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Title of Paper: Characterisation and engineering properties of Tiller clay

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23 **Characterisation and engineering properties of Tiller clay by**

24 **A. Gylland et al.**

25 ABSTRACT

26 A detailed characterisation of the quick clay underlying the NTNU research site at Tiller,
27 Trondheim is presented. The objective of the work is to provide guidance on quick clay
28 parameters to engineers and researchers working with similar clays in Scandinavia and
29 North America especially on landslide hazard assessment. The material is lightly
30 overconsolidated and is characterised by its high degree of structure and very high
31 sensitivity (quick clay). Clay and water contents are both about 40%. The plasticity index
32 is low (5%). This relates to the low active minerals of the clay and silt fractions (illite /
33 chlorite and quartz / feldspars respectively). Undrained shear strength is of the order of
34 30 kPa to 50 kPa (medium stiff) and increases with depth. The deposit is consistent
35 across the site and its properties are similar to other Norwegian quick clays. Significant
36 efforts have been made into examining sample disturbance effects on the material. It was
37 found that thin walled steel fixed piston samples can yield results similar to those of
38 block samples provided the work is carried out with extreme care and storage time is
39 minimised. The piezocone (CPTU) test proved very useful in characterising the material.

40 KEYWORDS: soft clay; quick clay; laboratory testing; in situ testing; landslides

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44 1. INTRODUCTION

45 Deposits of marine clay which have been leached of their salt content, and thus have high
46 sensitivity, are found over large areas of Norway, Sweden and Canada. These deposits
47 pose many difficulties for engineers working in such areas. In addition, landslides caused
48 by both natural and man induced factors frequently occur. Many quick clay slides have
49 occurred in the Trondheim area (Sveian et al., 2006) and recent examples of such slides
50 include those at Kattmarka (2009), Lyngen (2010) and Esp (2012). Research into the
51 engineering properties and behaviour of these deposits has been undertaken at the
52 Geotechnical Division of the Norwegian University of Science and Technology (NTNU
53 formerly NTH) for many years. This work has included the establishment of a number of
54 research sites where a detailed characterisation of the site is made and different ground
55 investigation and foundation techniques can be tried out.

56 The Tiller site has been used for such purposes since at least the early 1980's due to
57 the thickness and uniformity of the clay deposit, its high sensitivity and its proximity to
58 the city of Trondheim. The site is sometimes referred to as Kvenild (after the
59 neighbouring farm) and it is located at +125 m above sea level (a.s.l.) some 10 km south-
60 east of the centre of Trondheim in Sør-Trøndelag, Mid Norway, see Figure 1.

61 The site is located within a quick clay hazard zone (www.skrednett.no). The slide
62 hazard is classified as "high" due to active stream erosion and locally steep ravines. A
63 major event in historic time in the Tiller area was the Tiller quick clay landslide of 1816
64 (Jensås, 1980) which took place 3.5 km north - northwest of the Tiller test site. The
65 landslide involved about 7,000,000 m³ of soil and 15 people were killed. No major
66 landslide events are known in recent time, but it is apparent from the outline of the

67 ravines today that the location is geological active with frequent minor surface slips. A
68 nearby stream was erosion protected in 2010 in relation to industry development of land
69 area to the west of the site. A summary of the main research campaigns is given on Table
70 1 and the general site layout showing the test locations is shown on Figure 1c.

71 Despite the importance of these materials in Scandinavia and elsewhere there are few
72 publications that report on the properties of quick clay at an individual site. The objective
73 of this paper is to address this issue by presenting a detailed characterisation of the soils
74 at Tiller based on the results of routine and advanced laboratory and field testing. It is
75 intended that the results presented will form a useful reference to engineers working on
76 such soils.

77 2. ENGINEERING GEOLOGY

78 *2.1. Geological setting*

79 The area is characterised by thick deposits of clay and minor ravines and slide scars. The
80 bedrock in the area is dominated by greenstones, meta-sediments and volcanics (Wolff,
81 1976). These metamorphosed and moved into place during the Caledonian orogenesis.
82 The clay deposit formed during the retreat of the glacier after the Younger Dryas stadial
83 between 10,800–10,500 years before present (Reite et al., 1982). Due to the isostatic
84 depression caused by the weight of the inland glacier, the sedimentation took place in sea
85 water. Most of the material was derived from glacial erosion of the rock types mentioned
86 above and the major components are quartz, feldspars, illite and chlorite with the latter
87 making up the main proportion of the clay fraction.

88 In the salt water these platy shaped phyllosilicates were strongly bonded in an edge to
89 surface “card house structure”, stabilised by strong van der Waals forces (Rosenqvist,

90 1953; Rosenqvist, 1966). Due to post glacial rebound following the ice melting, the upper
91 marine limit of that time corresponds to a level of +175 m.a.s.l. at the Tiller site today
92 (Reite, 1983). This has exposed the marine clays to meteoric water which in some
93 locations has diluted the salt pore water. In this process, the bonds between the clay
94 grains have been reduced as the diffuse double layer has expanded (van Olphen, 1977). In
95 this situation the repulsive electrostatic forces on the mineral surfaces increase to finally
96 balance the attractive van der Waals forces. The original structure of the clay is intact, but
97 upon a small mechanical disturbance collapse occurs. This causes liquefaction due to the
98 excess pore water. The clay is in this state referred to as “quick”.

99 2.2. *Stress history*

100 From the geological history of the area, no exceptional loading events are known; only
101 normal sedimentation processes. Once above sea level, groundwater fluctuations may
102 have induced some changes in stress history. Groundwater level is presently located
103 about 0.5 m below ground level and the in situ pore pressure distribution is hydrostatic
104 (Sandven, 1990).

105 Preconsolidation stress (p_c') has been estimated from oedometer tests, which were
106 carried out in the 1990, 1999/2000, 2010, 2011/12 and 2012 investigations using samples
107 from various sampling techniques. These values have been obtained using the Janbu
108 approach (Janbu, 1970) which involves selecting the effective stress value where the
109 constrained modulus (M), coefficient of consolidation (c_v) and creep number (r_s) reach a
110 minimum in plots of these parameters versus vertical effective stress. Lunne et al. (2008)
111 showed that, for tests on 22 high quality Sherbrooke block samples of marine clay, the p_c'

112 from the Janbu approach was on average 7% higher than that obtained from the classical
113 Casagrande (1936) technique.

114 The results for the Tiller site are shown on Figure 2a. All of the values are well above
115 the in situ vertical effective stress (σ_{v0}) line throughout the profile. The corresponding
116 overconsolidation (OCR) values are shown on Figure 2b and the results suggest there is a
117 slight decrease in OCR from typically 3.0 at 5m to 2.0 at 10 m. The reason for the
118 slightly overconsolidated state of the material is thought to be due to “delayed
119 consolidation” or natural ageing effects (Bjerrum, 1973).

120 As can be seen from Figure 2, samples have been obtained using various sampler
121 types (Table 2) and the effects of sample disturbance will be discussed below. Excluding
122 the most shallow data point, OCR values from the block, 54 mm steel and 54 mm plastic
123 samples are on average similar (≈ 2.4) and are slightly higher than those obtained from
124 the 75 mm steel sampler (1.9).

125 3. MATERIAL COMPOSITION

126 *3.1. Mineralogy*

127 The mineralogy of the Tiller deposit was investigated in detail by Hilmo (1989) where
128 XRD analyses were performed at several depths with the material divided according to its
129 grain size. Figure 3 illustrates the main trend of the mineralogical composition together
130 with the typical range for Norwegian marine clays as found by Augedal (1978) and
131 Rueslåtten (1990). The Tiller material appears to be typical of other Norwegian marine
132 clays. It is seen that phyllosilicates such as illite and chlorite dominate the clay fraction
133 while the coarser fractions are made up of quartz and feldspars. These are mostly K-
134 feldspar and plagioclase. The Tiller clay contains a low amount of carbonates; less than

135 2% according to Hilmo (1989). A main source of these carbonates is fossils of
136 foraminifera. Quartz and feldspars contribute to more than 50% of the total mass and
137 make up 40% of the clay fraction.

138 3.2. *Grain size distribution*

139 Particle size distribution curves are shown on Figure 4a and clay content with depth is
140 given on Figure 4b. Typical range of values for marine clays from south-eastern Norway
141 are also shown on Figure 4a (Rueslåtten, 1990) and it can be seen that the Tiller clays are
142 typical of these deposits. There is a good degree of consistency between the three sets of
143 tests and they suggest that between 2.5 m and 13.5 m the material is very consistent, with
144 average clay content of about 38% and the remainder of the material being made up of
145 approximately equal percentages of fine, medium and coarse silt. Below 13.5 m there is
146 some tendency for a decrease in clay content with depth towards an average of about
147 20% at 17.5 m.

148 3.3. *Grain shapes and form of clay fraction*

149 Figure 5 shows the backscatter image from an electron probe micro analyser (EPMA)
150 performed on a thin section from the Tiller deposit. This is an advanced scanning electron
151 microscope allowing for mapping of the material elements which has made it possible to
152 distinguish the mineral of each grain observed in the scanning. Some selected grains are
153 identified in Figure 5. The clay sample was tested and scanned in relation to the
154 experiments of Gylland (2012) on shear band formation. A shear fracture is thus apparent
155 in the scan. The clay fraction of the particles is mainly flaky in appearance. These are
156 laminated phyllosilicates. There is also a portion of rounded grains in the clay fraction
157 which are quartz and feldspars. Examination of the silt fraction shows that these grains

158 are mainly rounded and oblong with sharp corners. Some long and flat sheet silicates are
159 present, but the larger grains are mostly quartz and feldspars.

160 The particle density (ρ_s) of the soil particles is shown on Figure 6c. Although there is
161 some scatter in the data (due to the nature of the test and the small amounts of material
162 involved), the values are reasonably constant with an average value of about 2.76, which
163 is typical for Norwegian clays.

164 3.4. *Organic content and form*

165 The organic content in the clay is low. Hilmo (1989) measured loss on ignition at 440°C
166 in the range of 0.5 to 1.2 %.

167 3.5. *Specific surface area and cation exchange capacity*

168 The specific surface area of the Tiller deposit is in the order of 15 m²/g on average being
169 about 5 m²/g for the fine silt fraction (2 to 20 µm) and 80 m²/g for the fraction below 0.6
170 µm. For reference the specific surface of illite is in the range 65 to 100 m²/g (Mitchell
171 and Soga, 2005).

172 The corresponding values of the cation exchange capacity (CEC) are 7, 4 and 40 meq
173 /100g respectively (Hilmo, 1989). For comparison, illite and chlorite have a CEC in the
174 order of 10 to 40 meq /100g at a pH of 7 (Carroll, 1959).

175 3.6. *Pore water chemistry*

176 Salt content values for the pore fluid are shown on Figure 7c. Values are considered to be
177 low and average about 1.5 g/l suggesting the material has been leached post deposition.
178 Hilmo (1989) analysed the cation composition of the pore water of the Tiller deposit and
179 found the following values (in mg/l): Na (200), K (20), Si (8), Ca (6) and Mg (2).

180 4. STATE AND INDEX PARAMETERS

181 *4.1. Water content / degree of saturation*

182 Water content (w) values from the various investigations are shown on Figure 6a. The
183 values are uniform, indicate the homogenous nature of the material and show no tendency
184 to decrease with depth. The range of values is 25% to 45% and the average value is
185 37.8%. The material below the dry crust (i.e. below about 2 m) is fully saturated.

