



Title	Quality of conventional fixed piston samples of Norwegian soft clay
Authors(s)	Long, Michael (Michael M.), El Hadj, Nouri, Hagberg, Knut
Publication date	2009-02
Publication information	Long, Michael (Michael M.), Nouri El Hadj, and Knut Hagberg. "Quality of Conventional Fixed Piston Samples of Norwegian Soft Clay" 135, no. 2 (February, 2009).
Publisher	ASCE
Item record/more information	http://hdl.handle.net/10197/3077
Publisher's version (DOI)	10.1061/(ASCE)1090-0241(2009)135:2(185)

Downloaded 2023-03-15T17:09:45Z

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

Journal: ASCE Journal of Geotechnical and Environmental Engineering

Title of paper: Quality of conventional fixed piston samples of Norwegian soft clay

Names of authors: Michael Long¹ Nouri El Hadj² and Knut Hagberg²

Position / affiliation of authors: 1: Senior Lecturer, School of Architecture,
Landscape and Civil Engineering, University College Dublin, Earlsfort Terrace,

Dublin 2, Ireland (Mike.Long@ucd.ie)

2: Norwegian Public Roads Administration (Statens vegvesen), Vegdirektoratet, Oslo,
Norway (el.nouri@vegvesen.no, knut.hagberg@vegvesen.no))

Corresponding author contact details: Dr. Michael Long, School of Architecture,
Landscape and Civil Engineering, University College Dublin (UCD), Earlsfort
Terrace, Dublin 2, Ireland.

Phone: +353-1-7163221

Fax: +353-1-7167399

e-mail: Mike.Long@ucd.ie

Date paper originally written: May 2007

Date paper revised: October 2007

ABSTRACT:

It is well accepted that the quality of soft clay samples obtained using standard fixed piston samplers can be relatively poor and that block samples are necessary to yield very high quality samples. However for many practical projects it is not economically viable or physically practical to obtain block samples. In this project the quality of standard 54 mm composite piston samples of soft clay is examined by comparing six separate sets of 54 mm samples to parallel block sampling. Sampling and laboratory testing was carried out by three different organisations at a well characterised highly uniform soft clay site in Norway. As expected the work showed that the block samples behaved significantly differently from those obtained using the 54 mm sampler and were of higher quality. Block sample derived parameters were considerably different from those obtained from the 54 mm sample tests. However significant differences were also found between the different sets of 54 mm samples. Although the differences are less than when compared with block samples, the consequences of poor quality 54 mm sampling will be significant in engineering design. It is concluded that the differences are due to small details in the sampling operation such as the need to keep the piston effectively stationary at all times, to avoid overcoring and to handle the recovered sample carefully. If a well trained driller follows good quality practice, then relatively good samples can be obtained by the fixed piston sampler, which are suitable for analysis and design of routine engineering works.

Key words: soil sampling, soft clay, quick clay, cone penetration testing

INTRODUCTION

The need to obtain high quality samples for the purposes of designing engineering works on soft soils is well accepted. Much research work has been done on comparing the quality of samples retrieved from different samplers. It is now well understood by engineers in Canada, Scandinavia, the US and elsewhere that it is possible to obtain very high quality samples from Sherbrooke block sampling and that those recovered by fixed piston samplers can be relatively poor (e.g. Lunne et al., 1997a and 2006, Landon et al., 2007). However for many practical projects it is not economically viable or physically practical to obtain block samples. For example the Norwegian Public Roads Administration (NPRA) carries out several hundred ground investigations per annum many of which are on soft clay and quick clay sites. On all of these soft soil sites samples are retrieved by the Geonor 54 mm diameter fixed piston sampler. Occasionally thin walled steel sample tubes are used but mostly they are of the composite type with a plastic inner liner.

The main objectives of this paper are to examine the influence on the sample quality of various parameters associated with this standard sampler and to provide recommendations as to how sample quality, for use in routine projects, can be optimised. Relevant parameters include details of the drilling rig, minor details of the sampler itself particularly the piston, the technique which is used to push the sampler into the ground, the rate of penetration, the method by which the sampler is withdrawn etc.

Six series of NGI / Geonor 54 mm samples were recovered by three different organisations. Parallel laboratory tests were also carried out by each firm. In addition Sherbrooke block samples were retrieved to provide reference for the testing of the piston samples.

TEST SITE

Location

The test site is situated some 35 km north of Oslo and approximately 2 km east of Kløfta along national road Rv. 2 in southern Norway. Locally the area is known as Hilleren and is at Profile 850 on the Rv. 2 project. It was selected for the project as the NPRA, had performed several relevant site investigations in the area, for example total soundings, piezocone (CPTU) tests and vane borings. It was known therefore that the area was underlain by a substantial thickness of uniform marine clays, typical of those encountered elsewhere in Norway. In addition the distance between the test site and the participating laboratories is relatively short.

All of the sampling and in situ testing reported here was carried out within the same, generally flat, area with boreholes located as close as practically possible to one another.

Background geology

The soil deposits present in the area mainly date back to the end of the last ice age, i.e. the deposits are seldom older than 9,000 to 10,000 years. The melt water transported large amounts of soil particles into the fjords where the coarsest particles (cobbles, gravel and sand) were deposited as deltas along the ice rim or beaches. The finest particles like clay and silt were transported further out into the fjords (ocean bottom sediments). Due to the weight of the enormous glaciers that covered the country during the ice age, the earth crust was pressed down. When the ice melted isostatic uplift occurred and large areas with fine grained marine deposits (silt/clay) were lifted above ocean level.

The highest level the ocean reached in an area after the glaciers melted is called the marine level or ML. In the area where the test site is located the ML is 190 m to

200 m above the present sea level. The thickness of the fine grained marine deposits in the area may be up to 70 m.

Summary of ground conditions

A summary of the ground conditions is given on the piezocone profile shown on Figure 1. The following measured and derived parameters were used to analyse the CPTU test results (Lunne et al., 1997b):

q_t = cone resistance corrected for out of balance pore pressure effects

$$q_n = \text{net cone resistance} = q_t - \sigma_{v0} \quad (1)$$

f_s = measured sleeve friction

$$R_f = \left(\frac{f_s}{q_t} \right) \times 100\% \quad (2)$$

u_0 = in situ or hydrostatic pore pressure with water table at 3.5 m

u_2 = pore pressure measured just behind conical tip

σ_{v0} = total overburden stress

$$B_q = \text{pore pressure parameter} = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \quad (3)$$

Over a dry crust of some 4 m in thickness the site is underlain by about 11 m of low sensitivity soft clay over medium to high sensitivity soft clay. Corrected cone resistance (q_t) increases gradually from about 0.4 MPa below the crust to about 0.7 MPa at the base of the profile. These values are typical for Norwegian soft clays. However both R_f and u_2 (and consequently B_q) are relatively high. R_f decreases from about 4% in the low sensitivity clay to 2.5% in the medium to high sensitivity clay. B_q increases throughout the profile from about 1.0 to 1.6. This decrease in R_f and corresponding increase in B_q reflects the increasing sensitivity of the soil (Lunne et al., 1997b).

Adjacent total pressure sounding tests confirm the soft deposits in the test site are at least 70 m thick.

FIELDWORK

Description of drilling and sampling techniques

Six boreholes were formed and 6 samples were taken in each borehole. Each borehole was divided into three levels with 2 samples for each level from 5.0 m to 5.8 m and 6.0 m to 6.8 m, 10.0 m to 10.8 m and 11.0 m to 11.8 m and finally 17.0 m to 17.8 m and 18.0 m to 18.8 m respectively. Boreholes were drilled by three different organisations who formed two holes each. The crews used 2 days each to complete their work. Sampling was carried out during the period 15th to 26th of November 2004 under the supervision of the Directorate of Public Roads, Technology Department.

In each case the sampling technique involved use of NGI (Norwegian Geotechnical Institute) 54 mm composite samples. This sampler was developed and designed by NGI at the end of the 1970's (Andresen and Kolstad, 1979) and is the most common sampler used in Norway. The sampler is a composite piston sampler using plastic inner tubes, Figure 2a. 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. The sampler has an area ratio of 44%, and inside clearance of 0.6% and a cutting edge angle of 5°.

Prior to the development of the composite sampler, 54 mm thin walled steel tubes were used in Norway. However inherent problems associated with the thin walled steel tubes such as strength properties, corrosion of the cylinder material, tolerance

imperfections and damage to the cutting edge led to the development of the composite sampler. It was also difficult to obtain steel tube of this dimension. As all of the ancillary sampling and laboratory equipment was designed for 54 it was desirable to retain this dimension.

