

1 **Title:**

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

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6 **Authors:**

7 Bruno Di Buò¹

8 Juha Selänpää²

9 Tim Tapani Länsivaara³

10 Marco D'Ignazio⁴

11

12 ¹ Tampere University of Technology, Department of Civil Engineering, Tampere, Finland.

13 Address: Korkeakoulunkatu 5, 33720, Tampere, Finland (email: bruno.dibuo@tut.fi)

14 ² Tampere University of Technology, Department of Civil Engineering, Tampere, Finland.

15 Address: Korkeakoulunkatu 5, 33720, Tampere, Finland (email: juha.selanpaa@tut.fi)

16 ³ Tampere University of Technology, Department of Civil Engineering, Tampere, Finland.

17 Address: Korkeakoulunkatu 5, 33720, Tampere, Finland (email: tim.lansivaara@tut.fi)

18 ⁴ Norwegian Geotechnical Institute, Oslo, Norway

19 Address: Sognsveien 72, N-0855 Oslo, Norway (email: marco.dignazio@ngi.no)

20

21

22 **Corresponding author:**

23 Bruno Di Buò

24 Tampere University of Technology, Department of Civil Engineering

25 Korkeakoulunkatu 5, 33720, Tampere, Finland

26 Mob: +358418077815

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29 **ABSTRACT**

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

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

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57 **INTRODUCTION**

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59 The importance of sample quality in the determination of strength and deformation properties
60 of soft sensitive clays has been extensively documented (e.g., Hvorslev, 1949; Lunne et al.,
61 2006; Karlsrud and Hernandez–Martinez, 2013; Karlsson et al., 2016; Mataic, 2016).
62 Conclusions from these studies highlight the difficulties encountered while retrieving
63 undisturbed samples using different sampling techniques, pointing out the implications in terms
64 of measured soil properties from laboratory testing. The most commonly-employed sampler in
65 Finnish geotechnical practice is the stationary piston sampler ST:1 with 50 mm diameter inner
66 tube (Kallstenius, 1971). The main reason for using such a sampling technique is its cost-
67 effectiveness. Other types of piston samplers have been used mainly for research purposes,
68 such as the NGI 54 mm diameter (Berre et al., 1969; Lunne et al., 2006) and the Aalto 86 mm
69 diameter piston samplers (Mataic, 2016). The aim was to evaluate possible improvements of
70 piston sample quality by collecting larger specimens. These studies revealed that piston samples
71 often result in low quality, especially in highly sensitive clays (e.g. Lunne et al., 1997; Lunne
72 et al., 2006; Karlsson et al., 2016). On the other hand, the use of tube and block samplers in
73 such soils provides enhanced sample quality (e.g., Bjerrum, 1973; Lefebvre and Poulin, 1979;
74 La Rochelle, 1981; Lunne et al., 2006; Berre et al., 2007; Karlsrud and Hernandez–Martinez,
75 2013). However, these techniques present the disadvantage of being expensive since they are
76 more laborious and require longer time than piston sampling.

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

85 (ii) and (iii) can be notably improved by using tube or block samplers (e.g. Lunne et al., 1997;
86 Lunne et al., 2006).

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

96

97 **TEST SITES**

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

101

102 **Perniö**

103 The Perniö test site is located in the southwestern coast of Finland, about 140 km west from the
104 city of Helsinki. In October 2009, Tampere University of Technology (TUT) and the Finnish
105 Transport Agency (FTA) conducted a full scale embankment failure test, gathering extensive
106 amount of data on the undrained behaviour of soft clays (Lehtonen et al., 2015; D'Ignazio et
107 al., 2017). The stratigraphy consists of a 1–1.5 m thick dry crust layer overlaying an 8–9 m
108 thick soft clay layer followed by silty and stiff sandy layers located at greater depth. The
109 groundwater table is located at 1 m depth. Geotechnical properties of Perniö clay are presented
110 in Fig. 1. The sensitivity (S_t), as evaluated by the laboratory fall cone (FC), indicates values
111 between 40 and 60 without showing any particular trend with depth. The measured intact shear
112 strength (s_u) from FC test varies between 10 kPa and 15 kPa while the remoulded undrained

113 shear strength (s_{u}^{re}) is nearly constant with values between 0.20 and 0.30 kPa over the entire
114 deposit. Based on the definition proposed by Torrance (1983), the soil can be defined as quick
115 clay. The plasticity index (PI) varies between 30% and 40% above 4 m and below 6 m depth
116 while lower values ($\approx 20\%$) can be noticed at around 5 m depth. The water content (w) is clearly
117 higher than the liquid limit (LL) with values varying between 80 and 100%. The clay content
118 increases with depth from about 60% at 3 m depth to 90% at 8 m depth. The organic content is
119 less than 2% over the entire deposit.

