al. 1997; Lunne et al. 2006; Karlsson et al. 2016). On the other hand, the use of tube and block samplers in such soils provides enhanced sample quality (e.g., Bjerrum 1973; Lefebvre and Poulin 1979; La Rochelle 1981; Lunne et al. 2006; Berre et al. 2007; Karlsrud and Hernandez–Martinez 2013). However, these techniques present the disadvantage of being expensive since they are more laborious and require longer time than piston sampling.

Hvorslev (1949) summarized possible mechanisms associated with sample disturbance as: (i) mechanical stress caused during transportation, handling and trimming prior to testing, (ii) changes in water content and void ratio, (iii) disturbance of soil structure, (iv) chemical changes, and (v) mixing of soil components. Despite the inevitable disturbance induced by the changes in stress state from *in situ* to laboratory condition, all the other aforementioned mechanisms or phenomena can be somewhat limited or even avoided by choosing the appropriate equipment and following correctly the test procedures (Lunne et al. 2006). In particular, while (i), (iv) and (v) can be considered independent of the chosen type of sampler, (ii) and (iii) can be notably improved by using tube or block samplers (e.g. Lunne et al. 1997; Lunne et al. 2006).

The research presented in this paper focuses on the effect of sample disturbance in Finnish soft clay deposits induced by different sampling techniques. In particular, laboratory test results on soft clay specimens obtained using two traditional piston samplers (ST:1 50 mm and Aalto 86 mm) and a new 132 mm open drive tube sampler are compared. The 132 mm open drive tube sampler used is a downscaled and upgraded version of the well-known Laval type tube sampler (La Rochelle 1980; Larsson 2011). The performance of the different sampling techniques is assessed from constant-rate-of-strain (CRS) oedometer tests. The criterion proposed by Lunne et al. (1997), based on the normalized change in void ratio ($\Delta e/e_0$) to achieve the *in situ* effective vertical stress (σ_{v0}') , is adopted to evaluate the quality of the different specimens.

TEST SITES

The present study is conducted on five clay test sites located in the southern region of Finland. Some preliminary test results were reported by Di Buò et al. (2016) for three of these five sites. In the following, the main geotechnical properties of the different sites are illustrated.

Perniö

The Perniö test site is located in the southwestern coast of Finland, about 140 km west from the city of Helsinki. In October 2009, Tampere University of Technology (TUT) and the Finnish Transport Agency (FTA) conducted a full scale embankment failure test, gathering extensive amount of data on the undrained behaviour of soft clays (Lehtonen et al. 2015; D'Ignazio et al. 2017). The stratigraphy consists of a 1–1.5 m thick dry crust layer overlaying an 8–9 m thick soft clay layer followed by silty and stiff sandy layers located at greater depth. The groundwater table is located at 1 m depth. Geotechnical properties of Perniö clay are presented in Fig. 1. The sensitivity (S_t), as evaluated by the laboratory fall cone (FC), indicates values between 40 and 60 without showing any particular trend with depth. The measured intact shear strength (s_u) from FC test varies between 10 kPa and 15 kPa while the remoulded undrained shear strength (s_u^{re}) is nearly constant with values between 0.20 and 0.30 kPa over the entire deposit. Based on the definition proposed by Torrance (1983), the soil can be defined as quick clay. The plasticity index (*PI*) varies between 30% and 40% above 4 m and below 6 m depth while lower values (≈20%) can be noticed at around 5 m depth. The water content (*w*) is clearly higher than the liquid limit (*LL*) with values varying between 80 and 100%. The clay content increases with depth from about 60% at 3 m depth to 90% at 8 m depth. The organic content is less than 2% over the entire deposit.

Lempäälä

The Lempäälä test site is located near the city of Tampere, along the railway track to Helsinki. The main soil properties are presented in Fig. 2. The soil stratigraphy includes a 1.5 m thick layer of weathered clay crust followed by 1–1.5 m of organic soil underlain by soft sensitive clay. The groundwater table is located at 0.60 m depth. The natural water content is relatively high above 4 m depth, compared to what commonly observed in Finnish clays (D'Ignazio et al., 2016), with values varying between 120% and 140%. Below, *w* varies in the range 70–80%. The *LL* is generally lower than *w* in the investigated layers. The FC test indicates S_t to vary between 20 and 60. The scatter of the S_t data in Fig. 2 may suggest the presence of interlayers in the deposit. The intact strength varies between 6 kPa and 15 kPa without any particular trend with depth while the s_u^{re} is slightly lower than 0.50 kPa. The *PI* ranges between 25-30% in the soft clay layer, even though thin lenses characterized by lower PI can be noticed between 5 and 6 m depth. The clay content is relatively constant below 5 m depth and on average equal to 60%, while smaller value can be observed in the upper layer. The organic content is approximately 5% above a depth of 3 m and less than 1% in the soft clay layer.

Masku

The Masku test site is situated near the city of Turku, along the southwestern coast of Finland. The stratigraphy consists of 8 m thick soft clay layer overlaying a 1.5 m weathered clay crust layer. The groundwater table is located at 1.20 m depth. Samples were taken only at 3 m, 5 m and 8 m depth. The water content is 80% at 3 m and 8 m depth while values up to 120% can be found in the intermediate layer. The *PI* is about 40%, with higher values in the intermediate layer. The *LL* is lower than the water content. The measured S_t varies between 10 and 30. The Masku clay is the least sensitive of the clays presented in this study. Moreover, s_u^{re} is generally higher than 0.5 kPa with a maximum value of 1.5 kPa at 5 m depth while the intact strength (s_u) increases with depth, from 15 kPa at shallow depth to 20 kPa measured at 8 m depth. The clay content varies with depth between approximately 60% and 90% while the organic content is less than 2%. The principal geotechnical properties of the soil at Masku site are summarized in Fig. 3.

Paimio

The site is located 25 km far from the city of Turku, in the southwestern region of Finland. Soft clay is found between 2 and 10 m depth, overlain by a 2 m dry crust layer. The groundwater table is located at a depth of 0.80 m. Test results shown in Fig. 4 reveal the presence of a leaner upper clay layer (above 6.5 m), characterized by *w* of 50%–80% and *PI* of 15%–20%. Below 6.5 m depth, a more plastic clay with *w* varying between 90 and 110%, and average *PI* of 30% is found. The measured clay content falls between 40 and 60% in the top part of the deposit. Higher values were measured at greater depths, with clay content reaching almost 100% between 6 m and 7 m depth. The organic content is less than 1%. The sensitivity varies between 60 and 90 without following any particular trend with depth, and the *LL* is generally well below the water content. The intact strength measured by means of the FC varies between 13 kPa and 17 kPa while s_u^{re} is lower than 0.3 kPa over the entire deposit, thus indicating that the clay can be defined as quick (Torrance, 1983).

Sipoo

The Sipoo test site is located in the South of Finland, about 30 km north of Helsinki. The investigation revealed the presence of a homogeneous soft clay deposit between 2 and 9 m depth. The groundwater table is located at 1 m depth. Index test results are illustrated in Fig. 5. The deposit is characterized by the highest PI values among all the five investigated sites. In particular, a *PI* of 60% is measured from samples taken between 5 and 6 m depth. The water content increases with depth to a maximum of 120% at 6 m depth, decreasing then to 90–100% at 9 m depth. As for all the other sites, the *LL* is below the natural water content over the entire deposit. Fall cone test results indicated a nearly constant s_u^{re} with depth varying between 0.50 and 1 kPa, while the intact strength (s_u) is approximately equal to 15 kPa. The sensitivity varies between 20 and 30. The clay content shows values of about 60% at 3 m depth, increasing to 90% at lower depth. The organic content is consistently lower than 2% throughout the deposit.

SAMPLING EQUIPMENT AND PROCEDURE

Three different types of sampling apparatus were used to collect samples: (a) an open drive 132 mm diameter tube sampler (TUT 132), (b) the ST:1 50 mm piston, and (c) the Aalto 86 mm diameter piston sampler. The main features of the samplers are presented in Table 1. The table presents three parameters (area ratio A_r, inner clearance C and cutting edge angle α) given by:

$$A_r = \frac{D_e^2 - D_i^2}{D_i^2} \quad (1)$$

$$C = \frac{D_s - D_i}{D_i} \quad (2)$$

$$\alpha = arctan\frac{D_e}{4} \quad (3)$$

where D_e and D_i represent the external and the internal diameter of the sampler cutting edge, respectively, while D_s is the inner diameter of the sampling tube (Fig. 6). The apparatuses and sampling procedures are described in the following paragraphs.

ST:1 50 mm stationary piston sampler

Apparatus

The ST:1 stationary piston sampler (Fig. 7) was developed by the Swedish Geotechnical Institute (SGI) for taking high quality samples of soft sensitive clay. This sampler is also described in the Finnish geotechnical investigation and testing standard SFS–EN ISO 22475–1:2006E (SFS 2004). It consists of a piston located inside a sampler body connected with inner extension rods, extension pipes and removable plastic sampling cylinders. The piston is fixed and connected to the inner rods while the outer sampler body is connected with extension pipes. The external diameter is 53.8 mm while the inner diameter is 49.6 mm giving a considerable area ratio of 17%. The cutting edge angle is 9.7°. Three 170 mm long plastic cylinders are placed inside the sampler body, resulting in a total sampling length of 510 mm.