186 *4.2. Atterberg limits*

187 Plasticity index (I_p) is plotted against depth on Figure 8a. There is a good degree of
188 consistency between the various investigations. In general the material is classified as
189 being of “low plasticity” (NGF, 1982) with an average I_p value of 6.3%. There is some
190 tendency for a decrease in I_p with depth.

191 The data are also plotted on the “A” line chart on Figure 9. It can be seen that the
192 measured values straddle the “A” line and that the material is classified as “CL”, i.e. a
193 clay of low plasticity.

194 According to standard Norwegian practice, (NGF, 1982), based on particle size
195 distribution the material should be termed CLAY. This is consistent with the definition
196 derived from the Atterberg limits.

197 *4.3. Density / void ratio*

198 Bulk density values are shown on Figure 6b again show the relative consistency of the
199 material with depth with no apparent trends. Measured values range between 1.8 Mg/m^3
200 and 1.95 Mg/m^3 with an average of about 1.89 Mg/m^3 . The average in situ void ratio (e_0)
201 is about 1.07 with no clear trend with depth as would be expected from the water content
202 and bulk density relationships

203 *4.4. Liquidity / void index*

204 Liquidity index (I_L) can be a very useful parameter for assessing the structure and stress
205 history of the material. It is defined as:

$$206 \quad I_L = \frac{w - w_p}{I_p} \quad (1)$$

207 where: w_p = plastic limit

208 I_L values, shown on Figure 8b, clearly separate the site into two main strata; an upper
209 layer between the bottom of the dry crust at 2 m and 8 m where the average liquidity
210 index is about 2.0. Below 8 m the I_L values is significantly higher and has an average
211 value of about 4. As will be seen later these two layers correspond to an upper non
212 sensitive clay and a lower quick clay.

213 Burland's (1990) in situ void index (I_{v0}) can similarly be used to study the stress
214 history and structure of the material. I_{v0} is defined as:

$$215 \quad I_{v0} = \frac{e_0 - e_{100}^*}{C_c^*} \quad (2)$$

216 where:

217 e_{100}^* = the void ratio on Burland's intrinsic compression line (ICL) for $\sigma_v' = 100$ kPa

218 C_c^* = Burland's intrinsic compression index.

219 As no specific test data is available for Tiller clay e_{100}^* and C_c^* have been obtained
220 from the correlations published by Burland (1990) and average values of 0.531 and 0.133
221 respectively were obtained. Above 8 m I_{v0} has an average value of about 1.95 and below
222 8 m, in the quick clay the average I_{v0} is 4.12 with no apparent trend with depth.

223 5. STRUCTURE

224 5.1. Macrofabric

225 Tiller clay is a fairly homogenous dark lean grey clay. On the macro scale there are some
226 thin (1 to 2 mm) layers of silt. There is no evidence of any fissures. The EPMA analyses
227 of thin sections have revealed several fossils of foraminifera (Gylland, 2012). No larger
228 shells are observed, but there is occasional gravel pebbles which are likely deposited
229 from melting ice flakes.

230 5.2. *Microfabric*

231 Considering structure and microfabric it is useful to examine the behaviour of the
232 material within the framework proposed by Burland (1990). Typical oedometer tests for a
233 Sherbrooke block sample and a Geonor 54 mm plastic sample (see detailed discussion
234 later) are shown on Figure 10. The tests results are plotted in $\log \sigma'_v$ versus void index
235 (I_v) format so as to compare the results directly with those of Burland (1990). As
236 discussed above the in situ void index (I_{v0}) values are located well above Burland's
237 sedimentation compression line (SCL). This suggests that the material possesses a high
238 degree of structure and is consistent with that which has been deposited slowly in still
239 water leading to an open random fabric. The EPMA scans of Figure 5 suggest a preferred
240 horizontal orientation of the phyllosilicates. No sorting of minerals or grain fractions is
241 apparent.

242 From the shape of the block sample curve, in particular, it is clear that the specimen
243 has retained its structure. It remains close to horizontal before plunging steeply after
244 yield. In contrast, the 54 mm plastic sample shows a higher degree of curvature and
245 therefore shows less structure. Neither plot approaches the intrinsic compression line
246 (ICL), even with stress as high as 1175 kPa, suggesting that the oedometer test does not

247 impart sufficient mechanical energy to break down the natural fabric and bonding of the
248 material completely.

249 5.3. *Cementation*

250 The activity of the clay (I_p / clay fraction) (Skempton, 1953) is classified as low. This is
251 typical for leached marine clays and can be related to a clay fraction consisting of low
252 active minerals as illite and chlorite as well as the dominating role of quartz and
253 feldspars. In turn, low activity implies low colloidal activity and low cation exchange
254 capacity. This means that the potential of the minerals to form bonds is limited which
255 affects the material cohesion. A correlation showing reduced cohesion for reduced
256 activity was presented by Skempton (1953). Considering these mineralogical aspects as
257 well as the low OCR of the clay, it is argued that the amount of cementation in the
258 material is limited. This is further supported by the virtually non-existing cohesion and
259 friction softening in the triaxial tests of Figure 15.

260 5.4. *Sensitivity*

261 The Tiller-clay is expected to have high degree of sensitivity due to its high values of
262 liquidity index and in situ void index, the open structured nature of the material and the
263 low salt content of the pore water. According to NGF (1982) a material is “quick” if
264 sensitivity (S_t) values are greater than 30 and the remoulded shear strength (s_{ur}) values are
265 less than 0.5 kPa. Fall cone data shown on Figures 7a and 7b clearly show that above
266 about 8 m the material is not quick but that below 8 m quick clay is present. There is a
267 good degree of consistency between the various investigations and there is some evidence
268 that sensitivity increases progressively with depth.

269 Physical inspection of the behaviour of the samples confirms that the material in the
270 quick clay zone is highly sensitive and remoulds to a liquid easily on agitation.

271 It is interesting to observe that there are no significant variations in water content and
272 salt content of the non-sensitive and the quick zones. The non-sensitive zone has hence
273 been leached of the sea salt post deposition in a similar manner as the deeper quick clay,
274 and further, the porosity of the two layers is similar. Following Bjerrum (1971) this
275 observation can be related to a theory that quick clay is an intermediate state in the
276 geological process. As salt water is replaced by fresh water, some of the clay particles, in
277 particular chlorite, becomes unstable and starts to disintegrate. This releases ions, mainly
278 magnesium in the case of chlorite, which reduce the extent of the diffuse double layer and
279 hence increases the bonds between the grains. In turn, the sensitivity and the plasticity
280 increase. This is supported by the pore water analysis of Hilmo (1989). Whereas the
281 content of Na is close to constant with depth, the upper non-sensitive zone shows
282 increased content of Mg, Si and Ca ions.

283 6. ENGINEERING PROPERTIES

284 6.1. *Stiffness – G_{max}*

285 Small strain shear stiffness (G_{\max}) can be estimated from the shear wave velocity (V_s)
286 using the formula:

$$287 \quad G_{\max} = \rho V_s^2 \quad (3)$$

288 Values are shown on Figure 11, as obtained from a spectral analysis of surface waves
289 (SASW) survey. This showed V_s to increase from about 100 m/s at 0.5 m to 225 m/s at
290 10 m depth and the equivalent G_{\max} values (Figure 11) thus increase from 25 MPa to 100
291 MPa (average $\rho = 1.89 \text{ Mg/m}^3$ assumed). These are characteristic values for Norwegian

292 soft marine clays (Long and Donohue, 2007; Long and Donohue, 2010). Note the scatter
293 in the data is due to the approximate inversion procedure used for the SASW data.

294 6.2. *Behaviour in oedometer tests*

295 Some examples of the results of constant rate of strain (CRS) oedometer tests from the
296 quick clay zone between 8.75 m and 10.2 m are shown on Figure 12a. A similar set of
297 data from incrementally loaded (IL) oedometer tests are shown on Figure 12b. The test
298 results are presented in conventional $\log \sigma'_v$ versus strain (ϵ) format, as constrained
299 modulus ($M = \delta\sigma'/\delta\epsilon$) versus σ'_v and also as coefficient of consolidation (c_v) versus σ'_v . M
300 and c_v values are highest in the overconsolidated zone and then drop sharply as p_c' is
301 approached before increasing again linearly with stress post p_c' . (In this zone the slope of
302 the M - σ'_v line is the modulus number, m .)

303 The data from incrementally loaded (IL) oedometer tests include a plot of the Janbu
304 (1969) the creep resistance (r_s) against stress. This parameter shows a similar pattern to M
305 and c_v with high creep resistance at low stress, minimum creep resistance around p_c' and
306 then a gradual increase with stress.

307 6.3. *Stiffness – constrained modulus M*

308 Values of the constrained modulus in the overconsolidated range (M_0) and at the
309 preconsolidation stress (M_n) are shown on Figures 13b and 13c respectively. M_0 values
310 are typically about 4 MPa and there is no clear increasing trend in the values with depth,
311 at least until about 16 m.

312 On average M_n is about 2 MPa though there appears to be slightly higher values at the
313 top and bottom of the sequence.

314 6.4. *Compressibility in the normally consolidated range*

315 Values of the modulus number ($m =$ the slope of the $M - \sigma_v'$ plot after p_c') are shown on
316 Figure 13d. The values seem more or less uniform with depth. The measured values agree
317 very well with the correlations of Janbu (1985), for an average water content of 38%.

318 6.5. *Coefficient of consolidation*

319 Coefficient of consolidation values in the overconsolidated zone (c_{v0}) and at about p_c'
320 (c_{vn}) are shown on Figures 14a and 14b respectively. Values of c_{v0} are typically about 20
321 m^2/yr . However there is considerable scatter in the data and these values need to be
322 treated with caution. The scatter is likely to be caused by several overlapping factors such
323 as natural material variability combined with the small specimen size (20 mm),
324 interpretation of the incrementally loaded tests, and issues with saturation and analysis
325 techniques in the CRS tests.

326 The average value c_{vn} is about 5 m^2/yr which is at the lower bound of the minimum
327 value suggested by Janbu (1985) for material with w about 38%.

328 Coefficient of consolidation (c_h) values determined from the results of piezocone
329 (CPTU) dissipation tests varied between 5 m^2/yr and 9.5 m^2/yr and are also shown on
330 Figures 14a and 14b. These values were measured by Bihs et al. (2012) and are very
331 similar to those reported by Sandven (1990). Horizontal CRS oedometer tests on samples
332 cut from Sherbrooke block samples show that typically the lab c_{v0}/c_{h0} values are in the
333 range 0.7 to 0.9. In general the c_h values are at the lower bound of the laboratory c_{v0}
334 measurements and are much close to the c_{vn} values. The reasons for this are not clear but
335 are likely to be due to a combination of remoulding of this highly sensitive clay near to
336 the CPTU face and anisotropy of structures as indicted by the laboratory tests.

337 6.6. *Creep*

338 Creep data in the form of Janbu's (1969) creep parameter (r_s) are plotted against stress on
339 Figure 12b. Like M and c_v , r_s is dependent on stress, showing high values (large creep
340 resistance) in the overconsolidated zone before dropping significantly around p_c' and then
341 gradually increasing with stress. Values of r_s at around p_c' (i.e. minimum value of r_s) are
342 plotted on Figure 14c. It can be seen that the measured values plot to the lower bound of
343 the limits suggested by Janbu for material with water content of 38%.