120

121 **Lempäälä**

122 The Lempäälä test site is located near the city of Tampere, along the railway track to Helsinki.
123 The main soil properties are presented in Fig. 2. The soil stratigraphy includes a 1.5 m thick
124 layer of weathered clay crust followed by 1–1.5 m of organic soil underlain by soft sensitive
125 clay. The groundwater table is located at 0.60 m depth. The natural water content is relatively
126 high above 4 m depth, compared to what commonly observed in Finnish clays (D’Ignazio et
127 al., 2016), with values varying between 120% and 140%. Below, w varies in the range 70–80%.
128 The LL is generally lower than w in the investigated layers. The FC test indicates S_t to vary
129 between 20 and 60. The scatter of the S_t data in Fig. 2 may suggest the presence of interlayers
130 in the deposit. The intact strength varies between 6 kPa and 15 kPa without any particular trend
131 with depth while the s_{u}^{re} is slightly lower than 0.50 kPa. The PI ranges between 25–30% in the
132 soft clay layer, even though thin lenses characterized by lower PI can be noticed between 5 and
133 6 m depth. The clay content is relatively constant below 5 m depth and on average equal to
134 60%, while smaller value can be observed in the upper layer. The organic content is
135 approximately 5% above a depth of 3 m and less than 1% in the soft clay layer.

136

137 **Masku**

138 The Masku test site is situated near the city of Turku, along the southwestern coast of Finland.
139 The stratigraphy consists of 8 m thick soft clay layer overlaying a 1.5 m weathered clay crust
140 layer. The groundwater table is located at 1.20 m depth. Samples were taken only at 3 m, 5 m

141 and 8 m depth. The water content is 80% at 3 m and 8 m depth while values up to 120% can be
142 found in the intermediate layer. The PI is about 40%, with higher values in the intermediate
143 layer. The LL is lower than the water content. The measured S_r varies between 10 and 30. The
144 Masku clay is the least sensitive of the clays presented in this study. Moreover, s_u^{re} is generally
145 higher than 0.5 kPa with a maximum value of 1.5 kPa at 5 m depth while the intact strength (s_u)
146 increases with depth, from 15 kPa at shallow depth to 20 kPa measured at 8 m depth. The clay
147 content varies with depth between approximately 60% and 90% while the organic content is
148 less than 2%. The principal geotechnical properties of the soil at Masku site are summarized in
149 Fig. 3.

150

151 **Paimio**

152 The site is located 25 km far from the city of Turku, in the southwestern region of Finland. Soft
153 clay is found between 2 and 10 m depth, overlain by a 2 m dry crust layer. The groundwater
154 table is located at a depth of 0.80 m. Test results shown in Fig. 4 reveal the presence of a leaner
155 upper clay layer (above 6.5 m), characterized by w of 50%–80% and PI of 15%–20%. Below
156 6.5 m depth, a more plastic clay with w varying between 90 and 110%, and average PI of 30%
157 is found. The measured clay content falls between 40 and 60% in the top part of the deposit.
158 Higher values were measured at greater depths, with clay content reaching almost 100%
159 between 6 m and 7 m depth. The organic content is less than 1%. The sensitivity varies between
160 60 and 90 without following any particular trend with depth, and the LL is generally well below
161 the water content. The intact strength measured by means of the FC varies between 13 kPa and
162 17 kPa while s_u^{re} is lower than 0.3 kPa over the entire deposit, thus indicating that the clay can
163 be defined as quick (Torrance, 1983).

164

165 **Sipoo**

166 The Sipoo test site is located in the South of Finland, about 30 km north of Helsinki. The
167 investigation revealed the presence of a homogeneous soft clay deposit between 2 and 9 m
168 depth. The groundwater table is located at 1 m depth. Index test results are illustrated in Fig. 5.