The drilling crews were aware that the work was for a research project. They were instructed to follow the guidelines given in the Norwegian Geotechnical Society Handbook No. 11 (NGF, 1997) or the Norwegian Public Roads Administration Handbook No 015 (Statens vegvesen, 1987).

Participants 1 and 2 drilled and sampled 2 boreholes each, for a total of four boreholes, taking samples as described above from the same levels in each borehole. One set of samples was sent to the laboratory of that organisation (Series 850-1-1 and 850-2-1), while the second set was sent to the laboratory of Participant 3 (Series 850-1-2 and 850-2-2).

Participant 3 employed two different methods for taking the samples. The first sample series involved the standard displacement method used by both other crews as described above and these were sent to the laboratory of this participant (Series 850-3-1). The second sample series was taken using an auger to remove soil in the borehole by pre-drilling to the required sampling level. For this purpose a modified 75 mm auger drill was used with a flat sharp edge as shown in the picture on Figure 2b. In this way no soil was displaced down to the level where the samples were to be taken. In addition two hose clamps were attached to the outside of the sampler so as to reduce outside friction during sampling, see Figure 2c. It was intended that the combination of the larger borehole and the hose clamps would help release any possible vacuum that may have developed below the sampler when it is retrieved.

During this process no water was added to the borehole. These samples were also sent to the laboratory of Participant 3 (Series 850-3-2)

In order to provide high quality reference data samples were also taken with the Sherbrooke block sampler as described by Lefebvre and Poulin (1979). This work and the parallel laboratory testing were carried out by NGI who have experience with the use of the sampler (e.g. Lunne et al., 1997a and 2006).

In situ testing

In situ testing relevant to this project comprised field vane testing using a Geonor H10 field vane tester with a 5.5 cm by 11 cm vane and piezocone CPTU testing using a standard 10 cm² cone with pore pressure measured just behind the cone tip (u_2 position).

Observations made during field work and analysis of various techniques

A summary of the procedures used by each crew and some observations made during the drilling and sampling are summarised on Table 1. Despite each crew using the same sampler and working to the same set of guidelines there are some important differences between the three operations. Perhaps the most significant differences from the point of view of sample disturbance effects are:

- Upward movement of piston rods occurred immediately following release of piston due to lack of proper fixity. (Crew 1 and 2). During the subsequent insertion of the sampling tube, the rods were always held fixed.
- Overcoring (particularly by Crew 1 and 2) so as to ensure sample tube was filled. This may have imposed compression strain on the sampled material.
- Whether sample was twisted off or not prior to retrieval.

In each case there were some items of less than best practice employed by each crew, as detailed in Table 1.

LABORATORY TESTING

In addition to basic index testing, the principal means of studying the difference in behaviour of the material from the block and the various tube samples was by means of anisotropically consolidated undrained triaxial tests (CAUC) and constant rate of strain oedometer tests (CRS).

Triaxial Tests

The procedures used were broadly those adopted as standard by the NGI as describe by Berre (1982). For the piston samples the specimens were not trimmed and were used as extruded. For the block samples they were trimmed to 53.4 mm diameter. All samples were then cut to a height of between 10 cm and 11 cm. Initially some isotropic consolidation was carried out before slowly applying the in situ stress. K_0 was assumed to equal 0.65, based on correlation with plasticity index (I_p) from Brooker and Ireland (1965) and Berre (1982).

Unfortunately there were some small differences between the procedures used at the three labs as summarised on Table 2. Of some concern was the shorter consolidation time used by Laboratory 3 and the slower rate of loading adopted by Laboratory 2. Comparative tests using 20 hour and 48 hours consolidation times showed no appreciable differences in the results. Many researchers (e.g. Leroueil and Hight, 2003, Lacasse 1995) have shown that an order of magnitude change in the loading rate is required to change the results of CAUC tests and that the effects of rate of loading are highest for high plasticity clays. Here the difference in loading rate was much smaller than one order of magnitude and the clay has low plasticity index. It is concluded that any difference in the test procedures used will not be significant from the point of view of assessing sample disturbance.

Oedometer tests

Again the procedures used were broadly those adopted as standard by NGI (Sandbækken et al. 1986). Specimens were pushed carefully into 50 mm diameter, 20 mm high, lubricated oedometer rings. As for the triaxial tests there were some small differences between the laboratories as summarised on Table 2. It is felt that the rate used by Laboratory B was too low. As discussed above there seems to be no strong influence of this loading rate on the overall tests results although it might be argued that the consolidation coefficient (c_v) values determined from the low speed tests might be less reliable.

ANALYSIS OF ROUTINE LABORATORY TESTS

Basic index tests

Plots of natural water content (w), bulk unit weight (γ), clay content and sensitivity (S_t) from the fall cone and field vane are shown on Figure 3. All four plots show the material is relatively homogenous with little scatter in the data. There is no tendency for an increase in γ and reduction in w with depth, which may perhaps be due to some preconsolidation experienced by the soil.

Between 5.0 m and 6.8 m the data for sample Series 850-1-1 show a slight tendency for lower water content. This may possibly be due to the proximity of this hole to the previously drilled 450 mm Sherbrooke block sample hole and may also explain the lower pore pressure response in these samples during triaxial tests. At depths from 10.0 m to 11.8 m there is some scatter of water content values but unit weight values show less variation.

Clay content is relatively constant with depth with an average of about 40%. Above 15 m depth, the material is generally of low sensitivity (Janbu, 1970) with no

difference between the results from the different samplers. Field vane S_t values are somewhat lower. From about 15 m the material becomes medium to highly sensitive.

For the basic index testing there is no clear difference in the results between the different piston tube samples or the block samples. Therefore it is reasonable to assume that any differences in the results of the oedometer and triaxial tests, which are presented below, are due to effects of sampling and testing and not due to natural material variability.

Plasticity

Plasticity data is shown on the A-line chart on Figure 4. The soil has average liquid limit (w_L) of about 40% and I_p of about 15%. According to Janbu (1970) this corresponds to medium plastic clay. The water content is close to the liquid limit, meaning that the liquidity index I_L is close to one. Below 15 m, in the more sensitive clay, w_L and I_p values are approximately 25% and 5% respectively. Previous research on Norwegian clays (e.g. Lacasse et al. 1985) showed that these somewhat lean clays (low I_p) have greater sensitivity to disturbance than more plastic clays. Similar to the other basic index data discussed above there is no difference between the results for the different sample types.

Undrained shear strength from index testing

Undrained shear strength (s_u) values measured by fall cone and unconfined compression (UC) testing are shown on Figures 5a and 5b. Also shown for comparative purposes are lines representing $s_u = 0.41\sigma'_{v0}$. This corresponds to the triaxial compressive strength of clay with an overconsolidation ratio (OCR) of 1.5. As will be shown below the block samples indicate that OCR reduces from about 2.5 at 6 m to close to 1.0 at 18 m. Undrained shear strength (s_u) for an overconsolidated (OC) material can be estimated from the SHANSEP equation (Ladd and Foot, 1974):

$$\left(\frac{s_u}{\sigma'_v}\right)_{oc} = OCR^{0.8} \left(\frac{s_u}{\sigma'_v}\right)_{nc} \quad (4)$$

where: s_u/σ'_{v0} for normally consolidated conditions (nc) is taken as 0.3

Both sets of tests give similar results and are always less than $0.41\sigma'_{v0}$. This is probably due to a combination of mechanical sampling disturbance effects and the removal of the in situ confining stress (which is of course re-imposed in the triaxial tests). The influence of the removal of the confining stress can be seen in the consistent reduction in s_u with depth. Data from field vane testing is also shown on Figure 5a. Note that the mode of failure for the vane test is different from triaxial so the strength values may not match the triaxial profile. Between 5.5 m and 6.5 m s_u from the vane is similar to that from the fall cone. Below this the field vane values are somewhat higher as in situ stresses are maintained for these tests.

Results of UC tests are frequently used in Norway and elsewhere to give an indication of sample quality. This is performed by examining the strain to failure (ϵ_f), see Figure 5c. Unfortunately no UC results are available for the block samples. However inspection of Figure 5c shows the Series 2 samples have highest average strain to failure and lowest average s_u from the UC tests. The test results are analysed more rigorously on Table 3. As can be seen the tests results have been assessed using four categories namely average s_u for all tests in the relevant series, standard deviation (SD) on s_u , number of tests where $\epsilon_f \geq 15\%$ and average ϵ_f for the series (excluding those tests where the average value exceeds 15%). In the table an evaluation of sample quality has been made with a scale 1 – 6 (reflecting the six series of 54 mm samples with ranking 1 as best and 6 as poorest). High unconfined compressive strength and low strain to failure are taken as a measure of good quality. The water content in sample Series 850-1-1 was low as discussed above. Also this series shows

the highest standard deviation of s_u . If these values are discounted, the difference between the remaining results is small, but confirm that sample series 850-3 obtains the best ranking.