344 6.7. *Behaviour in triaxial tests*

345 Results of isotropically consolidated undrained compression tests (CIUC) are shown on
346 Figure 15. These tests were carried out on samples from the quick clay zone. Figure 15
347 includes test results from 54 mm, 75 mm and block samples. Back pressure was used for
348 the tests on the two shallower 75 mm samples. Results are presented in shear stress ($(\sigma_1' -$
349 $\sigma_3')/2$ versus axial strain (ϵ), pore pressure versus ϵ and in p' versus q' stress path format,
350 where $p' = (2\sigma_1' + \sigma_3')/3$ and $q' = \sigma_1' - \sigma_3'$. Peak strength occurs at low strain.

351 6.8. *Dilatancy and strain softening*

352 The triaxial tests in Figure 15 on the high quality block samples displays close to zero
353 dilatancy in the pre-peak regime. An exception is the 75 mm sample tests with back
354 pressure which show some dilatancy on initial loading. As the peak strength is
355 approached, the clay dilates slightly before contracting. The contraction comes from the
356 collapsing structure which in turn generates excess pore pressure in the undrained setting.
357 The excess pore pressure reduces the internal friction and forces the stress state to move
358 down along the Mohr-Coulomb failure line. The strain softening behavior of the Tiller
359 quick clay is hence driven by contractancy with limited or no elements of cohesion or
360 friction softening.

361 6.9. *Undrained strength from laboratory testing – index tests*

362 Index shear strength tests from fall cone and unconfined compression tests are shown on
363 Figure 16b and 16c respectively. Both sets of data show the same trend and are also
364 comparable to the field vane data (Figure 16a). Above about 8 m, i.e. in the non quick
365 zone, s_u values are relatively constant at about 20 kPa. The reason these values are
366 relatively constant is because the OCR reduces from about 3.0 to close to 2.0 in this zone.
367 Minimum s_u is recorded towards the top of the quick clay zone and then s_u values
368 increase gradually with depth but fall below $0.3\sigma_{v0}'$ line, which corresponds to a normally
369 consolidated material (Ladd and Foott, 1974). The reason for this is due to the combined
370 effects of sample disturbance and the fact that the laboratory tests are carried out without
371 a confining stress.

372 6.10. *Undrained strength from laboratory testing – triaxial tests*

373 Undrained shear strength values (s_u) from CIUC (isotropically consolidated compression
374 test) and CAUC (anisotropically consolidated compression test) triaxial tests are shown
375 on Figures 17b and 17c respectively. For the CAUC tests the best estimate of the in situ
376 stress was used for consolidation with K_0 assumed to be 0.6. For the CIUC tests the
377 average value of σ_{v0}' and σ_{h0}' was used.

378 It can be seen that there is relatively little difference between the CIUC and CAUC
379 test results. However, because the specimens were reconsolidated back to the in situ
380 stress these tests give s_u values higher than those of the index tests.

381 In the quick clay zone the normalised undrained shear strength (s_u/σ_{v0}') is
382 approximately 0.4. This suggests theoretically $OCR = 1.5$ (Ladd and Foott, 1974), see

383 Equation 6 below, which is relatively consistent (albeit on the low side) with the
384 oedometer test results.

$$385 \left(\frac{s_u}{\sigma_v} \right)_{oc} = OCR^{0.8} \left(\frac{s_u}{\sigma_v} \right)_{nc} \quad (6)$$

386 6.11. Rate effects

387 Data on the impact of varying the strain rate on the undrained shear response is presented
388 by Yesuf (2008) (54mm samples) and Gylland et al. (2013)(block samples). Consistent
389 with the dataset of Lunne and Andersen (2007), the rate has little impact below 1% to 3
390 % axial strain per hour (1% to 3 % increase / log cycle). Above this threshold rate, the
391 increase in peak undrained shear strength is in the order of 15% to 25% / log cycle.

392 6.12. Undrained strength anisotropy

393 Undrained strength anisotropy is an acknowledged feature of Norwegian soft sensitive
394 clays (Bjerrum, 1972). Distinct anisotropy is expected due to the low value of I_p and OCR
395 (Soydemir, 1976). Although only a limited number of triaxial extension (CIUE) and
396 direct simple shear tests (DSS) are available for Tiller clay, the following relationships of
397 the peak undrained shear strength of block samples is suggested:

$$398 s_{u:DSS}/s_{u:CAUC} = 0.48 \text{ and}$$

$$399 s_{u:CIUE}/s_{u:CIUC} = 0.38.$$

400 These values are well within the range of the experience data reported by Karlsrud et
401 al. (2005) and Lunne et al. (2006) based on block samples from a wide range of clay sites
402 in Norway.

403 6.13. Drained shear strength

404 Data shown on Figure 15 and other tests reported by Gylland (2012) suggests, $\phi' \approx 29^\circ$
405 and $c' = 6$ kPa, regardless of sample type or test type. Similar values are reported by
406 both Sandven (1990) and Ørbech (1999).

407 *6.14. In situ undrained strength – field vane strength*

408 A profile showing the peak undrained shear strength as obtained by the field vane is
409 shown on Figures 16a. Compared to the triaxial experiments, the shear vane gives a lower
410 value of the peak undrained shear strength. This can be attributed to soil strength
411 anisotropy (Flaate, 1966) combined with the low plasticity index of the clay (Soydemir,
412 1976) and also possibly to vane insertion disturbance effects.

413 *6.15. In situ strength – cone penetration testing*

414 The Tiller site has been used for research into use of the CPTU on a number of occasions
415 and several sets of data have previously been published, e.g. by Sandven (1990), Sandven
416 and Black (2004), Tumay et al. (2001), Titi and Tumay (2008) and Bihs et al. (2012). The
417 various tests include those with standard 10 cm² CPTU and a miniature 2 cm² tool. All of
418 the test results are very similar and confirm the uniform nature of the site. Some typical
419 results from the work of Tumay et al. (2001) and Bihs et al. (2012) are shown on Figure
420 18. The results generally show:

- 421 • Corrected cone resistance (q_t) high in the upper crust say to 2 m,
- 422 • q_t drops to a minimum of about 500 kPa at about 8 m, i.e. top of quick clay zone,
- 423 • q_t then increase steadily to 600 – 700 kPa at about 14.5 m, where there is a
424 pronounced jump towards 1 MPa,

425 • Generated pore water pressure (u_2) values are much greater than in situ values
426 (u_0), i.e. show undrained penetration and again show the pronounced jump at 14.5
427 m,

428 • Sleeve friction (f_s) values are close to zero except in the upper crust.

429 Undrained shear strength can be obtained by empirical correlation from CPTU data
430 using various techniques for example (Lunne et al., 1997b):

$$431 \quad s_u = \frac{q_t - \sigma_{v0}}{N_{kt}} \quad (4)$$

$$432 \quad s_u = \frac{u_2 - u_0}{N_{\Delta u}} \quad (5)$$

433 where N_{kt} and $N_{\Delta u}$ are empirical bearing capacity factors.

434 Karlsrud et al. (2005) derived a series of bearing capacity factors for Norwegian clays
435 by comparing research standard CPTU tests with CAUC (anisotropically consolidated
436 compression test) triaxial tests on Sherbrooke block samples. They related N_{kt} and $N_{\Delta u}$ to
437 S_t and OCR. For Tiller clay typically N_{kt} and $N_{\Delta u}$ can be chosen to be equal to 10 and 8
438 respectively. The derived s_u values compare very well with the CAUC triaxial test results,
439 see Figure 17b. Perhaps the good fit here is not surprising as Karlsrud et al. (2005)
440 choose Tiller as one of the 17 sites used in their correlations.

441 7. SAMPLING DISTURBANCE EFFECTS

442 At the Tiller site, the following equipment have been used and compared:

- 443 • Geonor 54 mm steel fixed piston sampler (Andresen and Kolstad, 1979)
- 444 • 54 mm composite sampler with plastic inner tubes (Andresen and Kolstad, 1979)
- 445 • 75 mm steel fixed piston sampler (enlarged version of the 54 mm steel sampler)
- 446 • 95 mm steel fixed piston sampler (enlarged version of the 54 mm steel sampler)

447 • Sherbrooke block sampler (Lefebvre and Poulin, 1979)

448 Samples have mostly been obtained using the Geonor 54 mm steel fixed piston
449 sampler which for many years was the most common sampling technique used in
450 Norway. Piston sampling is carried out to the guidelines published by NGF (1997). The
451 displacement method is used; where the sampler (with the piston in front of the sample
452 tube) is pushed down to the desired depth without pre-augering. During sampling the
453 inner rods and the piston are fixed in a locked position, and the outer rods are pushed
454 down at a constant rate. After withdrawal of the sampler, the sample is sealed at the top
455 by the removable piston when the cylinder is disconnected from the sampler.

456 Since the early 1980's an important development in Norway has been the introduction
457 of the Sherbrooke block sampler (Lefebvre and Poulin, 1979) which is well known to
458 produce high quality samples. This sampler has been used at the Tiller site on two
459 occasions; in 1999 and again in 2011, see Figure 19.

460 A summary of the dimensions and properties of the samplers is given on Table 2. On
461 inspection of this table one would expect the quality of the 54 mm plastic samples to be
462 significantly poorer than those of the steel samplers or the Sherbrooke block sampler due
463 to the blunt cutting edge, the high area ratio and the non-favorable inside clearance ratio.

464 *7.1. Oedometer tests*

465 Sample quality can be assessed using the method of Lunne et al. (1997a) by comparing
466 the normalised void ratio change ($\Delta e/e_0$) during consolidation to in situ stress to a set of
467 standard criteria, see Figure 13a. Most of the samples are classified as “very good to
468 excellent” or “good to fair”. There is a clear decrease in sample quality with depth,
469 particularly for the block samples. The 54 mm steel and block samples have average

470 $\Delta e/e_0$ value of about 0.057 compared to 0.076 for the 54 mm plastic and 75 mm steel
471 samples. For the CRS tests, shown on Figure 12a, it can be seen that the quality of the
472 steel samples particularly the 54 mm ones are very good and are comparable to that of
473 the block sample.

474

475 For the IL oedometer tests (Figure 12b) again it can be seen that quality of the 54 mm
476 steel sample tests (provide they are taken carefully and storage time is minimised)
477 approaches that of the block and certainly the results are comparable for practical
478 engineering purposes.

479 These results for the steel samplers are possible provided that the sampling is done
480 carefully. The insides of the tubes were polished and coated with a thin layer of silicone
481 oil. As the 75mm tubes had no inside clearance more time was used to withdraw them.
482 They were initially withdrawn about 1 mm, followed by a 5 minute to 10 minute break,
483 followed by another 1 mm extraction and another break until extraction was completed.
484 In addition, the storage time between sampling and testing was limited to a few days.

485 As can be seen from Figure 13b, the M_0 values are greatest for the block samples
486 (average 5.5 MPa) and lower for the 54 mm steel, 75 mm steel and 54 mm plastic
487 samplers (average 5.2 MPa, 3.8 MPa and 3.5 MPa respectively). There appears to be little
488 effect of sampling on M_n and m (Figure 13c and 13d respectively).

489 Coefficient of consolidation (c_{v0}) values are sensitive to sampling induced disturbance
490 (Figure 14a) and the average values for the block samples ($23 \text{ m}^2/\text{yr}$) are higher than
491 those from the 54 mm samples ($20 \text{ m}^2/\text{yr}$) and the 75 mm samples ($16 \text{ m}^2/\text{yr}$). Sampling
492 appears to have little influence on c_{v0} .

493 The effects of sample disturbance on shallower specimens of non quick ($S_t \approx 25$) Tiller
494 clay have previously been described by Sandven et al. (2004), Lunne et al. (2006) and
495 Berre et al. (2007) based on the thesis work of Ørbech (1999) and Seierstad (2000).