169 The deposit is characterized by the highest PI values among all the five investigated sites. In
170 particular, a *PI* of 60% is measured from samples taken between 5 and 6 m depth. The water
171 content increases with depth to a maximum of 120% at 6 m depth, decreasing then to 90–100%
172 at 9 m depth. As for all the other sites, the *LL* is below the natural water content over the entire
173 deposit. Fall cone test results indicated a nearly constant s_{ur}^{re} with depth varying between 0.50
174 and 1 kPa, while the intact strength (s_u) is approximately equal to 15 kPa. The sensitivity varies
175 between 20 and 30. The clay content shows values of about 60% at 3 m depth, increasing to
176 90% at lower depth. The organic content is consistently lower than 2% throughout the deposit.
177

178 **SAMPLING EQUIPMENT AND PROCEDURE**

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

$$183 \quad A_r = \frac{D_e^2 - D_i^2}{D_i^2} \quad (1)$$

$$184 \quad C = \frac{D_s - D_i}{D_i} \quad (2)$$

$$185 \quad \alpha = \arctan \frac{D_e}{4} \quad (3)$$

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

189

190 **ST:1 50 mm stationary piston sampler**

191 **Apparatus**

192 The ST:1 stationary piston sampler (Fig. 7) was developed by the Swedish Geotechnical
193 Institute (SGI) for taking high quality samples of soft sensitive clay. This sampler is also
194 described in the Finnish geotechnical investigation and testing standard SFS–EN ISO 22475–
195 1:2006E (SFS, 2004). It consists of a piston located inside a sampler body connected with inner

196 extension rods, extension pipes and removable plastic sampling cylinders. The piston is fixed
197 and connected to the inner rods while the outer sampler body is connected with extension pipes.
198 The external diameter is 53.8 mm while the inner diameter is 49.6 mm giving a considerable
199 area ratio of 17%. The cutting edge angle is 9.7°. Three 170 mm long plastic cylinders are
200 placed inside the sampler body, resulting in a total sampling length of 510 mm.

201

202 **Sampling procedure**

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

220

221 **Aalto University 86 mm piston sampler**

222 **Apparatus**

223 The Aalto 86 mm piston sampler shown in Fig. 8 was only used at the Perniö site. This sampler
224 is a scaled version of the NGI 54 mm piston sampler (Hvorslev, 1949; Andresen & Kolstad,
225 1980), modified in terms of sampling cylinder and sampler body dimensions. In particular,
226 while the ST:1 sampler has plastic inner linings inside the sampler body, the Aalto piston has a
227 thin walled self cutting steel tube on which the sample is stored and extruded prior to laboratory
228 testing. The external diameter of the sampling cylinder is 88.94 mm, while the average inner
229 diameter of the cylinder is 85.88 mm giving an area ratio of 6.8%. The tube length is 650 mm.
230 However, the maximum sampling length is 450 mm. The cutting edge angle is 12°. The cylinder
231 does not have any inner clearance.

232

233 **Sampling procedure**

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

241

242 **TUT tube sampler**

243 **Apparatus**

244 A thin-walled open-drive sampler (Figs. 9 and 10) was developed at Tampere University of
245 Technology in 2014, inspired by the Laval tube sampler (La Rochelle, 1980) and its
246 modification by SGI (Larsson, 2011). The device consists of a thin-walled sampling tube
247 mounted on a sampler head equipped with a screw-type valve that can be opened or closed by
248 rotating the inner rod (Figs. 9b and 9c). This system ensures an effective vacuum above the
249 sample during withdrawal from the ground. To reduce the soil disturbance during penetration,
250 a cutting edge with inclination of 5° is introduced on the outer side of the sampling cylinder.

251 Differently from the 200 mm Laval sampler, the tube length and diameter are smaller. In
252 particular, the outer diameter is 139.7 mm with a tube thickness of 4 mm. Therefore, the inner
253 diameter is 131.7 mm and the area ratio is 12%. The standard length of the sampling tube is
254 500 mm. In addition, 750 mm long tubes were used at Paimio and Sipoo.