ANALYSIS OF OEDOMETER TESTS

Stress – strain behaviour and stiffness

Typical oedometer test results (in this case for all specimens at about 6.3 m) are shown on Figure 6. Plots of vertical strain (ϵ), tangent constrained modulus ($M = \delta\sigma'_v/\delta\epsilon$) and coefficient of consolidation (c_v) against vertical effective stress (σ'_v) are presented. Results for each of the three sample series are plotted separately for clarity but the result for the same block sample is included in each plot for comparison purposes.

In general the nature of the stress – strain curves are typical of Norwegian lightly overconsolidated marine clays (e.g. Janbu 1985). On initial loading the behaviour is stiff and then there is a reduction in stiffness, reaching a minimum near the preconsolidation stress (p'_c) before gradually increasing again as the stress increases. This behaviour is most clearly evident in the block samples with very high M values between the in situ vertical effective stress (σ'_{v0}) and p'_c and a clear discontinuity being evident in the M and c_v versus σ'_v plots. Similar behaviour, albeit less pronounced, can be seen in some of the 54 mm samples (850-2-1, 850-3-1 and 850-3-2). The modulus number m (slope of M versus σ'_v plot after p'_c) is clearly defined in all of the tests.

Analysis of sample quality

In Norway and elsewhere sample quality in oedometer tests is typically assessed by determining the normalised volume change ($\epsilon_{v0}=\Delta V/V_0$) during loading back to σ'_{v0} or alternatively the normalised void ratio change ($\Delta e/e_0$) to the same stress

(Andresen and Kolstad, 1979, Lunne et al., 1997a). It was found that there is little difference between the two assessment procedures and data for tests under discussion here are shown on Figure 7a together with the criteria of Lunne et al. (1997a). The clays from this site fall within the range for which the criteria were intended to be used. It can be noted:

- There is an overall trend for a decrease in sample quality with depth.
- Sample quality for the block samples is best.
- The 54 mm sample tests generally fall in the “poor” category.

This assessment criterion is not alone sufficient to examine the differences in quality between the various 54 mm samples. Some further analyses of these data will be presented later.

Parameters derived from CRS tests

Various parameters derived from the CRS tests, namely p'_c , c_v at σ'_{v0} , M_0 (i.e. M at σ'_{v0}) and m , are shown on Figure 8. Preconsolidation pressure (p'_c) has been determined by the Janbu (1970) technique, where it is chosen close to the point of minimum M or c_v , representing complete structural breakdown of the material. For this approach, it has not always been possible to determine p'_c due to lack of a clearly defined minimum M or c_v point and these tests have been denoted by a “zero” on the graph. This seems to have been particularly a problem with the 850-2 series of samples. Other than this there is no clear pattern between the results from the different 54 mm samples. However these will be analysed in more detail below. The clearest result from the tests is the significantly higher p'_c given by the block sample tests. These p'_c values correspond to an OCR of 2.5 to 3 at about 5.5 m. decreasing to 1.5 to 2 at about 11 m and falling close to 1 at 18 m.

A similar pattern emerges for the c_v values. The 54 mm sample results fall in the typical range of 7 m²/yr. to 16 m²/yr. suggested by Janbu (1985) and there is no clear pattern evident amongst the various 54 mm. Tube sampling damage results in block sample c_v values at σ'_{v0} being almost twice those of the 54 mm samples (see also Figure 6).

Values of M_0 (i.e. M at σ'_{v0}) and m are also significantly higher for the block samples when compared to the 54 mm tests. Several other researchers (e.g. Lunne et al., 1997a and Lacasse et al., 1985) have reported that sample disturbance due to tube sampling can reduce M_0 values as has been found here. However the finding that m is also affected by piston sampling is a somewhat unusual result. For the 54 mm tube samples M_0 is relatively constant with depth at values from 4 MPa to 6 MPa, with the block sample values being almost twice as high. Values for m from 54 mm tube samples fall in the range 15 to 23 and these are typical for clay with water content in the range 32% to 42% (Janbu, 1985). The block sample values are in the range 26 to 36 and fall towards the upper bound of Janbu's typical range.

Relative quality of 54 mm samples

A detailed assessment of the relative quality of the 54 mm samples was undertaken by:

- Choosing the parameters which have been proven to be most susceptible to sampling disturbance (Lunne et al. 1997a, Lunne and Long, 2006). For oedometer tests these are ε_{v0} , $\Delta e/e_0$, M_0 , m , OCR (Janbu or Casagrande) and c_v at p'_0 .
- In addition to this consideration was given to whether it was possible to determine p'_c using the Janbu approach.

- The average of each of these parameters for each 54 mm sample series was then compared to the results from the block samples.
- For each parameter a rank was assigned to the 850 series, e.g. 850-2-1 has a rank of 1 for ε_{v0} as the average value came closest to that of the block samples.
- An overall rank can then be determined.

Results of the analysis are summarised on Table 4. It can be seen that Series 850-1-1 and 850-1-2 have comparable rankings. Similarly 850-3-1 and 850-3-2 have the same ranking. The difference in ranking between series 850-2-1 and 850-2-2 is, however, significant.

Considering the different drilling techniques it would seem that on average the 850-1 Series are the best followed by the 850-3 Series and the 850-2 Series are the most inferior (when comparing samples tested at the same strain rate).

Summary for oedometer tests and implications for practicing engineers

An overall assessment of the results presented is that, from the point of view of practicing engineers if the 54 mm sample parameters were used in engineering analyses, the net result would be a conservative design.

According to Lunne and Long (2006) the potential consequences of sample disturbance are summarised in Table 5. These are linked to two key design parameters, i.e. the undrained shear strength (s_u) and the constrained modulus (M). The sample quality classes quoted on Table 5 are the same as those presented on Figure 7. In this case the highest ranked 54 mm samples have average M_0 of 49 % of that of the block samples. The equivalent values for OCR and m are 95% and 73% respectively.

Comparing the highest and lowest ranked 54 mm specimens shows that the lowest has average M_0 , OCR and m of 86 %, 80 % and 81 % of the highest respectively. This

indicates that the charts presented earlier, which show little difference between the various 54 mm test results, may be misleading. Although the differences are less than when compared with block samples, the consequences of poor quality 54 mm sampling will be significant in engineering design.

ANALYSIS OF TRIAXIAL TESTS

Results of typical CAUC triaxial tests (all piston tube samples from about 11.3 m and block from 12.2 m) are presented in Figure 9. The results are given in the form of:

- Shear stress $(\sigma'_a - \sigma'_r) / 2$ versus ϵ_a
- Pore pressure (u) versus ϵ_a
- Stress path (MIT or NGI plot) $t' = (\sigma'_a - \sigma'_r) / 2$ versus $s' = (\sigma'_a + \sigma'_r) / 2$

where:

σ'_a is the axial effective stress,

σ'_r is the radial effective stress,

ϵ_a is the axial strain.

Assessment of sample quality

As for the CRS tests sample quality is assessed by determining the parameters $\Delta V/V_0$ or $\Delta e/e_0$ during loading back to the in situ stress (σ'_{v0} , σ'_{h0}). Data for the series of tests under discussion here is presented on Figure 7b, together with the NGI quality criteria after Lunne et al. (1997a). The following can be noted:

- Overall the CAUC tests suggest higher sample quality than the CRS tests. This may be due to additional damage imposed on the specimens while inserting the oedometer ring.
- As for the CRS oedometer tests CAUC sample quality generally decreases with depth. An exception to this may be for Series 850-3-2, where the normal displacement technique of sampling was not used.

- The quality of the block samples is clearly the best.
- Above 12 m the 54 mm specimens show “good to fair” quality. At 18 m they are generally categorised “poor”.
- On balance the quality of the 850-2 series seems worst.
- It is difficult to distinguish between the quality of the 850-1 and 850-3 series using these procedures and some additional analysis of the data is reported as follows.

Stress – strain behaviour

The block sample specimens show a distinctively different behaviour to that of the 54 mm samples. A clear peak in the $(\sigma'_a - \sigma'_r) / 2$ plot occurs at a low axial strain and post peak there is clear evidence of strain softening. For the 54 mm specimens there is a more gradual build up in shear stress and peak $(\sigma'_a - \sigma'_r) / 2$ occurs at a higher strain than for the block samples. Post peak the strain softening behaviour evident in the block samples is not as pronounced.

These findings are as expected and very similar results have been reported by others. Some examples are the classic papers of La Rochelle and Lefebvre (1971) on Canadian Champlain clay, Lacasse et al. (1985) and Lunne et al. (1997a) on Norwegian clays, Hight et al. (1992) on Bothkennar clay from the UK and Tanaka et al. (1996) on Japanese clays.