496 Ørbech (1999) showed that comparative results could be obtained for carefully run
497 tests on 75 mm steel, 54 mm steel and block samples whereas the 54 mm plastic sample
498 gives the poorest results.

499 Overall the effects of sample disturbance:

- 500 • reduce M_0 , c_{v0} and r_s in the overconsolidated zone.
- 501 • reduce preconsolidation stress, p_c'
- 502 • minimal effect on modulus number, m , M_n and c_{vn} .

503 Similar findings to these have been reported for tests on several other soft Norwegian
504 clays (Lunne et al., 2006; 1997a).

505 7.2. *Triaxial tests*

506 Values for $\Delta e/e_0$ on consolidation to in situ stress are shown on Figure 17a. There is no
507 clear pattern of varying sample quality with depth. However it can be seen that the block
508 samples are clearly best (average $\Delta e/e_0$ of 0.031) and are generally all classified as “very
509 good to excellent”. These are followed in quality by the 75 mm steel samples (average
510 values of 0.081) and the 54 mm samples (both sets have average $\Delta e/e_0$ of about 0.09).
511 The average $\Delta e/e_0$ for the triaxial tests on the block samples is less than that for the
512 oedometer tests. This is a common finding and is attributed to some extra damage done to
513 the oedometer test samples when pushing them into the steel confining ring.

514 The results of the triaxial tests shown on Figure 15 and on Figures 17b and 17c
515 suggest that for practical engineering purposes the 75 mm steel and 54 mm steel samples

516 provide similar data to the block samples. The limited data available suggests that these
517 three samplers give similar s_u values (average 38 kPa to 40 kPa for the CIUC tests) which
518 are significantly higher than those from the 54 mm plastic samples (average 24 kPa).
519 Perhaps this result is not surprising, for the 75 mm steel samples, as the laboratory
520 specimens tested were actually 54 mm in diameter having trimmed them from 75 mm.
521 However the results for the 54 mm steel samples are exceptionally good and reflect the
522 care taken by the skilled personnel as described above. The 54 mm plastic tests are very
523 poor as has been found by other researchers e.g. Lunne et al. (1997a). These samples
524 seem to be not useful for any practical purpose other than as index tests.

525 Similar behaviour has been reported by Seierstad (2000) and Sandven et al. (2004) for
526 tests on 54 mm steel, 75 mm steel, 54 mm plastic and block samples, from the Tiller non
527 quick zone. The 54 mm plastic sample tests were again particularly poor. In fact Seierstad
528 (2000) showed the effects of very poor sampling can cause a sample, which usually
529 contracts on shearing, to dilate post peak. This could result in the choice of unsafe higher
530 s_u values. Long (2006) demonstrated that such behaviour was possible for soft
531 “intermediate” or laminated soils, especially when the clay content is less than about 40%
532 and the plasticity index is less than 20%.

533 Holsdal (2012) studied sample disturbance effects at Tiller related to using pure
534 tension or rotation to cut the soil at the cylinder base when withdrawing the sample. In
535 the upper non-quick clay the results were inconclusive with no clear indication of which
536 procedure that produced the best sample quality. However, in the quick clay zone it was
537 not possible to collect samples when rotation had been applied.

538 Overall the results shown are again characteristic for experience in Norwegian soft
539 clays where the effect of sample disturbance is to:

- 540 • reduce peak undrained shear strength s_u ,
- 541 • reduce initial / small strain stiffness,
- 542 • increase strain to failure ϵ_f ,
- 543 • result in a lower degree of strain softening post failure.

544 There seems to be minimal sampling induced effects on effective friction angle (ϕ')
545 and effective cohesion (c')

546 8. COMPARISON WITH OTHER QUICK CLAYS

547

548 It has been already demonstrated on Figures 3 and 4a that Tiller clay has properties very
549 similar to other Norwegian marine clays. In addition index test data, specifically for
550 quick clay from about 30 other sites in Norway, is compared to the Tiller data on Figure
551 20. These data include plots of water content (w_i), bulk unit weight (γ), plasticity index
552 (I_p) and clay content versus depth. The data has been sub-divided by region in Norway,
553 i.e. Trøndelag (the area around Trondheim), the city of Oslo, Sørlandet (southern Norway
554 and south-west of Oslo), Akershus and Østfold (east and south-east of Oslo) and the city
555 of Drammen as follows:

- 556 • Trøndelag (Sites at Buvika, Rødde, Kattmarka, Melhus, Esp, Møllenberg and
557 Grong), (Kornbrekke, 2011; Long et al., 2012),
- 558 • Oslo (Tøyen, Manglerud, Bekkelaget, Oslo-S and Ullevål) (Bjerrum, 1954),
- 559 • Sørlandet (Sites at Sandvika, Skøyen, Skien, Larvik, Hokksund, Hvitvingfoss),
560 (Long et al., 2012)

- 561 • Akershus / Østfold (Ellingsrud, Emmerstad, Hvalsdaalen), (Bjerrum and Aitchison,
562 1973; Karlsrud et al., 1996; Lacasse et al., 1985) and
- 563 • Drammen (Brageråsen, Old City Hall, Norge-bygget, Werring Gården), (Bjerrum,
564 1967)

565 Overall the data is very similar throughout Norway with the exception of the
566 “Drammen quick plastic clay”, which is found at relatively shallow depths on the east
567 bank of the Drammen River. In general the Tiller data is towards the lower end of the γ
568 and I_p values but more or less at the average of the w_i and clay content data. Hence in
569 terms of these key parameters, the Tiller clay is representative for a wide range of other
570 Norwegian quick clays. However considering the engineering strength, stiffness and
571 consolidation parameters local conditions such as the stress history of the site, the
572 position of the ground water table and drainage regime are of high importance.

573 9. CONCLUSIONS

- 574 1. This paper details the characteristics and engineering properties of Tiller clay, a
575 thick deposit of marine clay, located close to Trondheim, Mid Norway. The site is
576 underlain by two main layers; an upper non sensitive zone and a lower (> 8 m)
577 quick clay zone.
- 578 2. The Tiller clay is typical of quick clays encountered in Norway and the deposit is
579 consistent with depth and over the survey area. It thus forms a valuable reference /
580 research material.
- 581 3. The material possesses a high degree of structure as is evident from both the
582 results of the electron microscopy and mechanical laboratory tests. The liquidity

583 index appears to be a particularly useful simple parameter to express the soil's
584 structure.

585 4. The mineralogy of the Tiller material is similar to other Norwegian marine clays.
586 The clay fraction is dominated by phyllosilicates such as illite and chlorite while
587 the coarser fractions are made up by quartz and feldspars.

588 5. The soil is lightly overconsolidated, of medium strength and possess a degree of
589 anisotropy in both consolidation properties and shear strength.

590 6. The piezocone (CPTU) test can provide useful data both from the point of view of
591 the soil layering and its parameters such as undrained shear strength.

592 7. Careful work with thin walled steel fixed piston samplers can provide high
593 quality results similar to those of block samples. It is particularly important to
594 trim the specimens (e.g. from 75 mm to 54 mm) and minimise storage time. Poor
595 quality samples can give non conservative design parameters.

596 8. Data for Tiller clay is similar to that for a wide range of Norwegian quick clays
597 and thus the findings presented here are representative of these materials in
598 general.

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605 the Trondheim region and the formation of quick clay.

606

607

608 Table 1. Summary of main research campaigns at Tiller test site.

Date of work	Description	Reference
1982	General site characterisation by sampling and rotary pressure sounding	Sandven (1990)
1987 / 1988	CPTU testing	Sandven (1990)
1998 - 2000	Sherbrooke block sampling together with 54 mm and 75 mm sampling	Ørbech (1999), Seierstad (2000) Sandven et al. (2004)
1999	Miniature CPTU testing	Tumay et al. (2001)
2000	Preconsolidation pressure in quick clay	Schmidt (2000)
2005	Investigation of stress relief on quick clay	Long (2005)
2005	Investigation of strain localisation in quick clay including 95 mm diameter sampling	Thakur (2007)
2007	SASW (Spectral analysis of surface waves) by GDS Instruments / UCD / NTNU	Long and Donohue (2010)
2008	Study of strain rates on quick clay	Yesuf (2008)
2009	Viscosity of quick clay	Khaldoun et al. (2009)
2010	CPTU and piezoball work by UWA / NTNU /UCD	Bihs et al. (2012)
2010	Effect of ground water pressures on quick clay	Sandene (2010)
2011/12	Sherbrooke block sampling Strain localisation in quick clay Shear vane experiment	Gylland (2012)
2012	Sampling techniques and sample disturbance in clay	Holsdal (2012)
2012	Salt stabilisation of quick clay	Gjengedal (2012)

609

610 Table 2: Dimensions and features of samplers used

611

	54 mm steel	54 mm plastic	75 mm steel	95 mm steel	Sherbrooke block
Inside	54.5	54.5	75.8	95	250

diameter D _i (mm)					
Outside diameter D _w (mm)	57	65	80	101.6	n/a
Sample length (cm)	80	80	80	80	35
Cutting edge angle (deg.)	10	5	10	10	n/a
Area ratio*	9 - 11	44	11.4	11	n/a
Inside clearance** (%)	0 - 0.9	0.6	0	0.3	n/a

612
613
614
615
616

* AR = $(D_w^2 - D_i^2) / D_i^2$

**CI = $(D_s - D_i) / D_i$ where D_s is the enlarged diameter past the cutting edge.

SUMMARY OF FIGURES

Fig. No.	Title	File reference Lab tests/Tiller/Summary Report (unless stated otherwise)
1	(a) Site location, (b) section of Quaternary geological map (www.ngu.no) and (c) detailed test locations (map from www.google.com)	Anders
2	a) preconsolidation stress and (b) overconsolidation ratio	Tiller-oedometersum-1.grf
3	Mineralogy of Tiller deposit as a function of grain size.	TillerMineralogy.grf
4	(a) Particle size distribution curves and (b) clay content with depth	Tillerpsd.grf
5	Backscatter image from electron probe micro analyser (EPMA) scan	Anders
6	(a) water content, (b) bulk density and (c) particle density versus depth	Tiller-Basics1.grf
7	(a) sensitivity, (b) remoulded shear strength and (c) salt content of the pore fluid versus depth	Tiller-Basics2.grf
8	(a) plasticity index and (b) liquidity index versus depth	Tiller-Basics3.grf
9	“A” line plasticity chart	Tiller-Atterberg.grf
10	Behavior of material within framework of Burland (1990)	Tiller-Burland.grf
11	G _{max} from SASW	Report/SASWNorway/TillerSASW.

		grf
12	Typical oedometer tests results (a) CRS tests from 8.75 m to 10.2 m and (b) IL tests from 8.66 70 9.78 m	SummaryCRSOedtests.grf SummaryILOedtests.grf
13	Summary of oedometer tests results (a) $\Delta e/e_0$, (b) M_0 , (c) M_n and (d) m	Tiller-oedometersum-2.grf
14	Summary of oedometer tests results (a) c_{v0} , (b) c_{vn} and (c) r_s	Tiller-oedometersum-3.grf
15	Typical CIUC triaxial tests from quick clay zone	SummaryCIUCTriaxialtests.grf
16	Undrained shear strength from index tests (a) field vane, (b) fall cone and (c) unconfined compression test	Tiller-indexstrength.grf
17	Triaxial test results (a) $\Delta e/e_0$, (b) undrained shear strength from CIUC tests and (c) undrained shear strength from CAUC / CPTU tests	Tiller-triaxialstrength.grf
18	CPTU test results	Tiller-CPTUSummary.grf
19	Sherbrooke block sample from 2011 investigation at Tiller	Anders
20	Index properties of other Norwegian quick clays (a) water content, w_i , (b) unit weight, γ , (c) plasticity index, I_p and (d) clay content	Reports/ERTNorway/Otherquickclays.grf

