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Title of Paper: Characterisation and engineering properties of Tiller clay

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Characterisation and engineering properties of Tiller clay by

A. Gylland et al.

ABSTRACT

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

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

1. INTRODUCTION

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

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

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

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

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

2. ENGINEERING GEOLOGY

2.1. Geological setting

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

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

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

2.2. *Stress history*

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

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

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

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

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

3. MATERIAL COMPOSITION

3.1. Mineralogy

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

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

3.2. *Grain size distribution*

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

3.3. *Grain shapes and form of clay fraction*

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

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

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

3.4. *Organic content and form*

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

3.5. *Specific surface area and cation exchange capacity*

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

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

3.6. *Pore water chemistry*

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

4. STATE AND INDEX PARAMETERS

4.1. *Water content / degree of saturation*

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

4.2. *Atterberg limits*

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

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

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

4.3. *Density / void ratio*

Bulk density values are shown on Figure 6b again show the relative consistency of the material with depth with no apparent trends. Measured values range between 1.8 Mg/m³ and 1.95 Mg/m³ with an average of about 1.89 Mg/m³. The average in situ void ratio (e_0) is about 1.07 with no clear trend with depth as would be expected from the water content and bulk density relationships

4.4. *Liquidity / void index*

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

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

where: w_p = plastic limit

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

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

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

where:

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

C_c^* = Burland's intrinsic compression index.

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

5. STRUCTURE

5.1. Macrofabric

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

5.2. *Microfabric*

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

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

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

5.3. *Cementation*

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

5.4. *Sensitivity*

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

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

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

6. ENGINEERING PROPERTIES

6.1. *Stiffness – G_{max}*

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

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

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

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

6.2. Behaviour in oedometer tests

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

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

6.3. Stiffness – constrained modulus M

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

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

6.4. Compressibility in the normally consolidated range

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

6.5. Coefficient of consolidation

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

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

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

6.6. Creep

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

6.7. Behaviour in triaxial tests

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

6.8. Dilatancy and strain softening

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

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

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

6.11. Rate effects

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

6.12. Undrained strength anisotropy

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

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

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

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

6.13. Drained shear strength

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

6.14. In situ undrained strength – field vane strength

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

6.15. In situ strength – cone penetration testing

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

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

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

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

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

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

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

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

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

7. SAMPLING DISTURBANCE EFFECTS

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

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

- Sherbrooke block sampler (Lefebvre and Poulin, 1979)

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

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

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

7.1. Oedometer tests

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

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

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

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

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

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

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

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

Overall the effects of sample disturbance:

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

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

7.2. Triaxial tests

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

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

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

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

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

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

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

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

8. COMPARISON WITH OTHER QUICK CLAYS

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

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

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

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

9. CONCLUSIONS

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

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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

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	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

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

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

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

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

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

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.

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

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

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

Figure 9. "A" line plasticity chart

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

Figure 11. G_{max} from SASW

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

73
74

75
76
77
78
79

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

80
81
82

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}

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

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

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

Figure 18. CPTU tests

Figure 19. Sherbrooke block sample from 2011 investigation at Tiller

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