However there are also significant differences between the individual 54 mm sample results which will be discussed in more detail as follows.

Pore pressure response

As for the stress – strain behaviour there is a clear difference in the development of pore pressure between the block samples and the 54 mm specimens. After an initial rapid increase, the 54 mm samples show a fairly gradual build up in the pore pressure

and beyond axial strain of about 2 %, the increase in pore pressure is very low and in some case there is no further build up. This is due to the sampling induced destructuration of the material structure. In contrast the block samples show a significant increase in pore pressure throughout the tests.

Stress paths – small strain

According to Lunne et al. (1997a) for a “perfect” specimen, pre-peak, in which there is minimum plastic volumetric strain, the initial stress path (plotted in s' , t' space as here) slope will be 1 horizontal to 3 vertical. The block sample specimens exhibit this behaviour confirming the samples have retained their structure and are behaving in an “elastic” manner at low strains. For the 54 mm specimens the initial portion of the stress path is right orientated, as for an overconsolidated material, suggesting small or negative pore pressure. This behaviour is best represented by considering Janbu’s (1976, 1985) pore pressure dilatancy parameter (D), where:

$$D = \frac{\Delta\sigma_m}{\Delta\sigma_d} \quad (5)$$

$$\sigma_m' = \text{mean effective stress} = \frac{\sigma_a' + 2\sigma_r'}{3} \quad (6)$$

$$\sigma_d' = \text{deviator stress} = \sigma_a' - \sigma_r' \quad (7)$$

For the block samples initially $D = 0$ indicating elastic behaviour. For the 54 mm specimens $D > 0$ meaning the soil is behaving in a dilatant manner. Subsequently, when the axial strain exceeds about 0.1%, D becomes negative. This apparent overconsolidation of the 54 mm specimens could be a consequence of compression during sampling.

Stress paths – medium to large strains

When the axial strain exceed about 0.1% the stress paths for the 54 mm samples, compared to that of the block, rapidly become more left orientated ($D < 0$) indicating

some disturbance of the material structure. For the block sample specimens this contractive behaviour continues until critical state conditions are reached and the result is typical of structured lightly consolidated clay.

However subsequently for some of the 54 mm specimens, and in particular the 850-2 series, the direction of the stress paths changes and there is a strong tendency for dilatant behaviour. A small number of other researchers have found similar behaviour, i.e. the apparent reversal of the stress path caused by sampling induced disturbance. These are summarised by Long (2006) and were:

- NGI during a study of the very silty Eidsvold clay (Karlsrud, 1995. Lunne et al., 1997).
- NGI (Lunne et al., 2006) report that similar behaviour can occur with 54 mm diameter (composite) samples of “lean” Drammen clay.
- Seierstad (2000) during a study of another Norwegian marine clay, in this case quick clay from Kvenild near Tiller, just south of Trondheim
- Randolph et al. (1999) proposed a similar hypothesis in order to explain unusual stress paths for soft calcareous sediments.
- Long (2003, 2006) for the Bothkennar laminated facies and for soft laminated clay / silts from central Ireland respectively.

Long (2006) concluded that these effects were due to a combination of densification during sampling and during reconsolidation to in situ stress and can occur especially when the clay content is less than about 40 % and the plasticity index is less than 20 %, as is the case for the clays under study here. For this study, the resulting undrained shear strength (s_u) was always less than that for the block samples. However, from the point of view of practicing engineers, the main implication of

these findings is that s_u and stiffness can be overestimated from laboratory tests on poor samples.

Undrained shear strength

Undrained shear strength (s_u) values from the CAUC tests are plotted on Figure 10a. For the 54 mm samples s_u increases from about 35 kPa at 6 m to 40 kPa at 11 m and 60 kPa at 18 m. There is no clear pattern of significantly higher s_u values for the specimens which dilated. Block sample values are higher, consistent with the shape of the stress – strain and stress paths plots, as discussed above. On average the 850-2 and 850-3 series 54 mm specimens show s_u values closest to those of the block and the 850-1 series show the lowest values. Lines representing material with OCR = 2.5 and 1.0 (range of OCR for block samples, see Figure 8a) have also been plotted on Figure 10a (Ladd and Foot, 1974, see Equation 4). The test results generally follow the expected pattern and are reasonably consistent with OCR values determined from the oedometer tests.

Strain to failure

Values of the strain to failure (ϵ_f) are given on Figure 10b. As expected the block samples show the lowest values, being 0.5 % to 0.7%, with the 54 mm samples showing higher values of the order of 1% to 4%. Six of the 54 mm tests show very high values of greater than 8%. These correspond with those tests that dilated on shearing.

Other parameters obtained from triaxial tests

Data for Skempton's pore pressure coefficient at failure (A_f) and dilatancy parameter D are shown on Figures 10c and 10d respectively. As has been discussed above, Lunne et al. (1997a) suggested that the early part of the conventional (s' , t') stress path plot is dramatically influenced by sample disturbance and proposed that the pore

pressure dilatancy parameter, D , be used to express this effect. They suggested determining D at $2/3$ of the peak shear stress less the initial stress and showed that $D = 0$ (elastic behaviour or zero dilatancy) corresponds to a line with an inclination of 1 horizontal to 3 vertical. For a perfect specimen (except when close to failure) one would expect a minimum slippage between the soil particles and therefore a D value close to zero. For this site block sample values fall close to zero. Some of the other samples show the same tendency as the block samples, but the majority show negative values indicating the onset of contractive behaviour soon after the start of shearing and therefore indicating the samples have been destructured. It would seem that the 850-2 series show the most negative values, with the 850-3 series values being closest to those of the block samples.

Values for A_f are lowest for the block samples. Results for the 54 mm samples show significant scatter with those from the 850-2 series being the greatest.

Failure envelope

A line representing a Mohr-Coulomb strength of effective friction angle $\phi' = 28^\circ$ and effective cohesion $c' = 5$ kPa has also been plotted on Figure 9. Stress paths for all of the specimens, including those which dilate, ultimately fall on this line. This indicates sampling disturbance has only minimal influence on the effective stress strength parameters.

Relative quality of 54 mm samples

As for the CRS tests a detailed assessment of the 54 mm samples was undertaken by comparing average values of a selected number of parameters to the corresponding block sample values. The parameters chosen were again those deemed to be most susceptible to sampling disturbance (Lunne et al. 1997a, Lunne and Long, 2006) namely:

- $\Delta V/V_0$ or $\Delta e/e_0$
- s_u or s_u/σ'_{v0}
- ε_f
- A_f
- D
- Whether sample dilates on shearing or not.

The results of this analysis are presented in Table 6. Each pair of test series, e.g. 850-1-1 and 850-1-2 has very similar rank. This indicates that the influence of testing at different laboratories is not important for triaxial tests and that most of the differences may be accounted for in the different drilling techniques.

Considering the different drilling techniques it would seem that, as has been seen during the discussion of the various parameters, the quality of the 850-2 series are worst. The general impression is that series 850-3 and especially series 850-3-2 are better than series 850-1.

Summary for triaxial tests

Although the block and 54 mm specimens show very significantly different results, there are also important differences between the results from the various 54 mm specimens. For example average s_u for the 54 mm specimens with highest rank is about 78% that measured on the block samples and the 54 mm specimens with the lowest rank gives average values of 90% of the highest. Average ε_f for the highest ranked 54 mm specimen is 2.7 times that of the block average but the lowest ranked 54 mm values is 3.1 times that of the highest.

As was illustrated in Table 5 this is consistent with the best 54 mm specimens falling in the “good to fair” and the worst in the “poor” category.

CONCLUSIONS

In this study fixed piston samples obtained by three different crews using the same sampler and tested at three different laboratories are compared to high quality samples obtained using the Sherbrooke block sampler. The resulting data set provides an excellent basis for evaluating the effects of sampling with standard fixed piston samplers (in this case the NGI / Geonor 54 mm sampler with composite sample tubes). When samples from the same drilling rig were tested in different laboratories, the results are broadly similar suggesting differences between the various data sets is mainly due to drilling techniques rather than laboratory testing procedures.

Block samples were found to be significantly superior to 54 mm specimens, and show substantially different behaviour. For example the block samples yielded p_c' and m values up to 50% higher than those from the 54 mm specimens and M_0 and c_{v0} values which were twice those of the 54 mm samples. Similarly block samples triaxial s_u values were typically 30% higher than those of the 54 mm specimens.