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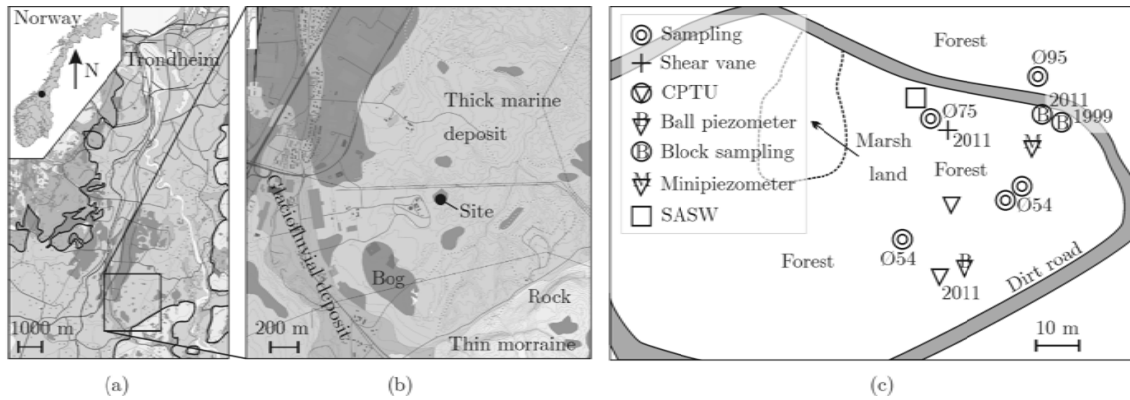
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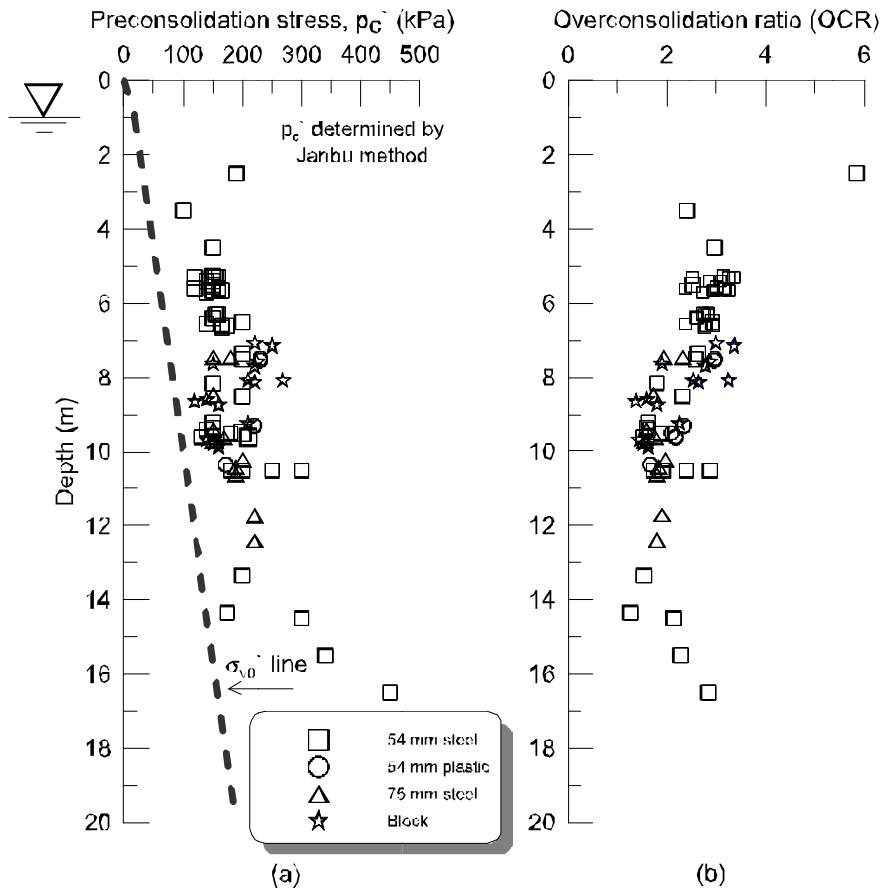
1 **Figures for paper by Gylland et al. on Tiller clay**

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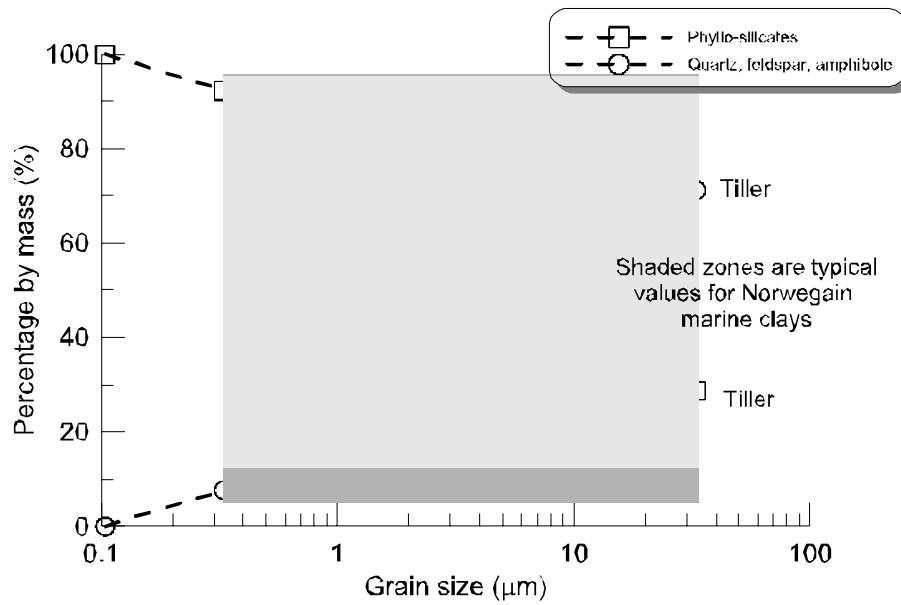
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Figure 1. (a) Site location, (b) section of Quaternary geological map (www.ngu.no) and (c) detailed test locations (map from www.google.com)



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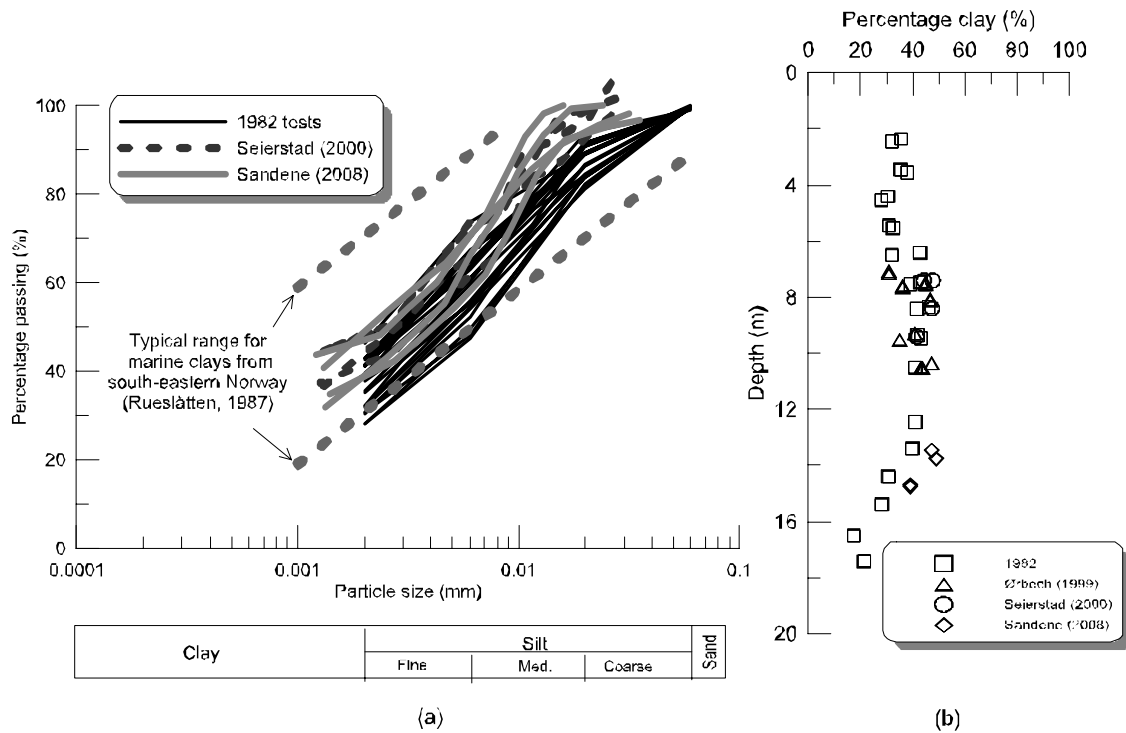
Figure 2. (a) preconsolidation stress and (b) overconsolidation ratio



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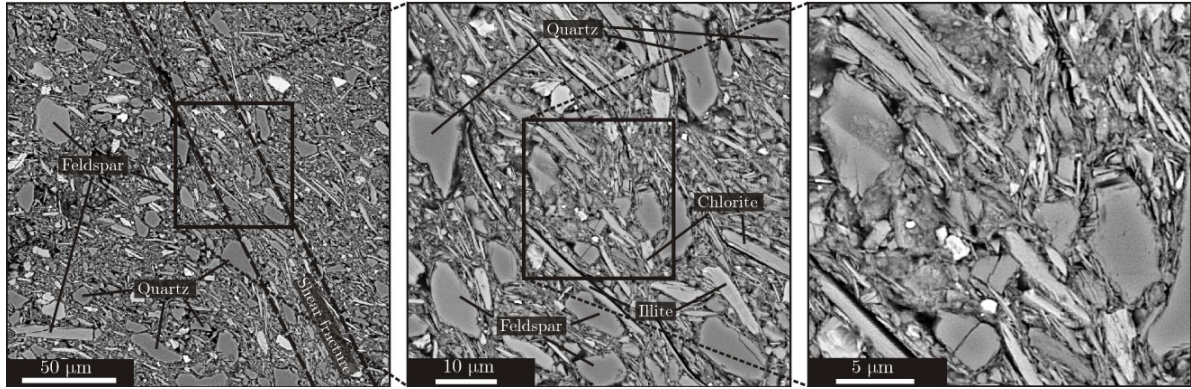
14 **Figure 3.** Mineralogy of Tiller deposit as a function of grain size. Adapted from Hilmo
 15 (1989)