255

256 **Sampling procedure**

257 The sampling operation using the TUT's tube sampler consists of four different phases. Firstly,
258 a borehole is made to the desired depth using a drilling apparatus. The sampler is moved down
259 to the hole while keeping the head valve opened. This is to ensure the mud to be flowing
260 upwards. Then, the sampling process starts with the insertion of the sampler into the soil at very
261 low speed (0.5 cm/s). In order to ensure the pore pressure dissipation around the sampling tube
262 and, therefore, a better adhesion between the soil and the sampler, a resting time of 20 minutes
263 is planned. However, the waiting time should be adjusted based on the investigated type of soil.
264 Finally, the head valve is closed and the soil at the bottom of the sampler is cut by means of a
265 wire system that is pulled from the ground surface (Fig. 9d). This procedure was introduced by
266 Larsson (2011) in order to avoid disturbance induced by the sampler rotation (La Rochelle,
267 1980). In order to separate the sample from the surrounding soil and prevent suction at the
268 cutting plane, air is injected into the pipe from the ground surface before and during sample
269 retrieval. Finally, the tube is disassembled from the apparatus and stored before the
270 transportation to the laboratory.

271 Unlike other sampling systems, several sources of disturbance are avoided. As already
272 mentioned, the use of cutting wire is beneficial in terms of sample quality since the torsion
273 typically induced by sampler rotation are avoided. In addition, differently from the standard
274 procedure adopted with the Laval sampler, the soil is stored inside the tube and extruded only
275 prior to the laboratory test rather than directly in situ.

276

277

278

279 **EXPERIMENTAL PROGRAM**

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

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

288

289 **CRS oedometer tests**

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

300 Consolidometer test data are given in Tables 2 to 6 for the various test sites, while the stress-
301 strain curves are shown in Figs. 12 to 16. Vertical strain (ε_v) and tangent constrained modulus
302 (M) are plotted against vertical effective stress (σ'_v). The observed stress-strain behaviour is
303 similar for all the tested specimens and characterized by distinct pre-yielding and post-yielding
304 responses. This is the typical behaviour of lightly overconsolidated marine clays described by
305 Janbu (1985). From the oedometer test results, it is possible to notice that the evaluation of the
306 geotechnical parameters is influenced by the adopted sampling procedure. Overall, the

307 preconsolidation stress (σ_p') and constrained modulus (M_0) evaluated on the TUT 132 tube
308 samples are systematically higher in Perniö and Lempäälä sites. However, comparable values
309 between piston and tube samples were observed for Paimio and Sipoo clays. This aspect is
310 discussed in detail in the following section since various factors such as soil properties,
311 apparatus condition and procedures are involved.

312

313 **Sample quality evaluation**

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

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

327

328 **DISCUSSION OF TEST RESULTS**

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

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

362 **EFFECT OF STORAGE ON SAMPLE QUALITY**

363 The adopted sampling method is one of the main contributors to the disturbance of a soil
364 sample. However, additional factors can affect the sample quality during the storage time such
365 as inadequate sealing, stress relief, migration of water, temperature and chemical changes
366 (Hvorslev, 1949; Kallstenius, 1963; Lessard and Mitchell, 1985). The influence of storage
367 effects on samples has been gaining importance in geotechnical practice, since samples may be
368 stored for long time before testing. La Rochelle et al. (1976) observed a decrease in peak
369 undrained shear strength up to 10–20% due to the long-term storage. The amount of reduction
370 is more evident in low plastic clays. A reduction of peak shear strength was also observed by
371 Bjerrum (1973), already after three days of storage. As discussed earlier in the paper, the TUT
372 132 tube sampler is designed to keep the soil stored inside the steel tube and extruded only prior
373 to testing. This feature provides enhanced sample quality compared to the traditional Laval-
374 type sampling as proved by the comparison between tests A4 and A5 (Fig. 18a and Table 2).
375 Test A4 is conducted on a tube sample extruded directly *in-situ* and tested the same day while
376 test A5 is related to a tube sample taken at the same depth, stored in and tested after six months.
377 From the ratio $\Delta e/e_0$ it appears to be clear that the quality achieved by the extruded sample
378 ($\Delta e/e_0=0.035$ vs $\Delta e/e_0=0.029$) is lower probably due to disturbance occurred during
379 transportation.