However there were also considerable differences between the 54 mm specimens. For example the lowest ranked series of 54 mm samples had OCR, M_0 and m values of about 80% of the highest ranked series. Undrained shear strength values of the lowest ranked were about 90% of those from the highest ranked series. One of the 54 mm series was clearly the worst. Comparing the drilling and sampling techniques used it would seem that the reasons for these poorest quality samples can be linked to the lack of a completely fixed piston, overcoring and other minor elements of poor practice.

For all the samples, with the possible exception of Series 850-3-2, there appears to be a decrease in quality with depth. For the piston samples this is clearly linked to the full displacement technique used. The deeper the sample the more soil needs to be

displaced and the zone of disturbed soil around the sampler increases. For the block samples it becomes increasingly more difficult to provide a clean base to the borehole and stability of the sides of the borehole with depth. Similar results are shown by Lunne et al. (2006) for block samples from 3 locations.

There is evidence however, particularly from the CAUC test results, that the quality of samples from Series 850-3-2 does not decrease significantly with depth. In this case a hole was pre-augered to just above the sampling location. However it is accepted that augering is still a reasonably high disturbance method. Other drilling methods such as mud rotary should be considered in future studies.

RECOMMENDATIONS FOR GOOD PRACTICE

The results show that it is possible to obtain relatively good samples with the 54 mm sampler with composite sample tubes for normal site investigation purposes. This requires that the procedures outlined in Norsk Geoteknisk Forening (1997) or Statens vegvesen (1987) are carefully followed. Furthermore the current tests indicate that special emphasis should be placed on the following:

- The competence of the drill rig operator is of major importance and he should be provided with information regarding to what use the samples are intended and requirements regarding sample quality in relation to the analyses to be performed in the laboratory.
- In addition to normal good maintenance and cleaning routines for the sampler it is essential to have an arrangement which allows the piston to be kept in a fixed position at all times.
- Overcoring should be avoided.
- Sample cutting should be smooth and continuous and should be fairly rapid (approximately 45 seconds for the 0.8 m samples under consideration here).

This should be followed by a rest period of at least 15 minutes so as to allow pore pressures to equalise somewhat.

- Twisting off the sample should be avoided if possible. Instead the sample should be retracted by a very small amount (1 mm to 2 mm), allowed to rest and then retracted again in gradual increasing intervals.
- Once the sample is retrieved it is necessary to handle and transport it very carefully.

RECOMMENDATIONS FOR A NEW SAMPLER

Given the significant difference between the 54 mm piston and block samples the original decision to abandon use of thin walled steel sample tubes for routine projects in Norway should be reviewed. Future sampling should be with a steel thin walled piston sampler of about 75 mm in diameter, with a sharp cutting edge (of about 6°) similar to that which has been proven to give high quality samples in Japan (JGS, 1995, Tanaka et al., 1996). This will give a much improved area ratio and sample length to diameter ratio. Consideration should also be given to omitting the inside clearance. Broms (1980) and Andresen (1981) described how a large clearance ratio permits swelling of the sample and the opening of fissures and thereby reduces the maximum shear stress. Clayton et al. (1995) concurred with the views of Broms and considered clearance to be a “necessary evil”. Theoretical studies (e.g. Clayton and Siddique, 1999) suggest that by omitting inside clearance tensile strains during sampler penetration will be eliminated and thus sample quality will be improved. In Japan the 75 mm sampler and in the UK the ELE 100 mm sampler has been adopted as standard and both have no inside clearance. Similarly the high quality Laval sampler (La Rochelle et al., 1981) has no inside clearance.

ACKNOWLEDGEMENTS

This project was carried out by the Soil Mechanics, Geology and Tunnel Section at the Technology Department of the Norwegian Public Roads Administration under R&D-project 601369.

REFERENCES

- Andresen, A. and Kolstad, P. (1979). The NGI 54 mm sampler for undisturbed sampling of clays and representative sampling of coarser materials. In Proc. Int. Sym. SOA Current Practice of Soil Sampling, Singapore, 13 - 21.
- Andresen, A. (1981). Exploration, sampling and in-situ testing of soft clay. Soft clay engineering. *Developments in Geotechnical Engineering*: 20, Elsevier, Eds.
- Brand, E.W and Brenner, R.P.
- Berre, T. (1982). Triaxial testing at the Norwegian Geotechnical Institute. *ASTM Geotech. Testing Journal*, **5** (1/2), March / June 1982, 3 - 17.
- Broms, B.B. (1980). Soil sampling in Europe: state of the art. *ASCE, Jnl. Geo. Eng. Div.*, 106, GT1, 65 - 98.
- Brooker, E.W. and Ireland, H.O. (1965). Earth pressures at rest related to stress history. *Canadian Geotechnical Journal*, **2**(1), 1 - 15.
- Clayton, C.R.I and Siddique, A. (1999). Tube sampling disturbance - forgotten truths and new perspectives. *Inst. Civ. Eng., Gotech. Eng.*, 137, July, 127 - 135.
- Hight, D.W., Boese, R., Butcher, A.P., Clayton, C.R.I. and Smith, P.R. (1992). Disturbance of Bothkennar clay prior to laboratory testing. *Géotechnique*, **42** (2), 199 - 217.
- Janbu, N. (1970). Grunnlag i geoteknikk. *Tapir Forlag*, Trondheim, Norway. (In Norwegian).

- Janbu, N. (1976). Soils under cyclic loading. *Proc. BOSS Conf., Trondheim, 2*, 373 – 385.
- Janbu, N. (1985). Soil models in offshore engineering. 25th Rankine Lecture, *Géotechnique*, 35 (3), 241 – 281.
- JGS (1995). Standards for soil sampling, JGS 1221 to 1224 and 1231, published by the *Japanese Geotechnical Society*.
- Karlsrud, K. (1995). Prøveforstyrrelse – siltig leire. *Proceedings Norwegian Geotechnical Society Geoteknikkdagen*, Norwegian Geotechnical Society, October, 27.
- Kleven, A., Lacasse, S. and Andersen, K.H. (1986). Foundation engineering criteria for gravity platforms. Soil parameters for offshore foundation design. Part II, *Norwegian Geotechnical Institute Report 40013-34*, April.
- Lacasse, S, Berre, T and Lefebvre, G. (1985). Block sampling of sensitive clays. In *Proc. 11th ICSMFE, San Francisco, 2*, 887 - 892.
- Lacasse, S. (1995). Stress – strain behaviour: Importance of mode and rate of load application for engineering problems. *Proceedings Pre-failure Deformation of Geomaterials*, Shibuya et al. (eds.), Balkema, 887 – 907.
- Ladd, C.C. and Foott, R. (1974). New design procedures for the stability of soft clays. *Jnl. of the Geo. Eng. Div., ASCE*. 100, GT7, 763 - 786.
- Landon, M.M., DeGroot, D.J. and Sheehan, T.C. (2007). Non-destructive sample quality assessment using shear wave velocity, *ASCE, J. Geotech. and Geoenviron. Engrg.*, 133, 4, 424-432.
- La Rochelle, P. and Lefebvre, G. (1971). Sample disturbance in Champlain clays. In *ASTM STP 483, Sampling in Soil and Rock*, ASTM, 143 - 163.

- La Rochelle, P., Sarrailh, J., Tavenas, F, Roy, M and Leroueil, S (1981). Causes of sampling disturbance and design of a new sampler for sensitive soil. *Can. Geo. Jnl.*, 18, 52 - 66.
- Lefebvre, G. and Poulin, C. (1979). A new method of sampling in sensitive clay. *Canadian Geotechnical Journal*, Vol. 16, 226 - 233.
- Leroueil, S. and Hight, D.W. (2003). Behaviour and properties of natural soils and soft rocks. *Proceedings International Workshop on Characterisation and Engineering Properties of Natural Soils ("Natural Soils 2002")*, NUS Singapore, December. Eds. Tan, T.S. et al. Published by Balkema, Vol. 1, pp 29 - 254.
- Long, M. (2003). Sampling disturbance effects in soft laminated clays. *Proc. Inst. Civ. Eng. Gotech. Eng.*, 156, October, 213 – 224.
- Long, M. (2006). Sampling disturbance effects on medium plasticity clay / silt. *Proc. Inst. Civ. Eng. Gotech. Eng.*, 159, April, 99 - 111.
- Lunne, T., Berre, T. and Strandvik, S. (1997a). Sample disturbance effects in soft low plasticity Norwegian clay. *In Proceedings Symposium on Recent Developments in Soil and Pavement Mechanics*, Rio de Janeiro, June 1997, Balkema, 81-92.
- Lunne, T., Robertson, P.K. and Powell, J.J.M. (1997b). Cone penetration testing in geotechnical practice. *Spon Press*, London.
- Lunne, T., Berre, T. Andersen, K.H., Strandvik, S. and Sjursen, M. (2006). Effects of sample disturbance and consolidation procedures on measured shear strength of soft marine Norwegian clays. *Canadian Geotechnical Journal*, 43, 726 - 750.
- Lunne, T. and Long, M. (2006). Review of long seabed samplers and criteria for new sampler design. *Marine Geology*. Elsevier Press. 226 (1-2), 145 – 165.
- Norsk Geoteknisk Forening (NGF). (1997). Veiledning for prøvetaking. *Melding Nr. 11*, Utgitt 1997. (In Norwegian).