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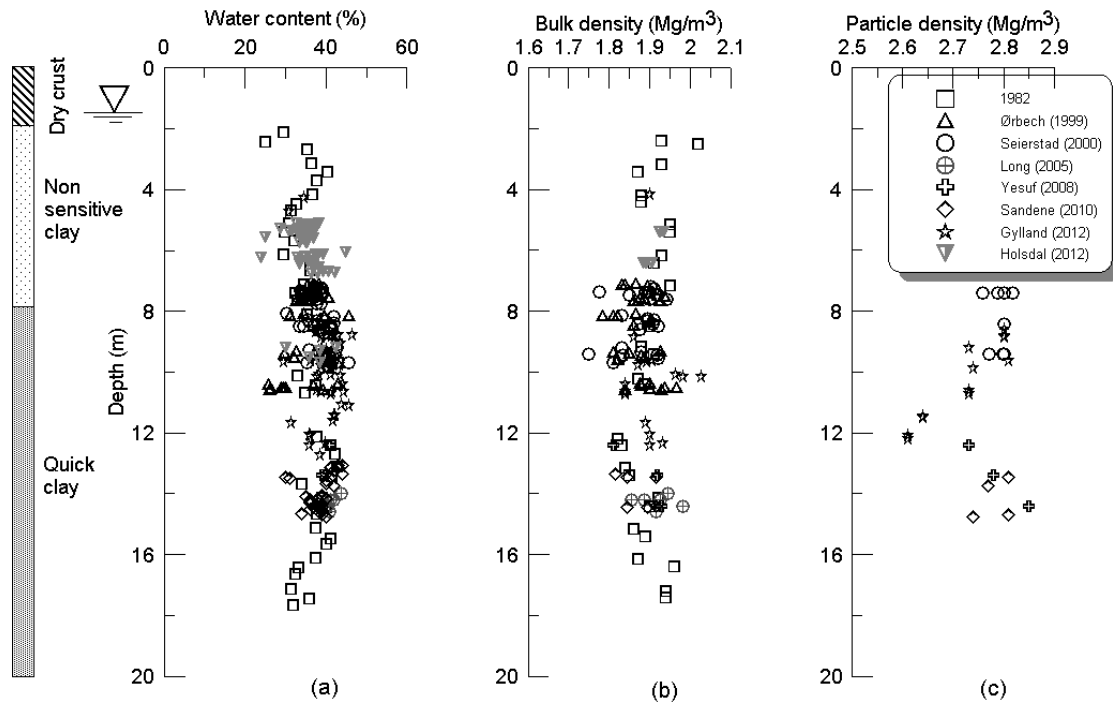
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18 **Figure 4.** (a) Particle size distribution curves and (b) clay content with depth.



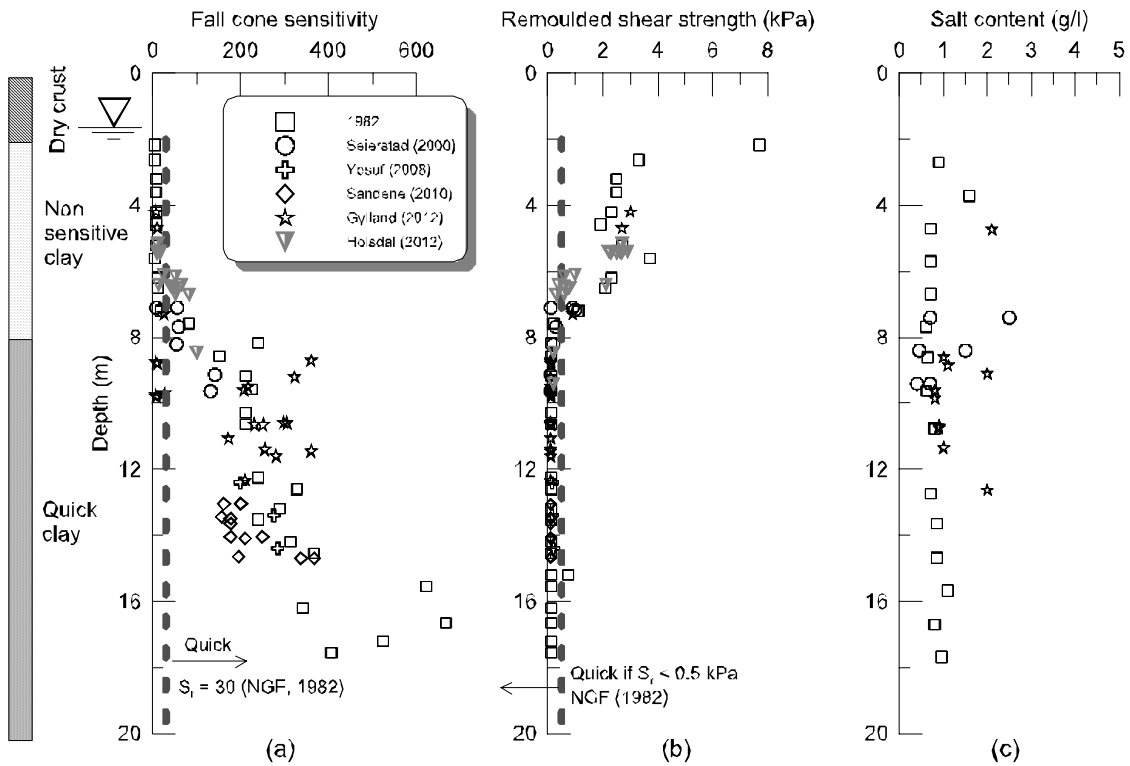
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Figure 5. Backscatter image from electron probe micro analyser (EPMA) scan. Three degrees of magnification are shown. Selected mineral grains are identified in the figures.



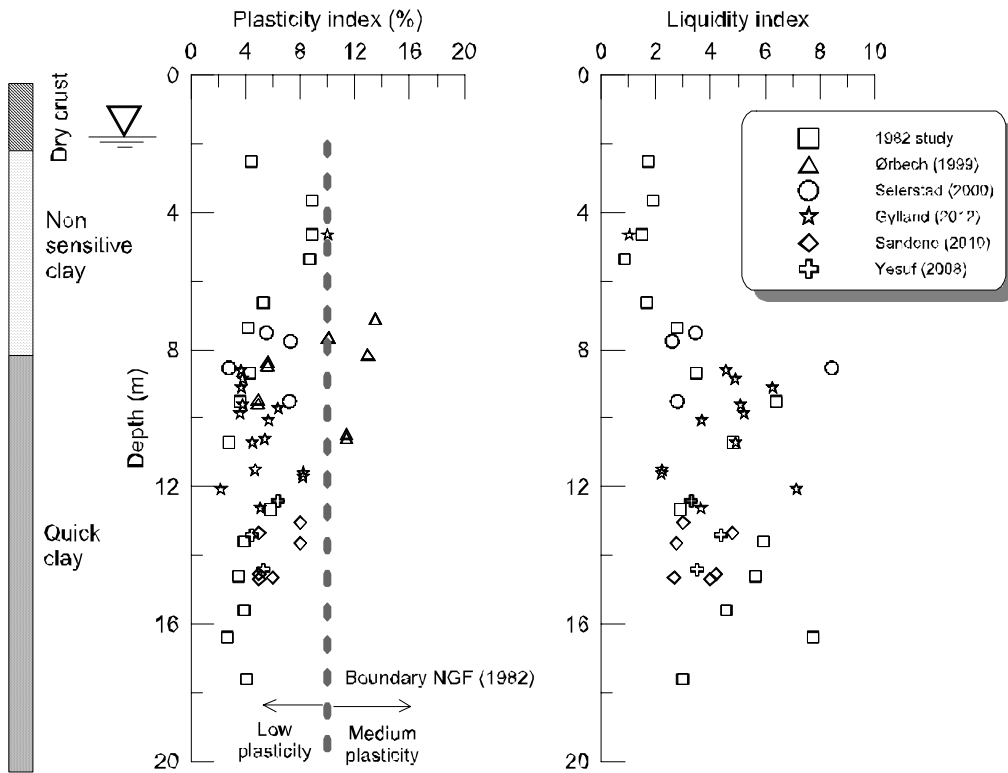
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Figure 6. (a) water content, (b) bulk density and (c) particle density versus depth



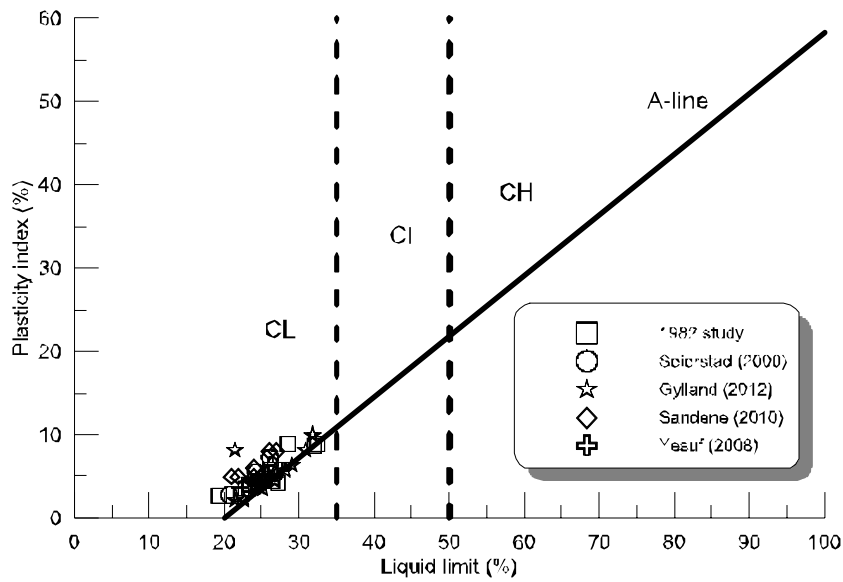
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Figure 7. (a) sensitivity, (b) remoulded shear strength and (c) salt content of the pore fluid versus depth



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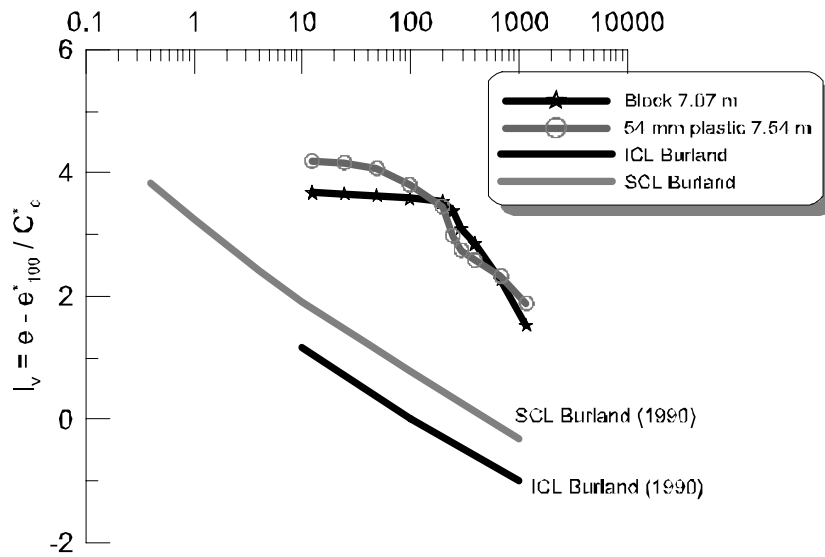
Figure 8. (a) plasticity index and (b) liquidity index versus depth



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Figure 9. "A" line plasticity chart

Effective axial stress (kPa)



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Figure 10. Behavior of material within framework of Burland (1990)