Sampling procedure

The sampling process consists of three phases: insertion, sampling and withdrawal. The entire sampler body is pushed into the soil with the piston locked by means of a threaded spindle. This is to prevent the entrance of the surrounding material into the cylinder. Once the desired depth is reached, the piston is kept locked and the outer steel sampler is pushed downwards. The sampling is performed at constant rate of speed between 1 and 2 cm/s in order to minimize the disturbance induced to the sampled soil (Andresen and Kolstad 1980). When the desired depth is reached, the vertical penetration is stopped and the sampler is recovered after a waiting time of about five minutes to ensure good adhesion between the cylinder and the soil. However, longer waiting time is recommended in quick clays (NGF 2013). At this stage, different cutting and recovery techniques were tested at some of the test sites presented in this study. This was done in order to investigate the disturbance induced by the different procedures. At Perniö and Lempäälä sites, the apparatus was recovered by pulling the entire system at very low speed. This procedure is typically used in the Norwegian geotechnical practice (NGF 2013). In contrast, at the Paimio and Sipoo sites, the apparatus was rotated 20 times in order to separate the sample from the surrounding soil. This procedure was adopted for all the samples obtained at these two sites. The influence of the procedure on sample quality is analyzed and discussed later in the paper.

Aalto University 86 mm piston sampler

Apparatus

The Aalto 86 mm piston sampler shown in Fig. 8 was only used at the Perniö site. This sampler is a scaled version of the NGI 54 mm piston sampler (Hvorslev 1949; Andresen and Kolstad 1980), modified in terms of sampling cylinder and sampler body dimensions. In particular, while the ST:1 sampler has plastic inner linings inside the sampler body, the Aalto piston has a thin walled self cutting steel tube on which the sample is stored and extruded prior to laboratory testing. The external diameter of the sampling cylinder is 88.94 mm, while the average inner diameter of the cylinder is 85.88 mm giving an area ratio of 6.8%. The tube length is 650 mm. However, the maximum sampling length is 450 mm. The cutting edge angle is 12°. The cylinder does not have any inner clearance.

Sampling procedure

The sampling operation is slightly different from the ST:1 sampler. The entire apparatus is pushed down to the desired depth with the piston locked to prevent the entrance of the soil into the cylinder, Then, once the desired depth is reached, the piston is released and withdrawn upwards by turning the inner rod, thus enabling the entrance of the soil into the sampler. The piston is kept fixed in its upper position and the sampler is pushed downwards at a speed of 1 cm/s until reaching the final sampling depth. Finally, the sampled soil is recovered by pulling upwards the entire apparatus without using any rotation.

TUT tube sampler

Apparatus

A thin–walled open–drive sampler (Figs. 9 and 10) was developed at Tampere University of Technology in 2014, inspired by the Laval tube sampler (La Rochelle 1980) and its modification by SGI (Larsson 2011). The device consists of a thin–walled sampling tube mounted on a sampler head equipped with a screw–type valve that can be opened or closed by rotating the inner rod (Figs. 9b and 9c). This system ensures an effective vacuum above the sample during withdrawal from the ground. To reduce the soil disturbance during penetration, a cutting edge with inclination of 5º is introduced on the outer side of the sampling cylinder. Differently from the 200 mm Laval sampler, the tube length and diameter are smaller. In particular, the outer diameter is 139.7 mm with a tube thickness of 4 mm. Therefore, the inner diameter is 131.7 mm and the area ratio is 12%. The standard length of the sampling tube is 500 mm. In addition, 750 mm long tubes were used at Paimio and Sipoo.

Sampling procedure

The sampling operation using the TUT's tube sampler consists of four different phases. Firstly, a borehole is made to the desired depth using a drilling apparatus. The sampler is moved down to the hole while keeping the head valve opened. This is to ensure the mud to be flowing upwards. Then, the sampling process starts with the insertion of the sampler into the soil at very low speed (0.5 cm/s). In order to ensure the pore pressure dissipation around the sampling tube and, therefore, a better adhesion between the soil and the sampler, a resting time of 20 minutes is planned. However, the waiting time should be adjusted based on the investigated type of soil. Finally, the head valve is closed and the soil at the bottom of the sampler is cut by means of a wire system that is pulled from the ground surface (Fig. 9d). This procedure was introduced by Larsson (2011) in order to avoid disturbance induced by the sampler rotation (La Rochelle 1980). In order to separate the sample from the surrounding soil and prevent suction at the cutting plane, air is injected into the pipe from the ground surface before and during sample retrieval. Finally, the tube is disassembled from the apparatus and stored before the transportation to the laboratory. Unlike other sampling systems, several sources of disturbance are avoided. As already mentioned, the use of cutting wire is beneficial in terms of sample quality since the torsion typically induced by sampler rotation are avoided. In addition, differently from the standard procedure adopted with the Laval sampler, the soil is stored inside the tube and extruded only prior to the laboratory test rather than directly in situ.

EXPERIMENTAL PROGRAM

The testing program included a total of 97 CRS oedometer tests on undisturbed samples. The present study focuses on the evaluation of stress-strain behavior under one-dimensional (1D) compression and on the evaluation of sample disturbance induced by the different sampling methods.

Standard procedures were adopted to evaluate the effect of sampling on the quality of the test results. All three different sampling techniques described earlier have been utilized at the Perniö site, while for the other sites the Aalto 86 mm piston samples are not available. Moreover, only tube samples were collected at the Masku site.

CRS oedometer tests

In order to evaluate the stress-strain behaviour of the clays from the five test sites, CRS oedometer tests were performed on specimens of 45 mm diameter and 15 mm initial thickness at a constant strain rate of 0.001 mm/min (0.4 %/h). The sample quality was assessed according to existing methodologies (Lunne et al. 1997; Lunne et al. 2006). The preconsolidation or yield stress (σ'_p) and constrained moduli are evaluated using a curve fitting procedure detailed by Sällfors (1975), as shown in Fig. 11. The constrained modulus is stress-dependent: in the overconsolidated part, a relatively high value (M_0) can be found, while it drops significantly till reaching a minimum value (M_L) when passing the preconsolidation stress. In the normally consolidated region, the modulus increases linearly with the effective stress and the modulus number (M') is evaluated as $\Delta M/\Delta\sigma'_v$.

Consolidometer test data are given in Tables 2 to 6 for the various test sites, while the stress-strain curves are shown in Figs. 12 to 16. Vertical strain (ε_v) and tangent constrained modulus (M) are plotted against vertical effective stress (σ'_v). The observed stress-strain behaviour is similar for all the tested specimens and characterized by distinct pre-yielding and post-yielding responses. This is the typical behaviour of lightly overconsolidated marine clays described by Janbu (1985). From the oedometer test results, it is possible to notice that the evaluation of the geotechnical parameters is influenced by the adopted sampling procedure. Overall, the preconsolidation stress (σ_p') and constrained modulus (M_0) evaluated on the TUT 132 tube samples are systematically higher in Perniö and Lempäälä sites. However, comparable values between piston and tube samples were observed for Paimio and Sipoo clays. This aspect is discussed in detail in the following section since various factors such as soil properties, apparatus condition and procedures are involved.

Sample quality evaluation

Although the importance of sample disturbance on the evaluation of strength and deformation properties is well established according to the existing literature, there is not yet a standard methodology to quantify the amount of disturbance. A qualitative method that is used in common practice is based on the recompression volume of the sample during reconsolidation to the *in situ* vertical effective stress σ'_{v0}, in terms of normalized change in void ratio ($\Delta e/e_0$), as detailed by Lunne et al. (1997). Based on this criterion, sample quality is classified as “Very good to excellent”, “Good to fair”, “Poor” and “Very poor”. Lunne et al. (1997) exploited four different samplers to derive the criteria: the NGI 54 mm diameter sample, 75 mm and 95 mm piston samplers, and the 250 mm Sherbrook block sampler (Lefebvre and Poulin, 1979). It was concluded that disturbance can be seen in the higher volumetric changes when reconsolidating the sample back to *in situ* stress.

In this paper, the Lunne et al.'s (1997) criterion is used to evaluate the sample quality achieved in the investigated sites using the described sampling methods.

DISCUSSION OF TEST RESULTS

A summary of the sample quality of the tested specimens is presented in Fig. 17 and Table 7, based on Lunne et al.'s (1997) criterion. The criterion is illustrated by means of two plots: (i) fig. 17a show the vertical deformation at reconsolidation to the *in situ* stress versus the natural water content (w); (ii) the $\Delta e/e_0$ versus depth is shown in Fig. 17b. The sample quality achieved by different sampling methods at the five investigated sites is summarized in Table 7.