- Randolph, M.F., Watson, P.G. and Fahey, M. (1999). Site characterisation and foundation design in soft sediments. *In Proceedings of the International Conference on Offshore and Nearshore Geotechnical Engineering*, Navi Mumbai, India, 2- 3 Dec., Edited by Singh and Lacasse, 35 - 47.
- Seierstad, H-H. (2000). Prøveforstyrrelse i leire vurdering av Ø75 mm stempelprøvetaker. *Diploma thesis, NTNU Trondheim*, Autumn, 2000.
- Sandbækken, G., Berre, T. and Lacasse, S. (1986). Oedometer testing at the Norwegian Geotechnical Institute. *In ASTM Sp. Tech. Pub. 892*, Philadelphia, Penn.
- Statens vegvesen (Norwegian Public Roads Administration). (1987). Feltundersøkelser ("Site investigations"). *Håndbok 015*, 2 opplag (In Norwegian).
- Tanaka, H., Sharma, P., Tsuchida, T. and Tanaka, M. (1996). Comparative study on sample quality using several different types of samplers. *Soils and Foundations, Japanese Geotechnical Society*, Vol. 36 (2), 67 - 68.

TABLES

Table 1. Summary of field observations during drilling and sampling

Item	Crew 1	Crew 2	Crew 3
Weight of drill rig (t)	2.5	4.5 to 5	7.5
Number in crew	1	1	2
Upward movement of piston rods (cm)	0 to 5. Average 3.3	1 to 5. Average 3.3	0
Sample cutting time (secs.)	40 to 45	15 to 20	40 to 45
Over coring (cm)	1 to 2	2 to 8	Less than 1
Twisting off sample	None	None	All twisted off
Resting time (mins)	10	5 to 35. Average 13.	3 to 40. Average 18.
Retraction time	Immediate 5 cm retraction then 2 min rest	Slow continuous	Slow continuous
Others	<p>Medium quality sample tubes (tubes not new, generally clean, occasional slight surface damage). All cutting edges sharp.</p> <p>Damage to O-ring and seals in cutting head for first 4 samples in Series 850-1-1. Screwdriver used to cut sample. Sample left hanging from rig while removing cutting edge causing tensile strain.</p>	<p>Medium quality sample tubes (tubes not new, occasional slight surface damage). Some sample tubes not clean. All cutting edges sharp. Cutting edge left resting on rig bottom clamps before sampling. Occasionally rubber piston drawn out of cylinder. Recovered samples kept in drill rod storage box with engine running.</p>	<p>Good quality sample tubes (i.e. effectively new). All cutting edges sharp. Knife used to cut soil sample. Occasional cross sectional change due to tensile strain at end of sample. Observed to maximum length of 2 diameters.</p>

Table 2. Summary of triaxial and oedometer test procedures

Item	Lab. 1	Lab. 2	Lab. 3
<i>CAUC tests</i>			
Consolidation time (hours)	48	48	16 – 20
Strain rate (% per hour)	2	0.7	2
Outer filter paper – strips	Yes	Yes	No
Back pressure (kPa)	~ 300	~700	In situ pore pressure
<i>CRS tests</i>			
Strain rate (% per hour)	2	0.5 – 0.7	2
Unloading - reloading	No	Yes	No

Table 3. Summary of unconfined compression tests

	850 1-1	Rank Ing ³	850 1-2	Rank ing	850 2-1	Rank ing	850 2-2	Rank ing	850 3-1	Rank ing	850 3-2	Rank ing
s_u^1 (kPa)	30.3	1	22.8	6	27.5	3	20.9	5	29.3	2	26.2	4
SD ² on s_u (kPa)	1.22	6	0.64	4	0.42	1	0.66	5	0.59	3	0.58	2
Avg. ϵ_f^1 (%)	7	1	11.5	6	10.33	5	9.2	3	7.38	2	9.78	4
No. of tests with $\epsilon_f \geq$ 15 %	0 of 4	2	4 of 8	5	0 of 6	1	7 of 12	6	1 of 9	4	1 of 10	3
Average ranking ⁴		2.5		5.3		2.5		4.8		2.8		3.3

Notes: 1 = average for series, 2: SD = standard deviation, 3: Individual rank of between 1 (best) and 6 (worst) given for each parameter, 4: Average ranking than calculated by calculating average of each individual rank.

Table 4. Assessment of relative quality of CRS tests on 54 mm samples

	850-1-1	Rank	850-1-2	Rank	850-2-1	Rank	850-2-2	Rank	850-3-1	Rank	850-3-2	Rank	Block
ε_{v0} (%)	4.78	4	4.4	2	3.55	1	5.93	6	4.58	3	4.78	4	2.95
$\Delta e/e_0$	0.096	5	0.085	2	0.07	1	0.118	6	0.091	3	0.094	4	0.058
M_0 (kPa)	4.7	6	5.15	4	5.44	1	5.08	3	4.9	5	4.6	2	11.6
m	18.9	4	17.9	6	20.6	2	20.6	2	18.4	5	18.4	1	30.4
Janbu possible?	3 of 4	4	4 of 4	1	4 of 6	5	2 of 6	6	5 of 5	1	5 of 5	1	3 of 3
OCR (Janbu)	1.99	1	1.99	1	1.95	3	1.6	5	1.83	4	1.59	6	2.09
OCR (Casa)	1.67	1	1.47	3	1.43	4	1.2	6	1.61	2	1.35	5	1.95
c_v at σ'_{v0} (m ² /yr)	16.4	1	14.3	3	12.5	5	10.8	6	13.2	4	13.2	2	30.3
Average rank	3.25		2.75		2.75		5.00		3.38		3.13		

Notes: See table 3 for explanation of ranking system

Table 5. Consequences of sample disturbance on soil design parameters (Lunne and Long, 2006)

Sample quality class	s_u (CAUC) % of perfect sample	M (σ'_{v0} to p'_c range) % of perfect sample
Very good to excellent	> 95	> 90
Good to fair	75 – 95	60 – 90
Poor	< 75	40 – 60
Very poor	< 50	< 40

Table 6. Assessment of relative quality of CAUC tests on 54 mm samples

	850-1-1	Rank	850-1-2	Rank	850-2-1	Rank	850-2-2	Rank	850-3-1	Rank	850-3-2	Rank	Block
ε_{v0} (%)	2.15	1	2.49	2	3.88	6	2.75	4	3	5	2.64	3	1.71
$\Delta e/e_0$	0.045	1	0.051	2	0.078	6	0.057	4	0.06	5	0.053	3	0.034
s_u (kPa)	42.4	5	41.3	6	44.6	3	46	1	46	1	44.4	4	59.3
ε_f (%)	3.55	4	2.13	2	5.2	6	4.63	5	3.3	3	1.7	1	0.63
s_u/σ'_{v0}	0.372	1	0.355	2	0.312	5	0.321	6	0.349	3	0.336	4	0.403
A_f	0.72	2	0.77	4	1.06	6	0.81	5	0.64	1	0.75	3	0.38
D	-0.29	5	-0.19	3	-0.5	6	-0.22	4	-0.11	2	-0.09	1	-0.09
Dilation	1 of 4	3	0 of 4	1	1 of 6	3	3 of 6	6	1 of 5	3	0 of 5	1	0 of 3
Average rank	2.75		2.75		5.13		4.38		2.88		2.50		