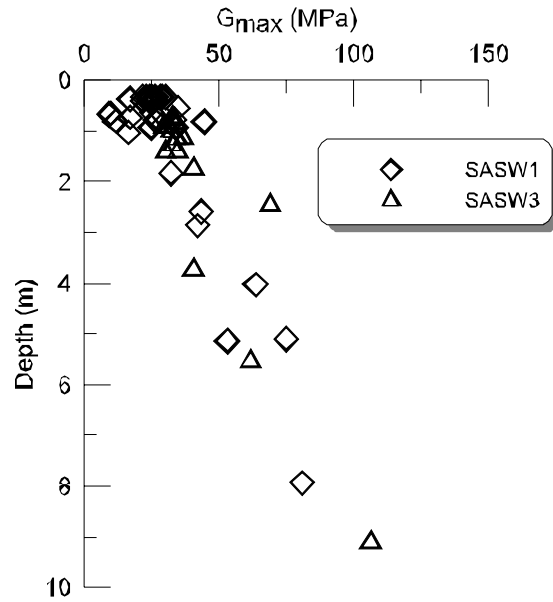


Figure 11. G_{max} from SASW

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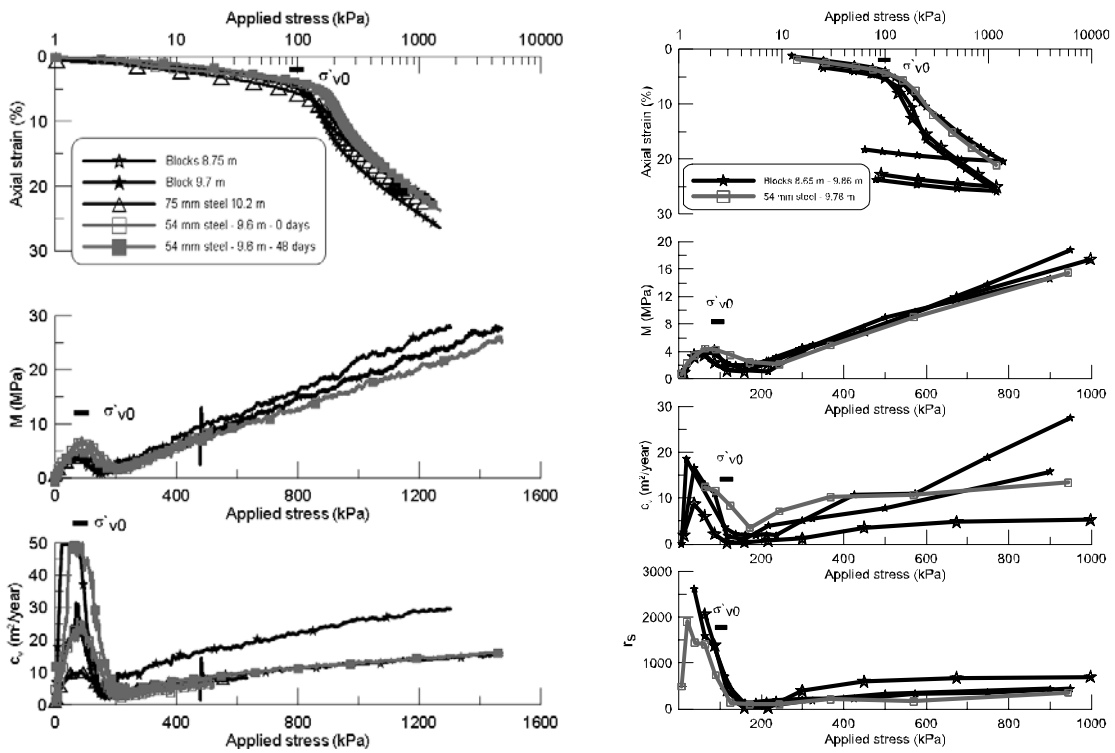
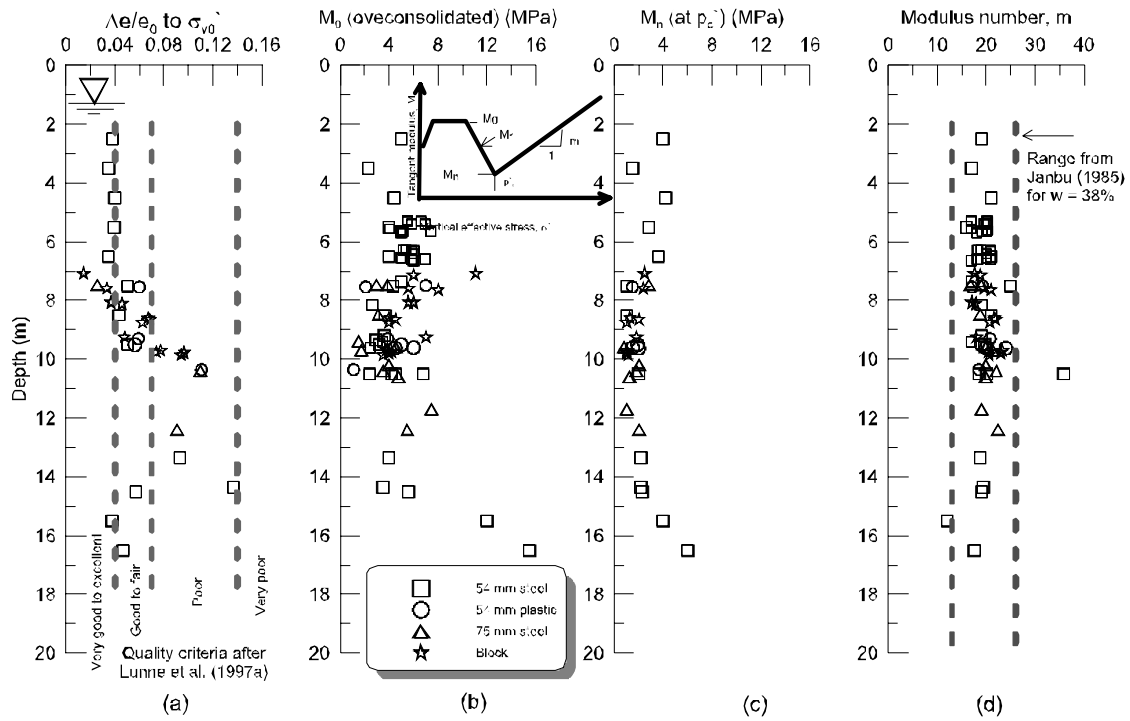


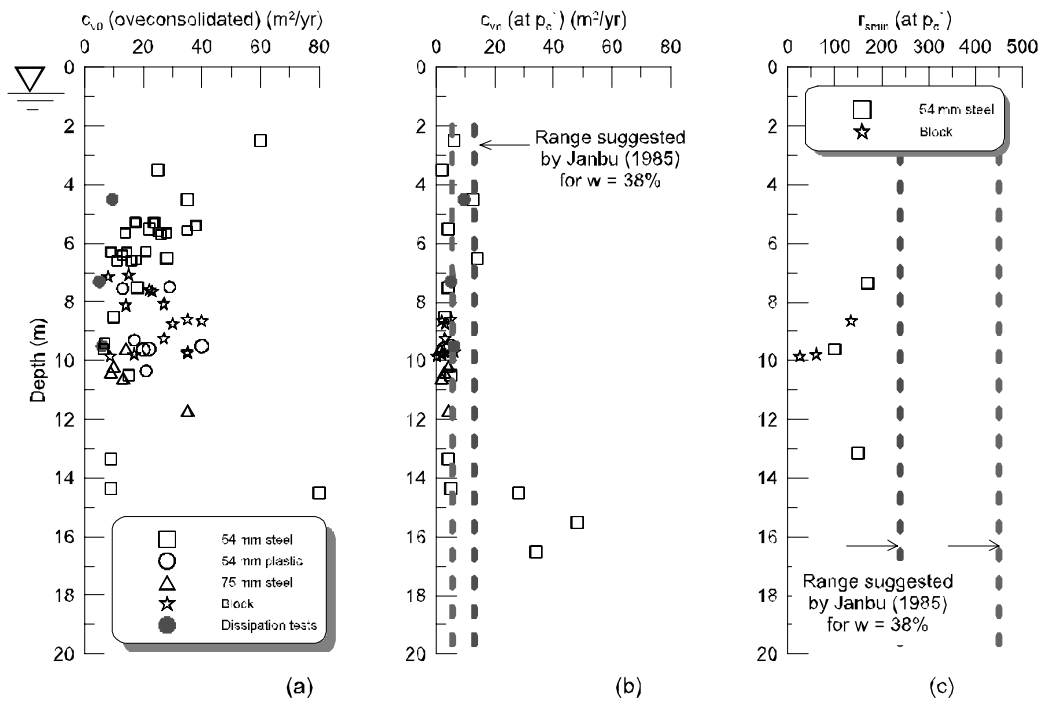
Figure 12. Typical oedometer tests results (a) CRS tests from 8.75 m to 10.2 m and (b) IL tests from 8.66 to 9.78 m

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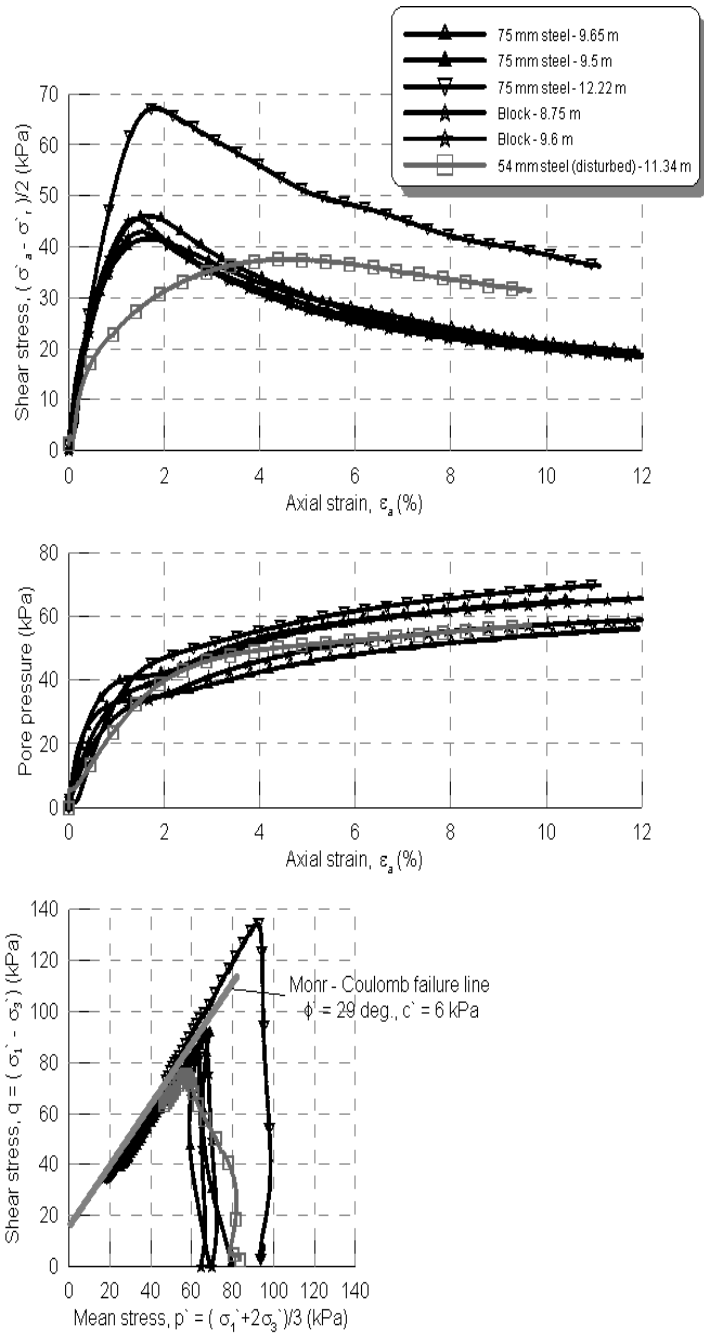
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Figure 13. Summary of oedometer tests results (a) $\Delta e/e_0$, (b) M_0 , (c) M_n and (d) m . See inset for explanation of terms