The results of the present study clearly show that the TUT 132 tube samples retrieved from all the investigated sites are generally characterized by "good" to "very good" quality. In contrast, the quality of the piston samples varies site by site. In particular, ST:1 samples retrieved from Perniö and Lempäälä show rather poor quality compared to those obtained from Paimio and Sipoo. The explanation for such observed phenomenon is not straightforward. It must be pointed out that various factors may have influenced the achieved sample quality. Firstly, the investigated clays are characterized by different soil properties. For instance, Perniö and Lempäälä clays have low PI and high S_t compared to the other sites. However, despite Paimio clay shows similar index properties, the achieved sample quality is higher. Several explanations can be given to justify this finding. Firstly, as mentioned earlier in the paper, different sampling operations were performed at these sites. In particular, no rotation was applied when using the ST:1 50 and Aalto 86 mm piston samplers to cut the sample from the surrounding soil at Perniö and Lempäälä sites. This procedure might have induced some tensile stresses in the soil during sampler withdrawal, resulting in higher amount of disturbance. Furthermore, the ST:1 sampler employed at these two sites suffered of lack of maintenance, in terms of sharpness of the cutting edge as shown in Fig. 7b. For this reason, a brand new piston sampler was used at Paimio and Sipoo sites, resulting in higher sample quality as shown in Fig. 17. The rotation applied to the ST:1 50 sampler to cut the soil from the deposit, along with the use of a brand new apparatus seems to have a beneficial effect on the sample quality. It is, however, not straightforward to discern which of these aforementioned factors had the most predominant effect. Moreover, it is worth to highlight that the stress-strain curves from CRS oedometer tests on piston samples of Paimio clay show a softer behavior than the tube samples above 6.5 m depth, while they nearly overlap for the samples taken at greater depth, which are characterized by higher *PI* (Fig. 15). This may indicate that samples characterized by low plasticity are more likely to be disturbed as observed in Perniö and Lempäälä clays (Figs. 12 and 13). The tube samples of Masku, Paimio and Sipoo show the highest quality among all the samples taken. Masku and Sipoo clays have higher *PI* and lower S_t than the other three clays. This could suggest that for medium and, possibly, low sensitive clays, the soil becomes less susceptible to disturbance.

EFFECT OF STORAGE ON SAMPLE QUALITY

The adopted sampling method is one of the main contributors to the disturbance of a soil sample. However, additional factors can affect the sample quality during the storage time such as inadequate sealing, stress relief, migration of water, temperature and chemical changes (Hvorslev 1949; Kallstenius 1963; Lessard and Mitchell 1985). The influence of storage effects on samples has been gaining importance in geotechnical practice, since samples may be stored for long time before testing. La Rochelle et al. (1976) observed a decrease in peak undrained shear strength up to 10–20% due to the long-term storage. The amount of reduction is more evident in low plastic clays. A reduction of peak shear strength was also observed by Bjerrum (1973), already after three days of storage. As discussed earlier in the paper, the TUT 132 tube sampler is designed to keep the soil stored inside the steel tube and extruded only prior to testing. This feature provides enhanced sample quality compared to the traditional Laval-type sampling as proved by the comparison between tests A4 and A5 (Fig. 18a and Table 2). Test A4 is conducted on a tube sample extruded directly *in-situ* and tested the same day while test A5 is related to a tube sample taken at the same depth, stored in and tested after six months. From the ratio $\Delta e/e_0$ it appears to be clear that the quality achieved by the extruded sample ($\Delta e/e_0$=0.035 vs $\Delta e/e_0$=0.029) is lower probably due to disturbance occurred during transportation.

In order to investigate the influence of storage time on the quality of TUT tube samples, CRS tests were carried out at different time intervals. Some results are presented in Fig. 18. It is possible to observe that samples do not show any significant decrease in terms of quality with time due to the proper confinement and sealing provided by the tube. Small differences can be observed from the comparison between samples C6, C7 and D4, D6 (Fig. 18). However, these samples are characterized by different *w* (Tables 4 and 5), which may justify the differences in stress-strain behavior. As discussed earlier, differences in water content can be caused by different factors such as the presence of thin layers within the deposit (e.g. Lempäälä) as well as the storage effect. Most of the tested samples did not show any significant change in the water content, thus proving that a proper sealing is guaranteed.

A pressurized system was applied to tube samples from Paimio and Sipoo. The method consists of applying a pressure equal to 80% of the *in situ* vertical effective stress by means of a rubber inner tube placed in the gap between the sample and the upper cap. The pressure was applied during the first period of storage, from sampling until the first round of testing. Finally, the inner tube is removed and sample is kept stored inside the tube. The first round of tests were performed after one month from sampling and the achieved quality is maintained constant even after eight months of storage (Fig. 18c). This procedure is thought to provide a beneficial effect due to the confinement of the sample that would reduce the stress relief in the soil ensuring a good sample quality during both transportation and the initial storage period. In particular, tests on samples obtained from Sipoo were performed after 2 years from sampling. Figure 18d clearly shows that tests repeated at different time intervals up to two years nearly overlap, thus proving that the storage time does not represent an issue in the achieved sample quality for TUT tube samples.

CONCLUSIONS

The paper presents an extensive investigation program conducted on five different soft clay deposits in Finland. The performance of a new Laval type tube sampler with 132 mm diameter (TUT 132) and two ordinary piston samplers (50 mm and 86 mm diameter) is analyzed in different soil conditions. Overall, tube samples are generally characterized by higher quality than piston samples, based on the recompression volume measured at the *in-situ* effective stress in the oedometer tests. The quality of piston samples seems to be influenced by various factors such as the sampling procedure and apparatus condition. In particular, the procedure adopted to cut the sample from the surrounding soil seems to notably affect the quality of piston samples. Tests conducted at Paimio and Sipoo sites revealed that the sampler rotation has a positive effect on sample quality compared to sampler lifting, which was carried out in Perniö and Lempäälä. This aspect indicates that the torsional stresses induce less disturbance compared to the tension caused by sampler lifting. For these reasons, the sampler rotation would seem to be more suitable for piston sampling in Finnish clay conditions. It must be pointed out that the piston sampling apparatus used at Paimio and Sipoo was brand new, while the one used at Perniö and Lempäälä suffered of lack of maintenance. Therefore, sample lifting and rotating procedures should be tested in the same soil condition using the same type of apparatus to confirm the observation reported in this study.

Another factor that seems to influence the sample quality is the soil plasticity. Results obtained from Masku and Sipoo suggest that high plastic clays are less susceptible to disturbance during sampling. Nevertheless, comparable quality of piston and tube samples was obtained from Paimio, which is characterized by low PI and high S_t, where rotation was applied to the piston sampler prior to sample withdrawal. Further studies are required for a better understanding of this finding.

The influence of storage on sample quality was further investigated on the tube samples. One of the innovative features of the TUT's sampler is that the soil is kept stored inside the tube and extruded only before laboratory testing. Moreover, a confining pressure was applied through a pressurized system to the tube samples obtained from Paimio and Sipoo sites in order to guarantee a proper confinement, especially during transportation. The test results showed that sample quality was preserved up to two years after sampling (Fig. 18d).

In conclusion, the TUT 132 sampler seems to reliably provide high quality samples in Finnish clay conditions. Therefore, its use is highly suggested in Finnish clay deposits, especially in those characterized by low plasticity. However, good sample quality can be also achieved with the piston sampler if the sampling procedure is performed correctly and the apparatus is in a good condition. Finally, further studies are required to investigate the performance of the Laval type sampler compared to the "block" sampler which is largely used in Norwegian low plastic sensitive clays.

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Captions

Fig. 1: Index test results, Perniö.

Fig. 2: Index test results, Lempäälä.

Fig. 3: Index test results, Masku.

Fig. 4: Index test results, Paimio.

Fig. 5: Index test results, Sipoo.

Fig. 6: Tube sampler parameters: (a) cylinder without inner clearance, (b) sampler with screw on cutting shoe, and (c) cylinder with rolled and reamed cutting edge (Mataic 2016)

Fig. 7: ST:1 sampler with 50 mm liner; a) sampler apparatus before punching, c) detail of sampler used in Perniö and Lempäälä sites.

Fig. 8. Aalto 86 mm sampler, a) Aalto University version, b) sampling cylinder and outdrawn piston position, c) sampling cylinder and withdrawn piston position (Mataic, 2016).

Fig. 9. TUT 132 mm tube sampler: (a) sampler apparatus, (b) screw cap, open configuration, (c) screw cap, closed configuration, (d) detail of the cutting wire, (e) cutting edge.

Fig. 10. TUT 132 mm tube sampler. Dimensions are in mm.

Fig. 11. Schematization of Sällfors's (1975) method used for the interpretation of CRS tests; a) evaluation of preconsolidation stress, b) evaluation of oedometer moduli.

Fig. 12. CRS oedometer tests results on tube and piston samples, Perniö.

Fig. 13. CRS oedometer tests results on tube and piston samples, Lempäälä.

Fig. 14. CRS oedometer tests results on tube and piston samples, Masku.

Fig. 15. CRS oedometer tests results on tube and piston samples, Paimio.

Fig. 16. CRS oedometer tests results on tube and piston samples, Sipoo.

Fig. 17. Sample quality according to Lunne et al (1997): a) vertical deformation at reconsolidation versus water content; b) change of normalized void ratio at reconsolidation versus depth.

Fig. 18. Storage influence on sample quality. CRS test results from (a) Perniö, (b) Masku, (c) Paimio, (d) Sipoo.