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

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

403

404 **CONCLUSIONS**

405 The paper presents an extensive investigation program conducted on five different soft clay
406 deposits in Finland. The performance of a new Laval type tube sampler with 132 mm diameter
407 (TUT 132) and two ordinary piston samplers (50 mm and 86 mm diameter) is analyzed in
408 different soil conditions. Overall, tube samples are generally characterized by higher quality
409 than piston samples, based on the recompression volume measured at the *in-situ* effective stress
410 in the oedometer tests. The quality of piston samples seems to be influenced by various factors
411 such as the sampling procedure and apparatus condition. In particular, the procedure adopted
412 to cut the sample from the surrounding soil seems to notably affect the quality of piston
413 samples. Tests conducted at Paimio and Sipoo sites revealed that the sampler rotation has a
414 positive effect on sample quality compared to sampler lifting, which was carried out in Perniö
415 and Lempäälä. This aspect indicates that the torsional stresses induce less disturbance compared
416 to the tension caused by sampler lifting. For these reasons, the sampler rotation would seem to
417 be more suitable for piston sampling in Finnish clay conditions. It must be pointed out that the

418 piston sampling apparatus used at Paimio and Sipoo was brand new, while the one used at
419 Perniö and Lempäälä suffered of lack of maintenance. Therefore, sample lifting and rotating
420 procedures should be tested in the same soil condition using the same type of apparatus to
421 confirm the observation reported in this study.

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

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

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

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517 **Tables**

518

519 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 <hr/> Pressure	Perniö, Lempäälä, Masku <hr/> Paimio, Sipoo
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523 Table 2. CRS oedometer tests, Perniö.

Site	Test	z (m)	Sampler	Storage time (days)	w (%)	PI	S _t	σ'v ₀ (kPa)	σ' _p (kPa)	Δe/e ₀	Oedometer modulus (MPa)		
											M ₀ (MPa)	M _L (MPa)	M'
	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
Perniö	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	<i>n.a.</i>	97.1	40	55	40.7	<i>n.a.</i>	0.196	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
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	<i>n.a.</i>	84.2	34	54	43.8	<i>n.a.</i>	0.213	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
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	<i>n.a.</i>	0.226	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>
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	<i>n.a.</i>	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

524 *sample extruded *in-situ*
525 n.a.: information not available
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536 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	<i>n.a.</i>	0.209	<i>n.a.</i>	<i>n.a.</i>	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	<i>n.a.</i>	0.167	<i>n.a.</i>	<i>n.a.</i>	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	<i>n.a.</i>	0.173	<i>n.a.</i>	<i>n.a.</i>	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	<i>n.a.</i>	0.201	<i>n.a.</i>	<i>n.a.</i>	17
	B17	6.30	ST:1 50	86	71.8	16	53	35.5	<i>n.a.</i>	0.190	<i>n.a.</i>	<i>n.a.</i>	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

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542 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_o (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

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553 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

554 n.a.: information not available

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558 Table 6. CRS oedometer tests, Sipoo.

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_o (MPa)	M_L (MPa)	M'
Sipoo	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
	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

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565 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

566 *The criterion is valid for OCR <2

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570 **Captions**

571 Fig. 1: Index test results, Perniö.

572 Fig. 2: Index test results, Lempäälä.

573 Fig. 3: Index test results, Masku.

574 Fig. 4: Index test results, Paimio.

575 Fig. 5: Index test results, Sipoo.

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

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

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

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

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

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

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

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

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

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

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

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

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

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598 **List of symbols**

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600 FC Fall cone

601 LL Liquid limit

602 OCR Overconsolidation ratio ($OCR = \sigma'_p / \sigma'_v$)

603 PI Plasticity index ($PI = LL - PL$)

604 PL Plastic limit

605 e Void ratio

606 M tangent constrained modulus

607 M_L oedometer modulus in NC range

608 M_0 oedometer modulus in OC range

609 M' oedometer modulus number

610 NC Normally consolidated

611 S_t Sensitivity ($S_t = s_u / s_u^{re}$)

612 s_u Undrained shear strength

613 s_u^{re} Remolded undrained shear strength

614 w Natural water content

615 $\Delta e / e_0$ Normalized change in void ratio

616 ε_v Vertical deformation

617 σ'_L Minimum vertical effective stress

618 σ'_p Vertical preconsolidation stress

619 σ'_v Effective vertical stress

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