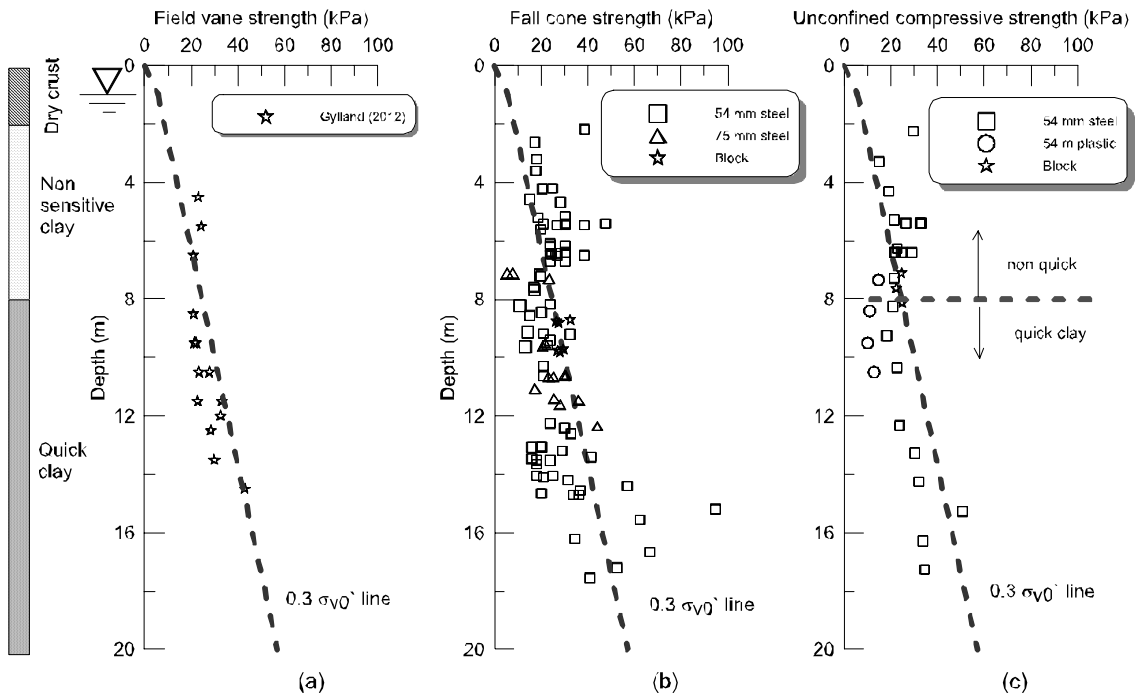
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Figure 14. Summary of oedometer tests results (a) c_{v0} , (b) c_{vn} and (c) r_{smin} . See inset on Figure 13 for definition of c_{v0} , c_{vn} and r_{smin} .



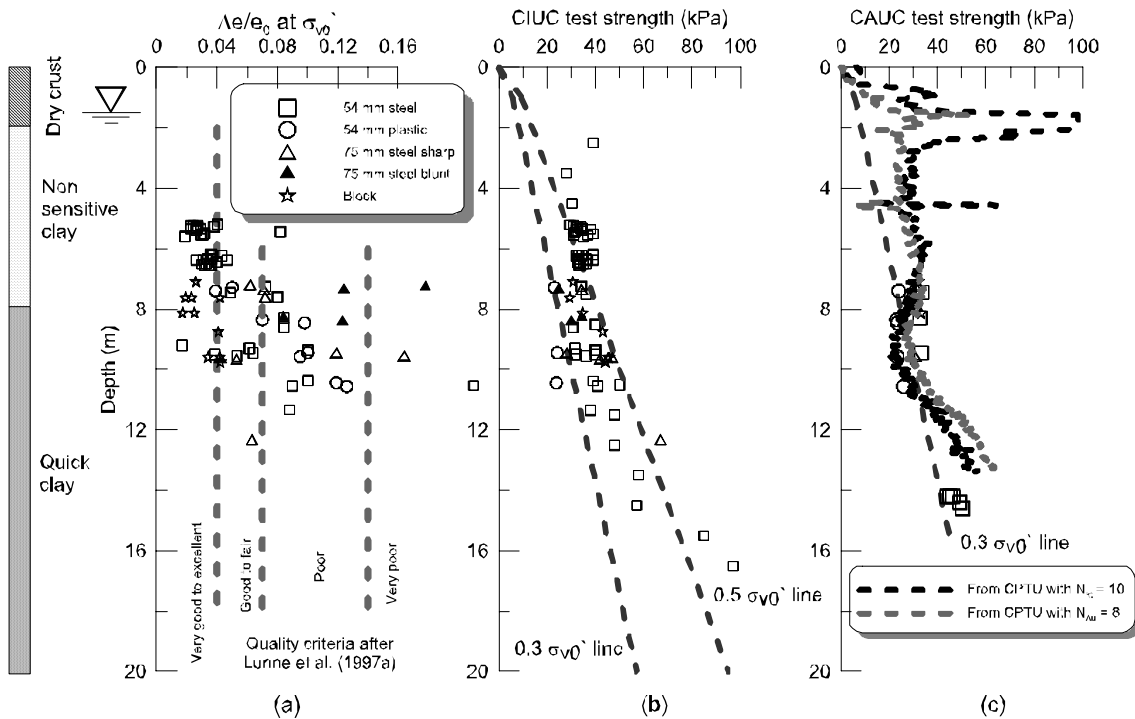
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Figure 15. Typical CIUC triaxial test results from quick clay zone



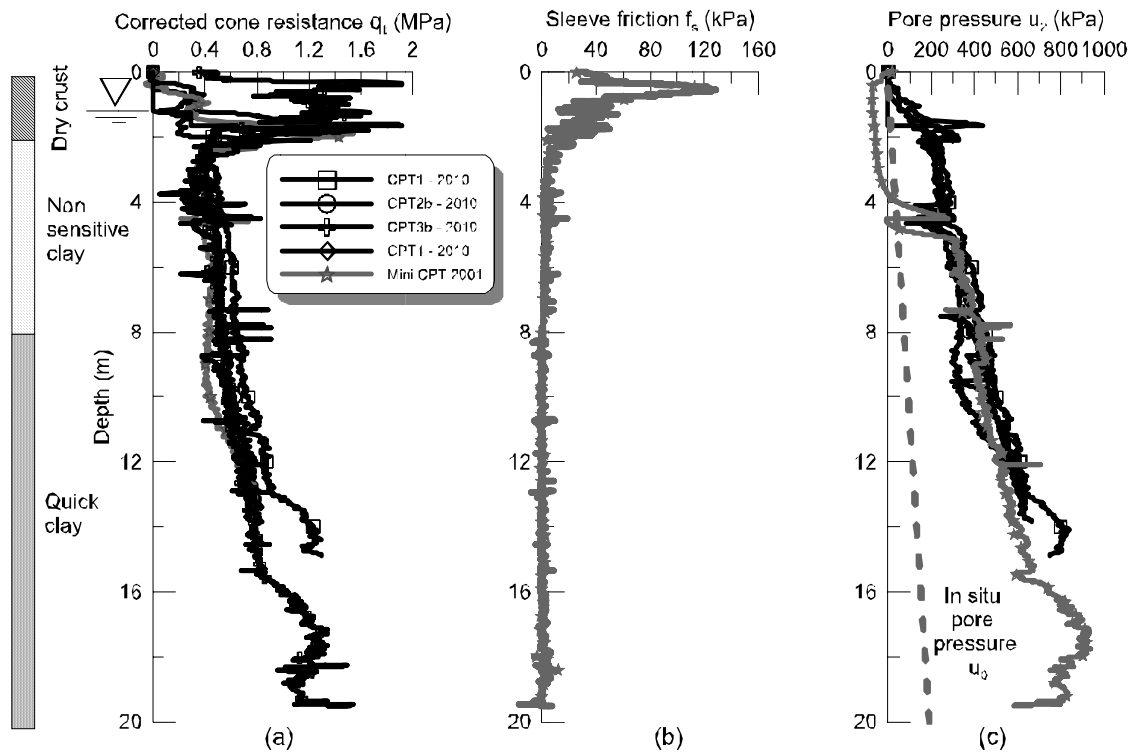
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Figure 16. Undrained shear strength from index tests (a) field vane, (b) fall cone and (c) unconfined compression test



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Figure 17. Triaxial test results (a) $\Delta e/e_0$, (b) undrained shear strength from CIUC tests and (c) undrained shear strength from CAUC / CPTU tests

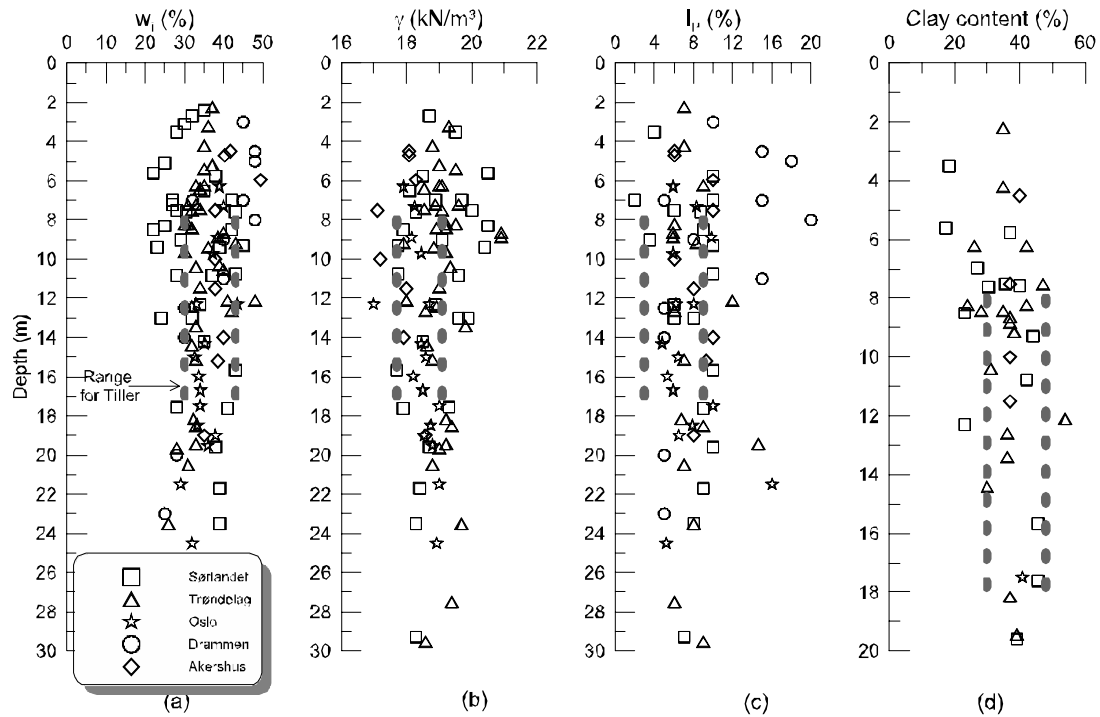


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Figure 18. CPTU tests



Figure 19. Sherbrooke block sample from 2011 investigation at Tiller



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Figure 20. Index properties of other Norwegian quick clays (a) water content, w_i , (b) unit weight, γ , (c) plasticity index, I_p and (d) clay content
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