List of symbols

FC	Fall cone
LL	Liquid limit
OCR	Overconsolidation ratio (OCR = σ'_p / σ'_v)
PI	Plasticity index (PI = LL – PL)
PL	Plastic limit
e	Void ratio
M	tangent constrained modulus
M_L	oedometer modulus in NC range
M_0	oedometer modulus in OC range
M’	oedometer modulus number
NC	Normally consolidated
S_t	Sensitivity ($S_t = s_u/s_u^{re}$)
s_u	Undrained shear strength
s_u^{re}	Remolded undrained shear strength
w	Natural water content
$\Delta e/e_0$	Normalized change in void ratio
ε_v	Vertical deformation
σ'_L	Minimun vertical effective stress
σ'_p	Vertical preconsolidation stress
σ'_v	Effective vertical stress

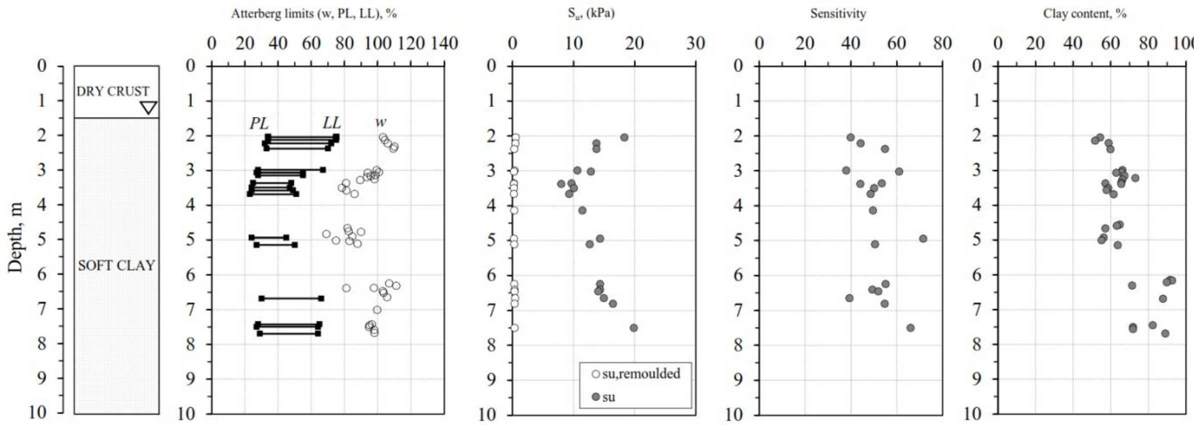


Fig. 1: Index test results, Perniö.

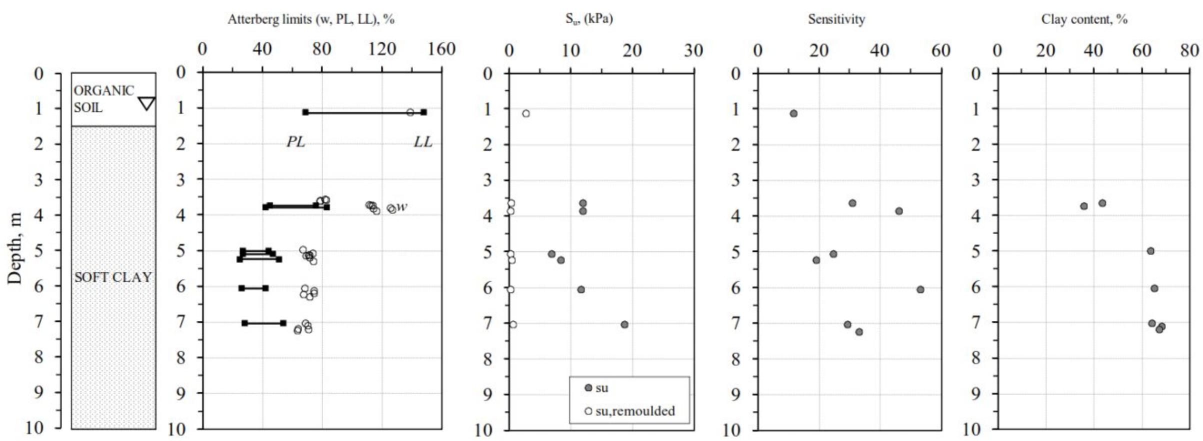


Fig. 2: Index test results, Lempäälä.

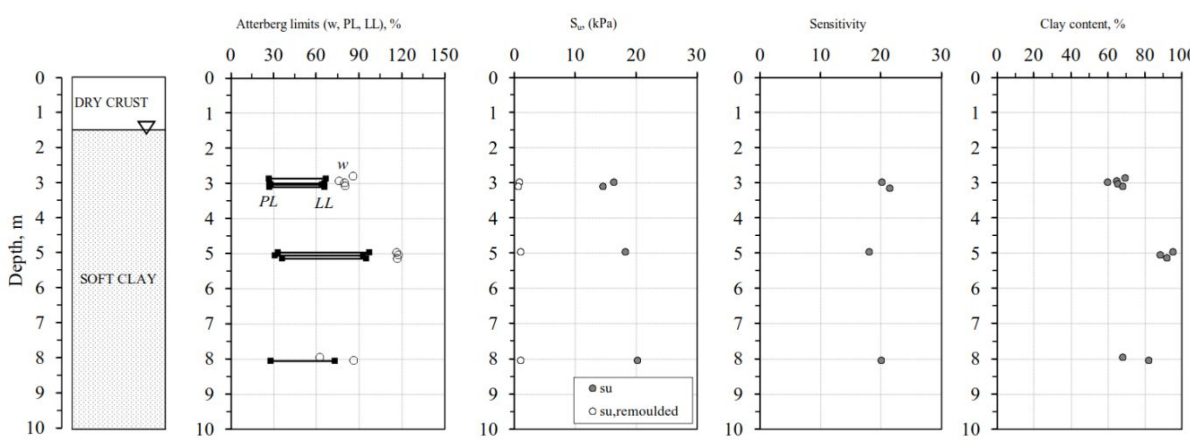


Fig. 3: Index test results, Masku.

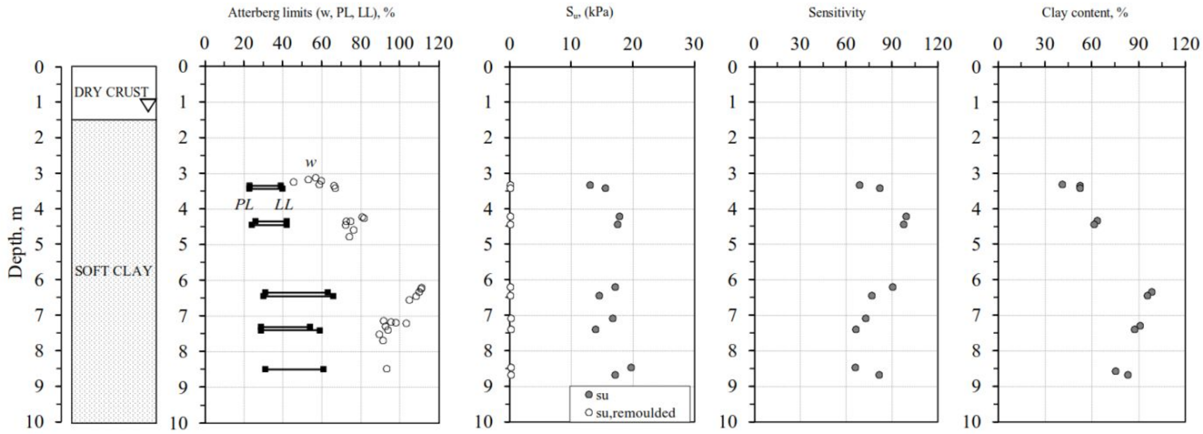


Fig. 4: Index test results, Paimio.

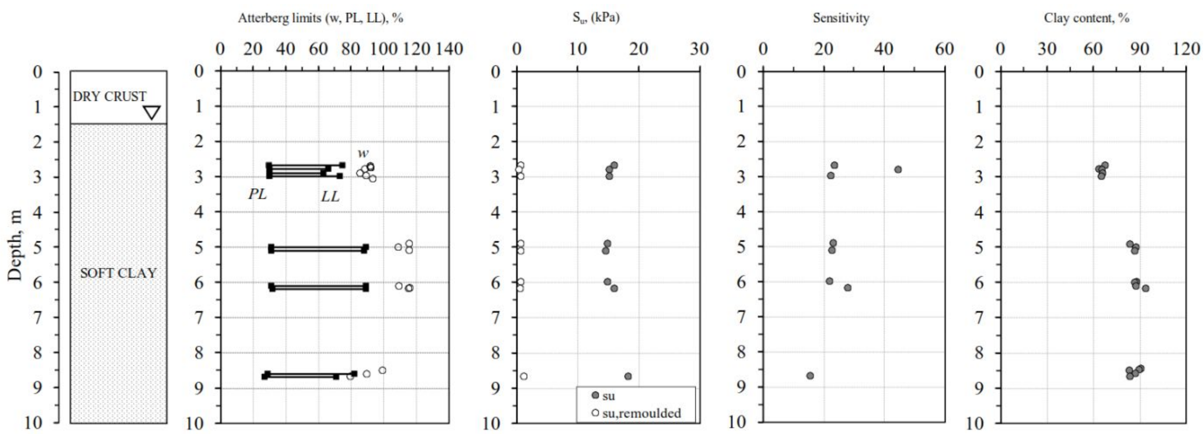
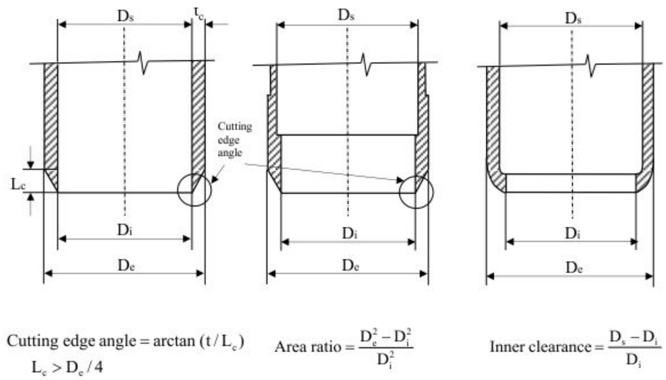


Fig. 5: Index test results, Sipoo.