Notes: See table 3 for explanation of ranking system

NOTATION

A_f	Skempton's pore pressure coefficient (at peak shear stress) related to change in shear stress
B_q	piezocone pore water pressure coefficient = $(u_2 - u_0) / q_{net}$
c'	effective cohesion
c_v	coefficient of consolidation (h / v refer to horizontal and vertical directions)
D	dilatancy parameter
e_0	initial void ratio
f_s	piezocone sleeve friction
I_p	plasticity index
K_0	co-efficient of earth pressure at rest = $\sigma'_{h0} / \sigma'_{v0}$
M	constrained modulus in oedometer test = $\delta\sigma'_v / \delta\varepsilon$
m	modulus number
p'_c	preconsolidation pressure
q_t	corrected piezocone cone end resistance
q_{net}	piezocone net end resistance = $q_t - \sigma_{v0}$
R_f	piezocone friction ratio = $f_s * 100 / q_t$
s'	mean effective stress = $(\sigma'_a + \sigma'_r) / 2$
s_u	undrained shear strength
S_t	sensitivity
t'	shear stress = $(\sigma'_a - \sigma'_r) / 2$
u	pore pressure
u_0	in situ pore water pressure
u_2	pore pressure measured by piezocone
V_0	initial volume

w	natural water content
w _L	liquid limit
Δe	change in void ratio
ΔV	change in volume
ε _a	axial strain
ε _f	strain at peak in unconfined compression or triaxial test
ε _{v0}	normalised volume change = ΔV/V ₀
φ'	effective friction angle
γ _b	bulk unit weight
σ' _a	axial effective stress in triaxial test
σ' _d	deviator stress = $\sigma'_a - \sigma'_r$
σ' _{h0}	in situ horizontal effective stress
σ' _m	mean effective stress = $\frac{\sigma'_a + 2\sigma'_r}{3}$
σ' _r	radial effective stress in triaxial test
σ _v	total vertical stress
σ' _v	vertical effective stress
σ _{v0}	in situ vertical total stress
σ' _{v0}	in situ vertical effective stress

FIGURE CAPTIONS

Fig. No.	Caption	File / Ref.
1	CPTU test results	DELL/Papers/ASCE/RVII/Figures/CPTUqtRfu2Bq.grf
2	(a) NGI 54 mm composite sample tubes, (b) modified auger with flat and sharp end for pre-drilling to sampling level and (c) sketch of 54 mm sampler cutting head	Photos by Nouri DELL/Papers/ASCE/RVII/Figures/Samplerdetails.grf
3	Basic index test results	DELL/Papers/ASCE/RVII/Figures/Basics.grf
4	Plasticity chart	DELL/Papers/ASCE/RVII/Figures/AtterbergB+W.grf
5	Undrained shear strength (s_u) from index testing	DELL/Papers/ASCE/RVII/Figures/suindextesting.grf
6	CRS oedometer tests at about 6.3 m	DELL/Papers/ASCE/RVII/Figures/CRS6.3msummary.grf
7	Sample quality for (a) CRS tests and (b) oedometer tests	DELL/Papers/ASCE/RVII/Figures/Oedandtriaxquality.grf
8	Various parameters derived from CRS tests	DELL/Papers/ASCE/RVII/Figures/Oedparameters.grf
9	CAUC triaxial tests at about 11.3 m	DELL/Papers/ASCE/RVII/Figures/CAUC11.3msummary.grf
10	Various parameters derived from CAUC tests	DELL/Papers/ASCE/RVII/Figures/Triaxparameters.grf

Figures for paper by Long, El Hadj and Hagberg on Quality of conventional fixed piston samples of Norwegian soft clay

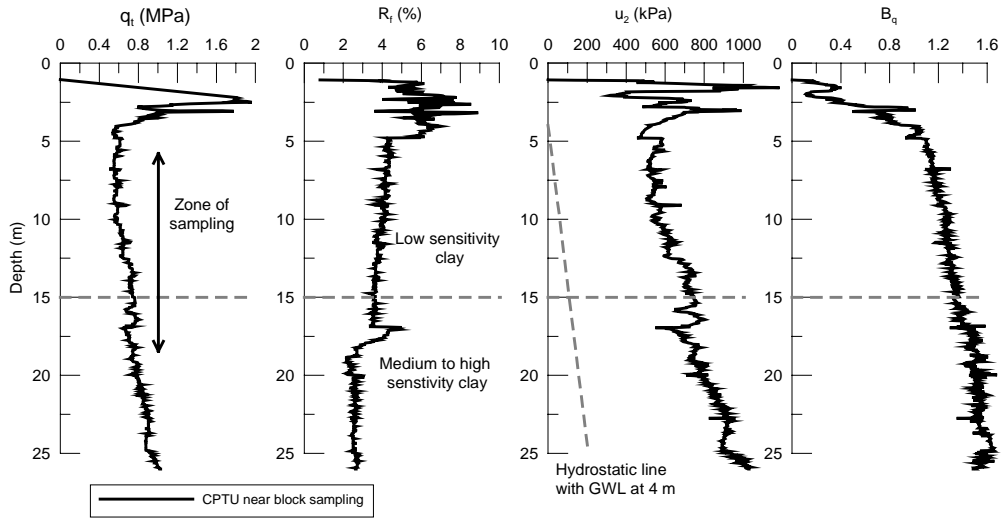


Fig. 1. CPTU test results

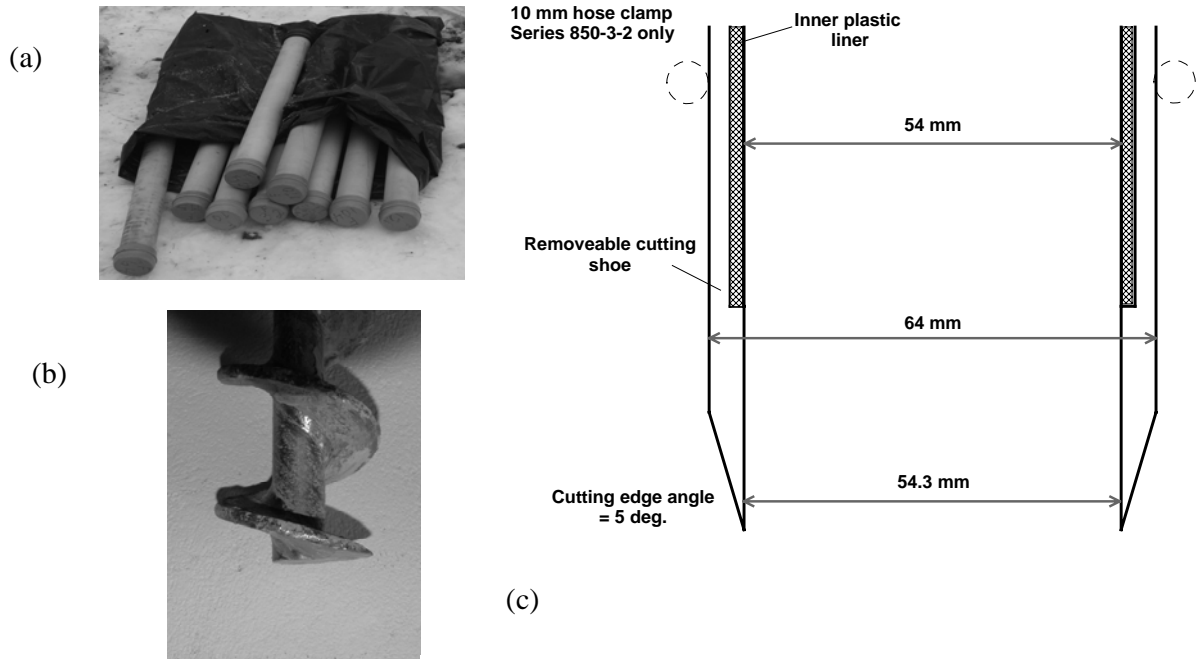


Fig. 2. (a) NGI 54 mm composite sample tubes, (b) modified auger with flat and sharp end for pre-drilling to sampling level and (c) line drawing of sampler cutting edge.