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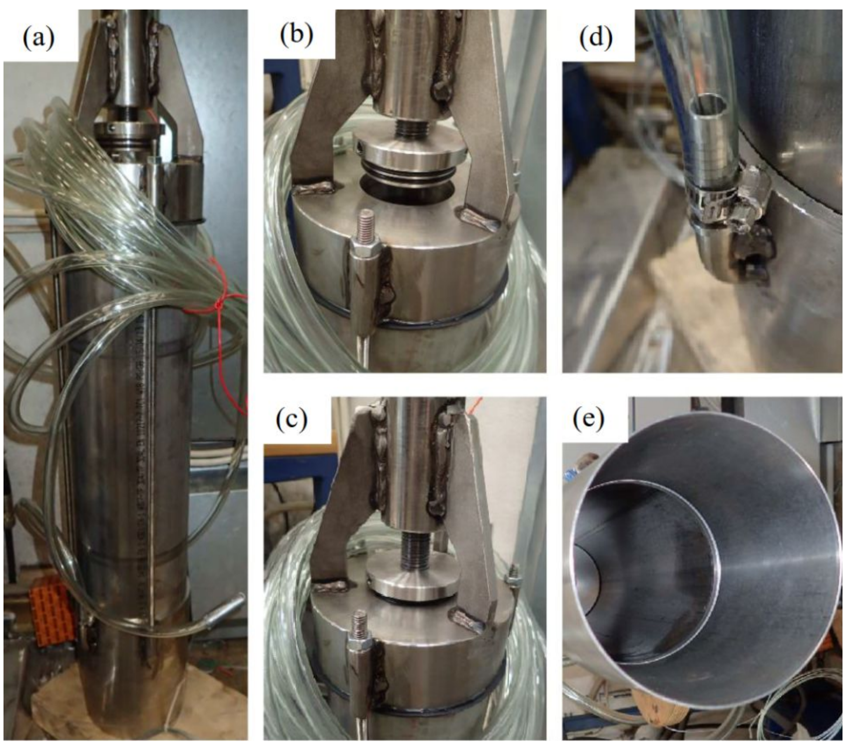


Fig. 9. TUT 132 mm tube sampler: (a) sampler apparatus, (b) screw cap, open configuration, (c) screw cap, closed configuration, (d) detail of the cutting wire, (e) cutting edge.

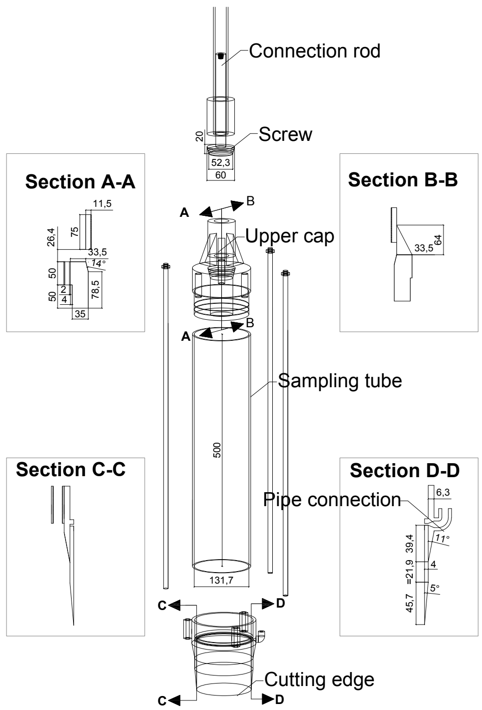


Fig. 10. TUT 132 mm tube sampler. Dimensions are in mm.

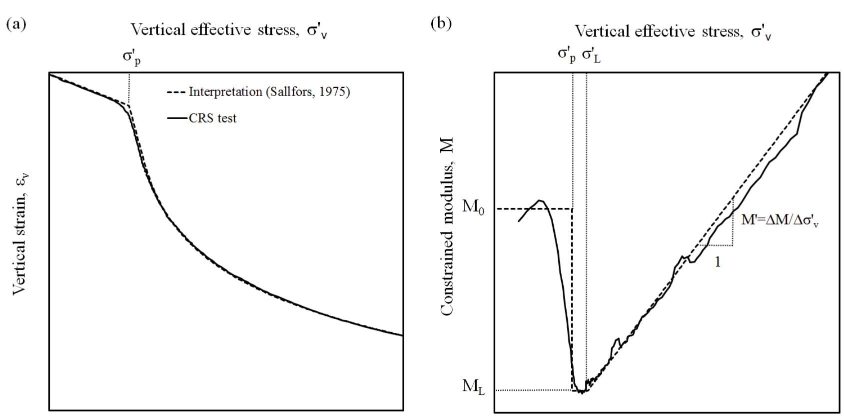


Fig. 11. Schematization of Sällfors's (1975) method used for the interpretation of CRS tests; a) evaluation of preconsolidation stress, b) evaluation of oedometer moduli.

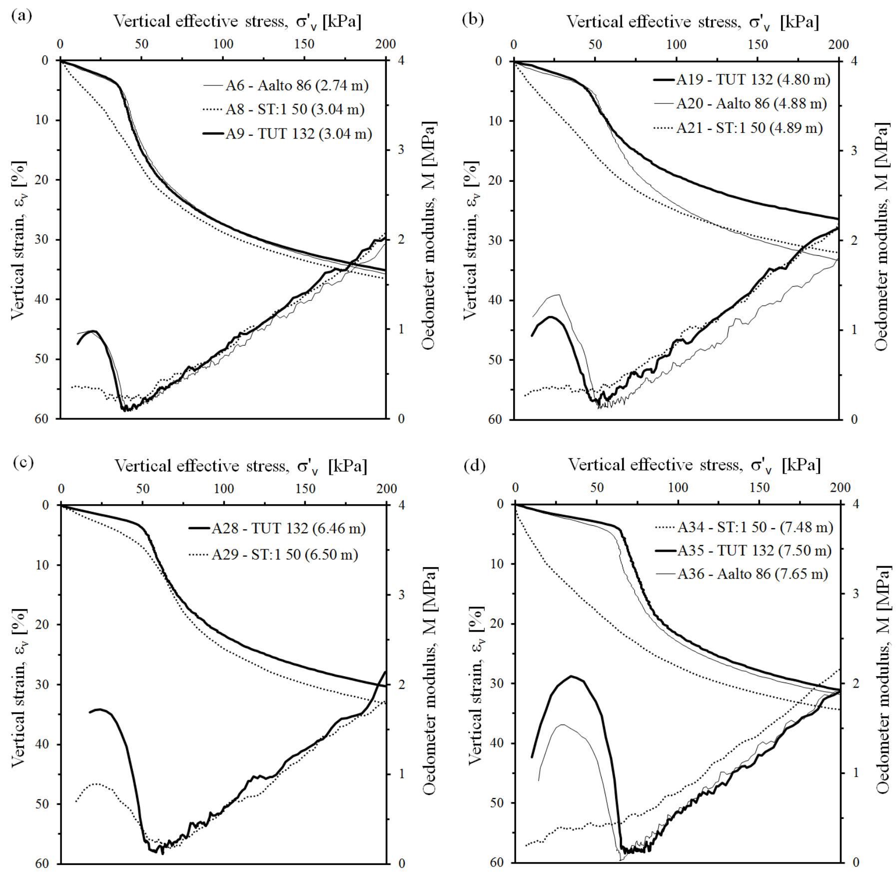


Fig. 12. CRS oedometer tests results on tube and piston samples, Perniö.

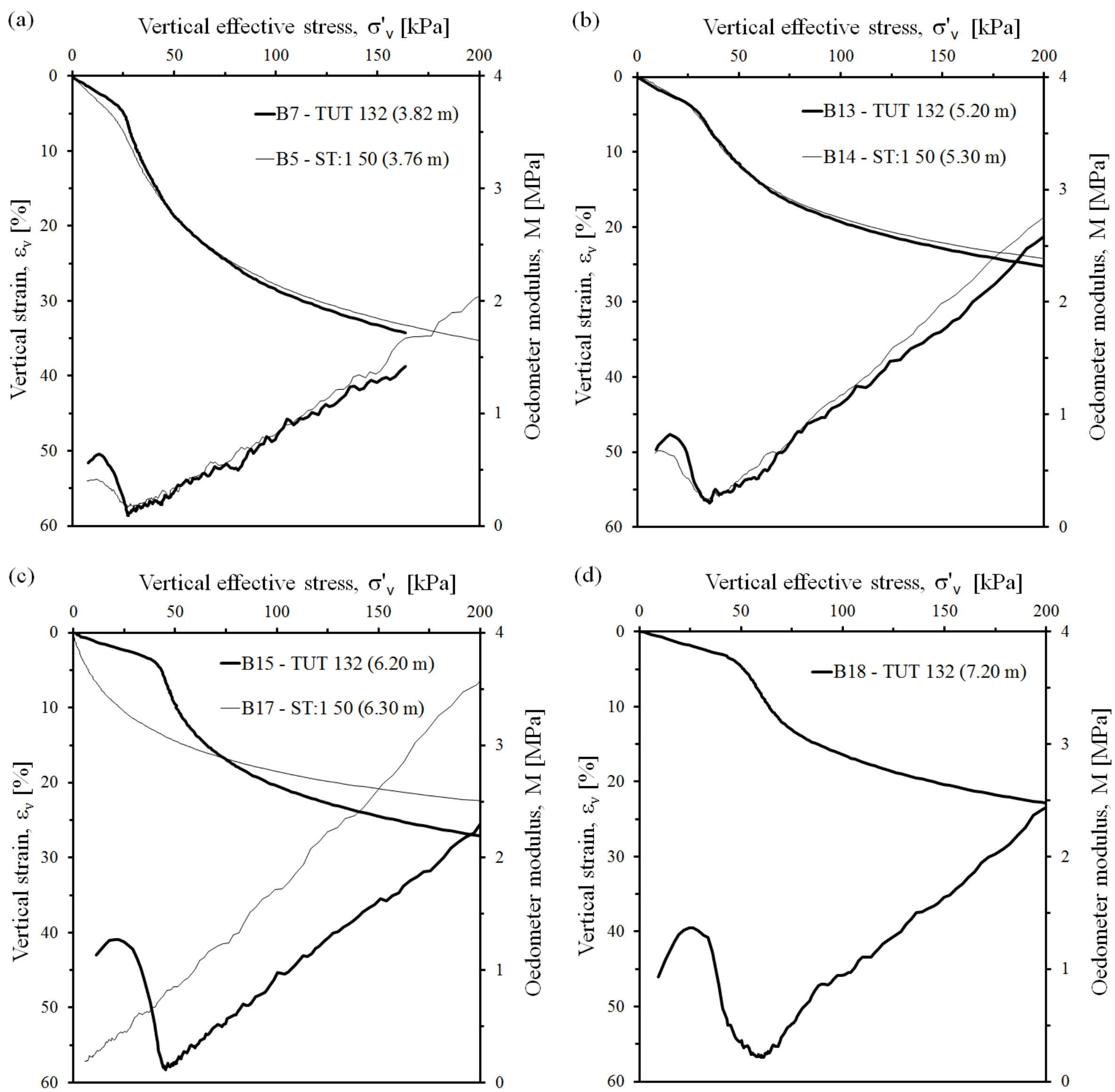


Fig. 13. CRS oedometer tests results on tube and piston samples, Lempäälä.

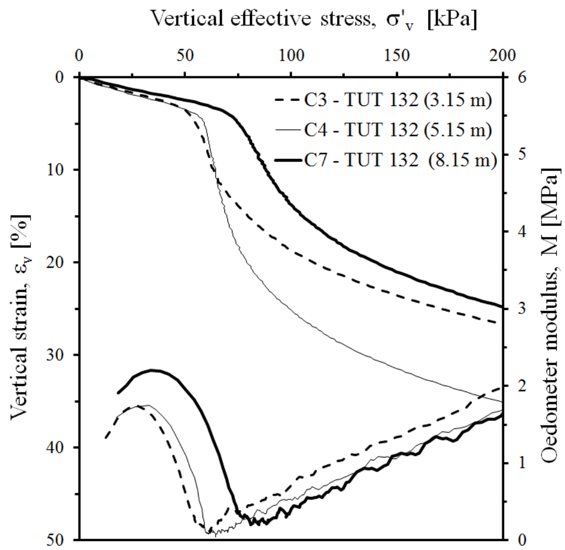


Fig. 14. CRS oedometer tests results on tube and piston samples, Masku.

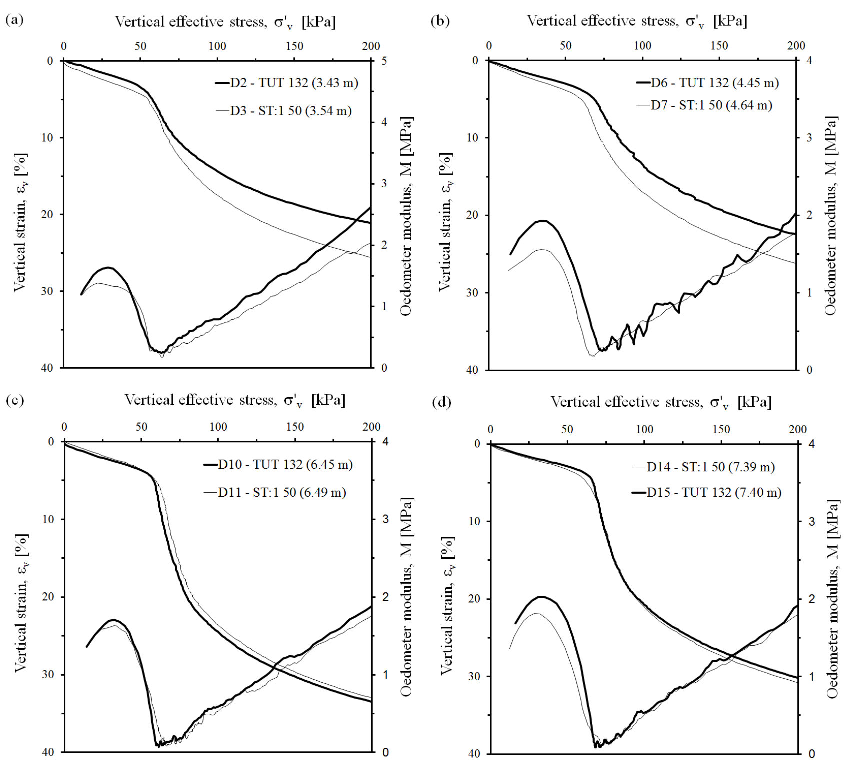


Fig. 15. CRS oedometer tests results on tube and piston samples, Paimio.

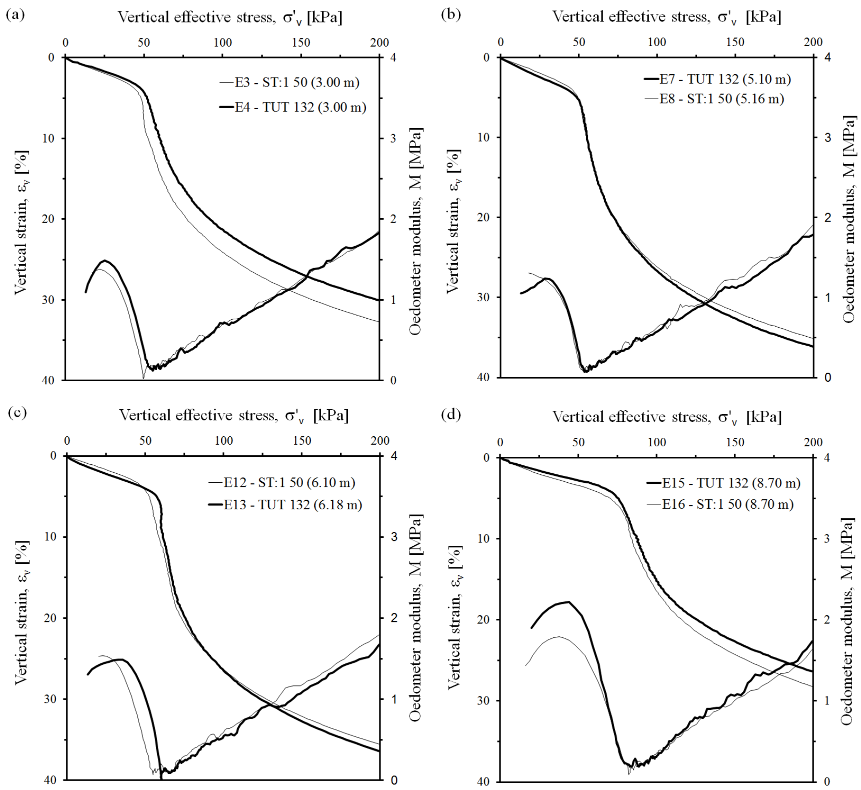
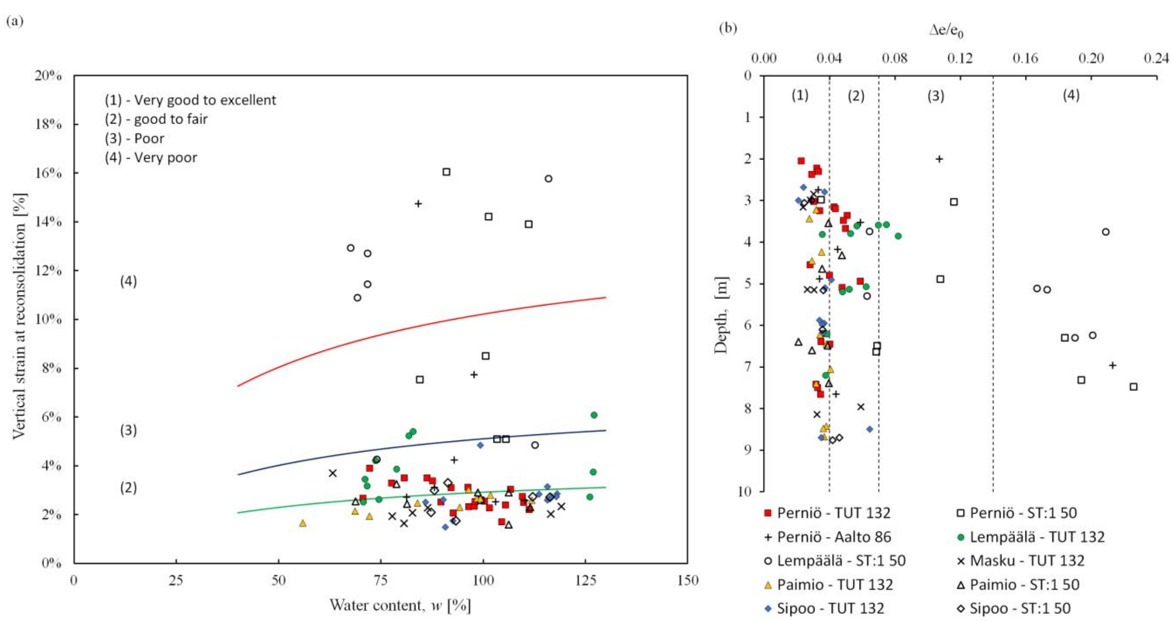


Fig. 16. CRS oedometer tests results on tube and piston samples, Sipoo.



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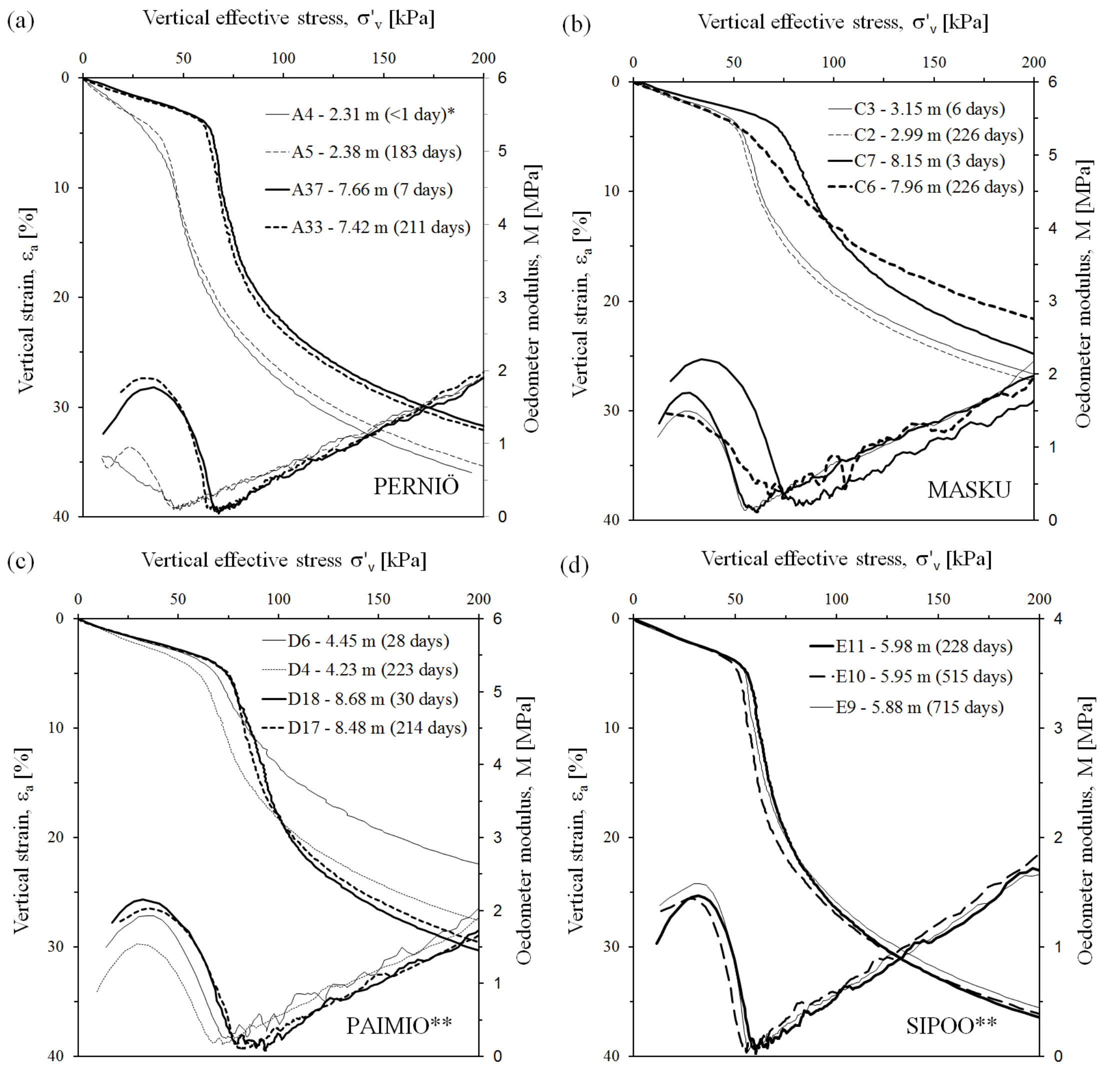

Note: *sample extruded *in-situ*.

** with pressurized system

Fig. 18. Storage influence on TUT 132 sample quality. CRS test results from (a) Perniö, (b) Masku, (c) Paimio, (d) Sipoo.

Tables

Table 1. Summary of employed sampling operations

Sampler	Sampling length (mm)	Internal diameter (mm)	Thickness (mm)	Area ratio (%)	Inside clearance (%)	Cutting edge (°)	Sampling technique	Storage	Sites
ST:1 50	510	49.6	2.05	17	0	9.7	No rotation	Standard	Perniö, Lampäälä
							20 times rotation		Paimio, Sipoo
AALTO 86	450	85.88	1.5	6.8	0	10-14	No rotation	Standard	Perniö
TUT 132	500 750	131.7	4	12	0	5	Cutting wire - no rotation	Standard	Perniö, Lempäälä, Masku
								Pressure	Paimio, Sipoo

Table 2. CRS oedometer tests, Perniö.

Site	Test	z (m)	Sampler	Storage time (days)	*w* (%)	*PI*	S_t	σ'_{v0} (kPa)	σ'_p (kPa)	$\Delta e/e_0$	Oedometer modulus (MPa)		
											M_0 (MPa)	M_L (MPa)	M'
Perniö	A1	2.00	Aalto 86	n.a.	97.8	41	40	21	*n.a.*	0.107	*n.a.*	*n.a.*	*n.a.*
	A2	2.05	TUT 132	207	104.6	41	40	21.2	52	0.022	1.10	0.10	11.50
	A3	2.22	TUT 132	182	105.5	40	44	22.0	42	0.032	0.80	0.10	11.50
	A4	2.31	TUT 132	<1*	110	37	54	22.4	43	0.035	0.80	0.10	12
	A5	2.38	TUT 132	182	111.3	37	54	22.7	43	0.029	0.80	0.10	12
	A6	2.74	Aalto 86	n.a.	110.3	39	42.	24.4	38	0.033	0.90	0.10	12
	A7	2.99	TUT 132	11	99.4	39	38	25.5	38	0.035	0.90	0.10	12.50
	A8	3.04	ST:1 50	2	100.7	28	37	25.8	36	0.116	0.30	0.20	12
	A9	3.04	TUT 132	153	101.6	28	37	25.8	40	0.030	1.00	0.10	13
	A10	3.15	TUT 132	10	96.3	27	38	26.3	37	0.043	0.75	0.15	13.50
	A11	3.20	TUT 132	160	92.2	27	40	26.5	37	0.046	0.80	0.10	13,5
	A12	3.25	TUT 132	15	100.4	27	40	26.7	39	0.033	0.90	0.10	13
	A13	3.36	TUT 132	8	80.8	23	44	27.2	36	0.050	0.80	0.15	14
	A14	3.48	TUT 132	220	77.7	23	44	27.8	38	0.048	0.85	0.15	14
	A15	3.52	Aalto 86	n.a.	92.9	25	50	28.0	33	0.059	0.45	0.15	13
	A16	3.68	TUT 132	182	86.3	28	48	28.7	37	0.050	0.80	0.13	13
	A17	4.17	Aalto 86	n.a.	81.3	28	49	30.9	42	0.045	1.10	0.12	13
	A18	4.55	TUT 132	148	92.7	21	50	32.7	46	0.028	1.20	0.13	13.50
	A19	4.80	TUT 132	15	70.7	21	51	33.9	48	0.040	1.00	0.15	14
	A20	4.88	Aalto 86	n.a.	103	21	71	34.2	49	0.034	1.30	0.12	12
	A21	4.89	ST:1 50	2	84.6	21	71	34.2	44	0.108	0.35	0.25	13
	A22	4.94	TUT 132	231	72.3	21	71	34.5	50	0.059	0.80	0.28	12
	A23	5.10	TUT 132	7	87.7	23	50	35.3	50	0.048	1.00	0.20	13

A24	6.20	TUT 132	47	109.6	36	55	40.3	50	0.036	1.40	0.80	13
A25	6.28	Aalto 86	*n.a.*	97.1	40	55	40.7	*n.a.*	0.196	*n.a.*	*n.a.*	*n.a.*
A26	6.30	ST:1 50	8	111.2	40	55	40.8	54	0.184	0.30	0.20	12
A27	6.40	TUT 132	15	89.7	32	49	41.2	52	0.033	1.60	0.10	13
A28	6.46	TUT 132	5	106.8	32	52	41.5	52	0.040	1.40	0.09	12.7
A29	6.50	ST:1 50	2	103.5	38	52	41.7	57	0.069	0.80	0.20	13
A30	6.64	TUT 132	5	105.6	36	40	42.3	57	0.069	0.85	0.18	13
A31	6.96	Aalto 86	*n.a.*	84.2	34	54	43.8	*n.a.*	0.213	*n.a.*	*n.a.*	*n.a.*
A32	7.32	ST:1 50	40	101.4	37	64	45.4	58	0.194	0.35	0.25	12
A33	7.42	TUT 132	211	96.5	37	66	45.9	62	0.032	1.80	0.11	14
A34	7.48	ST:1 50	40	91.1	37	66	46.2	*n.a.*	0.226	*n.a.*	*n.a.*	*n.a.*
A35	7.50	TUT 132	175	97.9	37	66	46.3	66	0.033	2.00	0.13	14.50
A36	7.65	Aalto 86	*n.a.*	88.1	35	41	46.9	61	0.044	1.50	0.11	14
A37	7.66	TUT 132	7	98.1	35	41	47.0	65	0.035	1.70	0.10	13.50

*sample extruded *in-situ*
n.a.: information not available

Table 3. CRS oedometer tests, Lempäälä.

Site	Test	z (m)	Sampler	Storage time (days)	*w* (%)	*PI*	S_t	σ'_{v0} (kPa)	σ'_p (kPa)	$\Delta e/e_0$	Oedometer modulus (MPa)		
											M_0 (MPa)	M_L (MPa)	*M'*
Lempäälä	B1	3.58	TUT 132	235	81.9	23	30.	18.5	27	0.07	0.35	0.21	15
	B2	3.59	TUT 132	235	82.9	23	31	18.5	23	0.070	0.40	0.20	13
	B3	3.60	TUT 132	228	78.9	12	31	18.6	27	0.057	0.50	0.20	15
	B4	3.75	ST:1 50	79	112.7	31	40	19.1	26	0.065	0.40	0.20	12
	B5	3.76	ST:1 50	86	116.7	31	46	19.1	*n.a.*	0.209	*n.a.*	*n.a.*	13
	B6	3.80	TUT 132	1	127.2	41	46	19.2	27	0.053	0.50	0.20	16
	B7	3.82	TUT 132	26	126.1	41	46	19.3	26	0.038	0.60	0.11	10
	B8	3.86	TUT 132	220	127.2	41	46	19.3	27	0.082	0.30	0.18	11
	B9	5.08	TUT 132	30	73.8	20	25	25.7	31	0.059	0.65	0.20	16.5
	B10	5.12	ST:1 50	79	69.3	20	25	26.0	*n.a.*	0.167	*n.a.*	*n.a.*	18
	B11	5.14	TUT 132	29	71.2	20	25	26.1	32	0.052	0.75	0.20	16
	B12	5.15	ST:1 50	86	71.8	20	25	26.1	*n.a.*	0.173	*n.a.*	*n.a.*	18
	B13	5.20	TUT 132	19	71.7	26	19	26.4	34	0.048	0.80	0.26	16.5
	B14	5.30	ST:1 50	84	74.1	26	19	27.0	30	0.036	0.65	0.25	16
	B15	6.20	TUT 132	2	74.6	16	53	32.0	44	0.039	1.20	0.15	15
	B16	6.24	ST:1 50	102	67.7	16	53	32.2	*n.a.*	0.201	*n.a.*	*n.a.*	17
	B17	6.30	ST:1 50	86	71.8	16	53	35.5	*n.a.*	0.190	*n.a.*	*n.a.*	16
	B18	7.20	TUT 132	6	70.8	26	33	37.5	50	0.040	1.30	0.20	16

n.a.: information not available

Table 4. CRS oedometer tests, Masku.

Site	Test	z (m)	Sampler	Storage time (days)	*w* (%)	*PI*	S_t	σ'_{v0} (kPa)	σ'_p (kPa)	$\Delta e/e_0$	Oedometer modulus (MPa)		
											M_0 (MPa)	M_L (MPa)	M'
Masku	C1	2.84	TUT 132	224	82.7	40	20	29.2	50	0.030	1.20	0.18	13
	C2	2.99		226	77.8	*39*	20	30.0	53	0.028	1.50	0.15	13.5
	C3	3.15		6	80.7	39	21	30.6	55	0.024	1.70	0.18	13
	C4	5.15		1	116.5	59	18	38.6	60	0.026	1.70	0.10	12
	C5	5.15		1	119.1	59	18	38.6	60	0.031	1.60	0.09	12.5
	C6	7.96		226	63.2	45	20	50.8	60	0.059	1.40	0.30	13
	C7	8.15		3	86.4	45	20	51.7	76	0.032	2.10	0.22	12.5

n.a.: information not available

Table 5. CRS oedometer tests, Paimio.

Site	Test	z (m)	Sampler	Storage time (days)	*w* (%)	*PI*	S_t	σ'_{v0} (kPa)	σ'_p (kPa)	$\Delta e/e_0$	Oedometer modulus (MPa)		
											M_0 (MPa)	M_L (MPa)	M'
Paimio	D1	3.22	TUT 132	214	68.7	16	69	29.3	54	0.032	1.30	0.28	15
	D2	3.43	TUT 132	28	55.9	17	82	30.6	56	0.028	1.60	0.21	16
	D3	3.54	ST:1 50	24	68.8	17	82	31.2	57	0.039	1.30	0.18	13
	D4	4.23	TUT 132	223	84	16	99	35.2	62	0.035	1.50	0.21	13
	D5	4.32	ST:1 50	90	78.8	16	99	35.6	60	0.047	1.10	0.25	11.5
	D6	4.45	TUT 132	28	72.2	18	98	36.3	65	0.029	1.80	0.22	13
	D7	4.64	ST:1 50	24	81.4	20	98	37.2	62	0.035	1.50	0.18	12
	D8	6.22	TUT 132	224	111.9	34	90	44.5	62	0.034	1.80	0.10	14
	D9	6.40	ST:1 50	267	106.2	36	76	45.3	71	0.021	2.40	0.20	12
	D10	6.45	TUT 132	30	101.8	36	77	45.5	60	0.038	1.55	0.09	13.5
	D11	6.49	ST:1 50	33	106.2	36	77	45.7	61	0.039	1.6	0.10	13
	D12	6.60	ST:1 50	186	111.5	36	76	46.2	68	0.029	2	0.10	12
	D13	7.05	TUT 132	515	96.4	30	*73*	48.2	62	0.041	1.50	0.13	12
	D14	7.39	ST:1 50	35	98.7	25	67	49.8	67	0.040	1.70	0.10	13
	D15	7.40	TUT 132	30	94.3	25	67	49.8	67	0.032	1.95	0.10	14.5
	D16	8.42	TUT 132	720	91.7	30	66	54.4	70	0.038	1.90	0.12	14
	D17	8.48	TUT 132	214	98.5	30	66	54.7	76	0.036	2.00	0.16	14
	D18	8.68	TUT 132	30	99.3	30	82	55.6	78	0.037	2.10	0.10	14

n.a.: information not available

Table 6. CRS oedometer tests, Sipoo.

Site	Test	z (m)	Sampler	Storage time (days)	*w* (%)	*PI*	S_t	σ'$_{v0}$ (kPa)	σ'$_p$ (kPa)	Δe/e$_0$	Oedometer modulus (MPa)		
											M_0 (MPa)	M_L (MPa)	*M'*
	E1	2.68	TUT 132	145	92.6	45	23	25.2	53	0.024	1.50	0.13	12
	E2	2.79	TUT 132	240	90.3	36	44	25.7	53	0.037	1.50	0.14	13
	E3	3.00	ST:1 50	62	87.3	43	22	26.2	48	0.029	1.20	0.11	12.5
	E4	3.00	TUT 132	40	90.8	43	22	26.6	52	0.021	1.45	0.13	12
	E5	3.06	ST:1 50	30	93.4	43	22	27.0	48	0.025	1.30	0.12	12
	E6	4.90	TUT 132	240	115.7	58	23	35.6	53	0.041	1.20	0.12	12
	E7	5.10	TUT 132	42	118.1	57	22	36.5	52	0.037	1.20	0.10	11.5
	E8	5.16	ST:1 50	30	112.1	57	22	36.8	50	0.036	1.25	0.10	12
Sipoo	E9	5.88	TUT 132	715	115.7	63	22	40.1	56	0.034	1.50	0.09	12
	E10	5.95	TUT 132	515	113.7	63	22	40.2	53	0,037	1.40	0.08	12
	E11	5.98	TUT 132	228	117.9	63	21	40.3	58	0.035	1.40	0.11	12
	E12	6.10	ST:1 50	34	116.3	58	21	41.1	52	0.036	1.45	0.09	12.5
	E13	6.18	TUT 132	48	116.8	57	21	41.2	60	0.036	1.35	0.09	12
	E14	8.50	TUT 132	225	99.3	53	16	52.2	67	0.065	1.10	0.17	12
	E15	8.70	TUT 132	80	85.9	44	15	53.1	77	0.035	2.15	0.16	12
	E16	8.70	ST:1 50	60	91.4	44	15	53.3	73	0.046	1.60	0.16	12.5
	E17	8.76	ST:1 50	35	88.1	44	53.5	53.5	78	0.042	1.70	0.15	12

n.a.: information not available

Table 7. Sample quality evaluation based on Lunne at al. criterion* (1997).

Site	Sampler	Total CRS oedometer tests	Sample quality ($\Delta e/e_0$) Percentage of the total test, (%)			
			Very good to excellent (<0.04)	Good to fair (0.04-0.07)	Poor (0.07-0.14)	Very poor (>0.14)
Perniö	ST:1 50	6	0	16.7	33.3	50
	Aalto 86	8	25	37.5	12.5	25
	TUT 132	23	56.5	43.5	0	0
Lempäälä	ST:1 50	7	14	14	0	72
	TUT 132	11	27	45	28	0
Masku	TUT 132	7	85	15	0	0
Paimio	ST:1 50	7	71.4	28.6	0	0
	TUT 132	11	91	9	0	0
Sipoo	ST:1 50	6	66.7	33.3	0	0
	TUT 132	11	81.9	18.1	0	0

*The criterion is valid for OCR