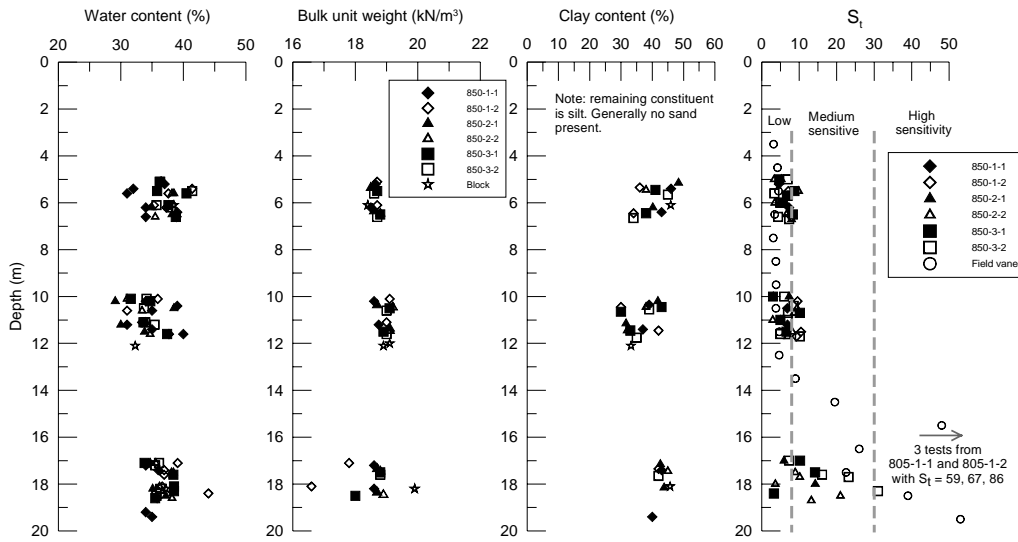


Fig. 3. Basic index test results

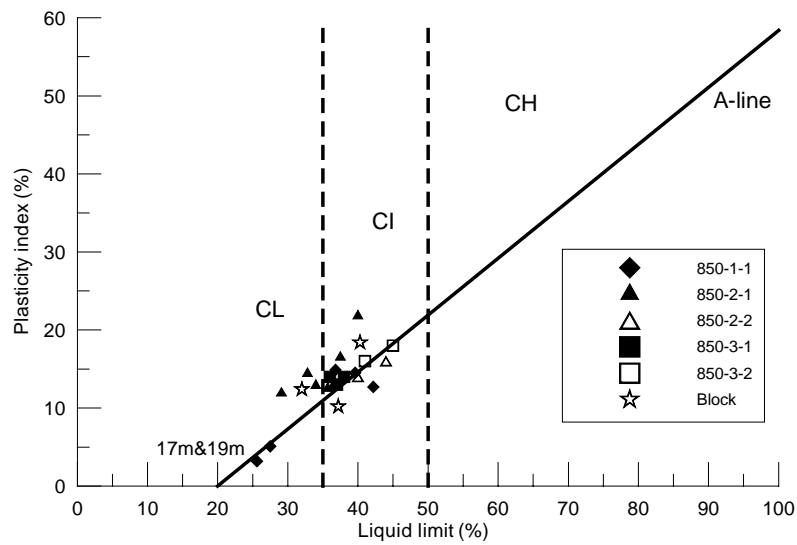


Fig. 4. Plasticity chart

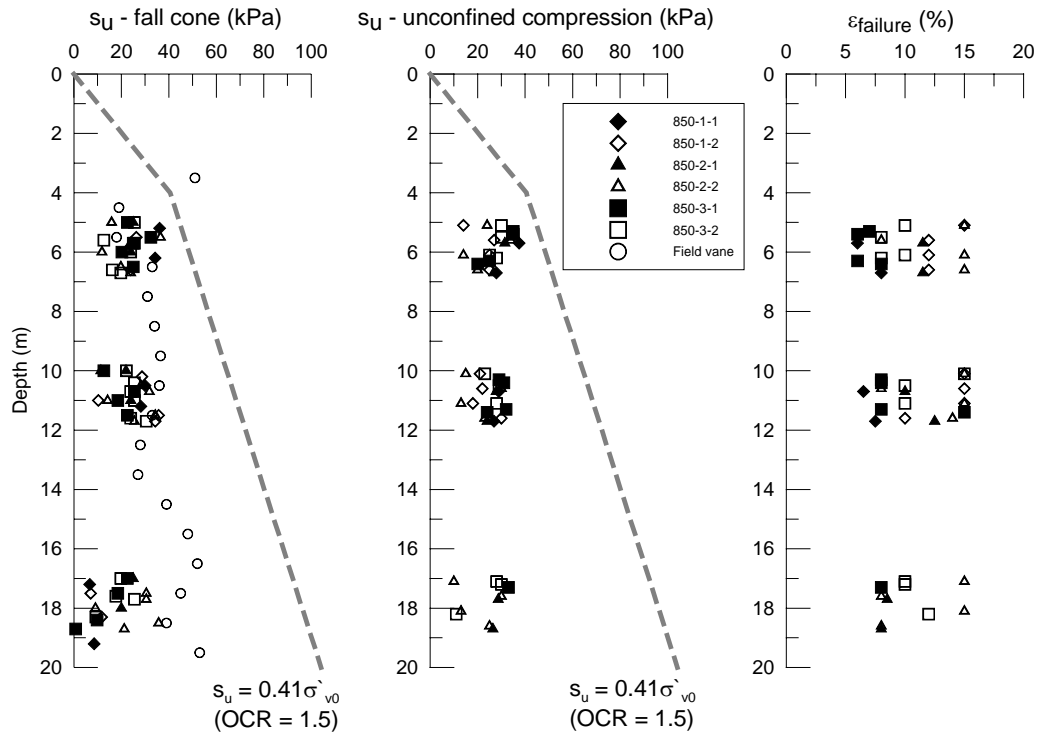


Fig. 5. Undrained shear strength (s_u) from index testing, (a) fall cone, (b) unconfined compression and (c) strain to failure in unconfined compression test

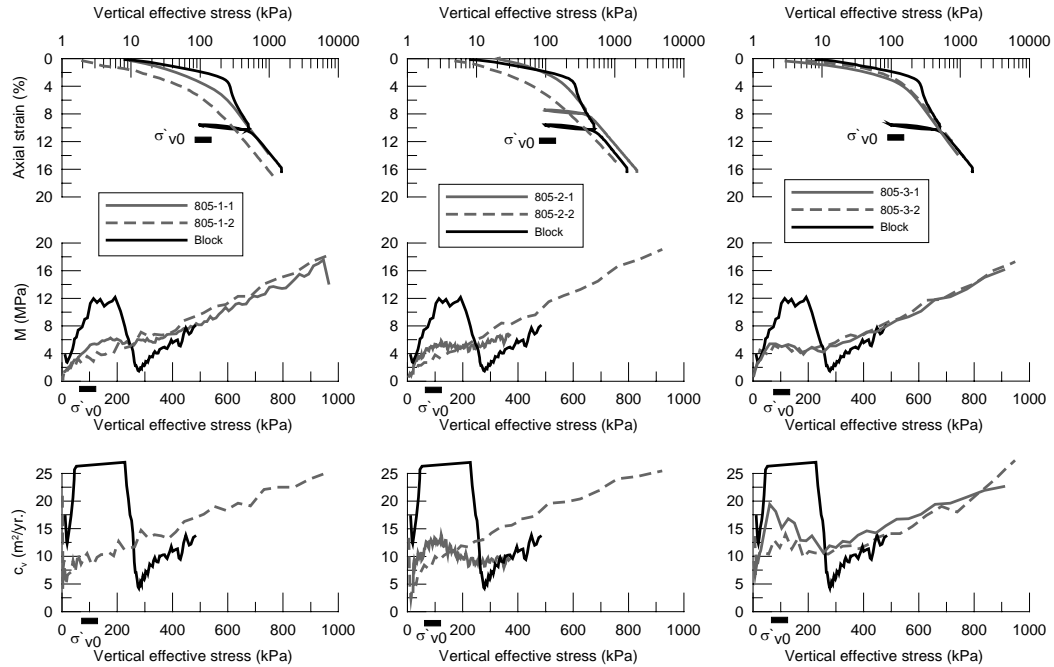


Fig. 6. CRS oedometer tests at about 6.3 m

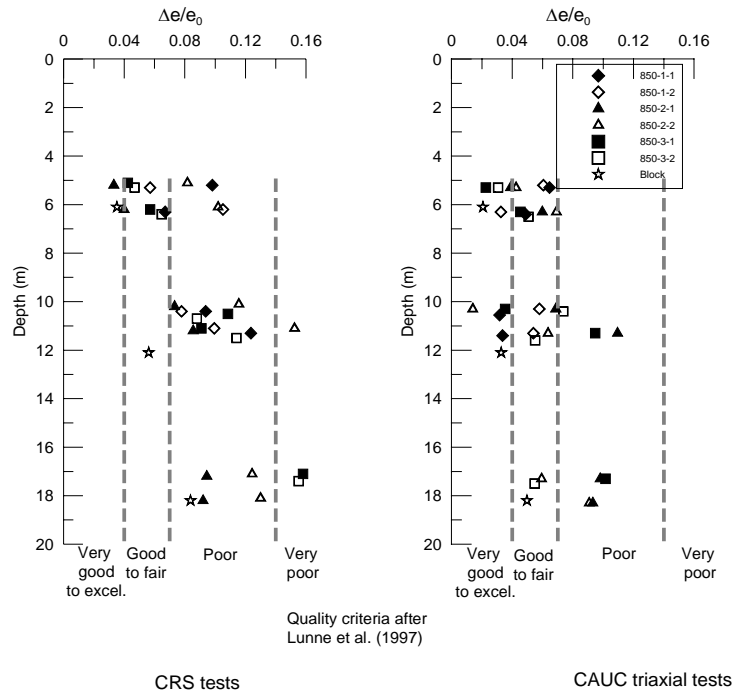


Fig. 7. Sample quality for (a) CRS oedometer tests and (b) CAUC triaxial tests

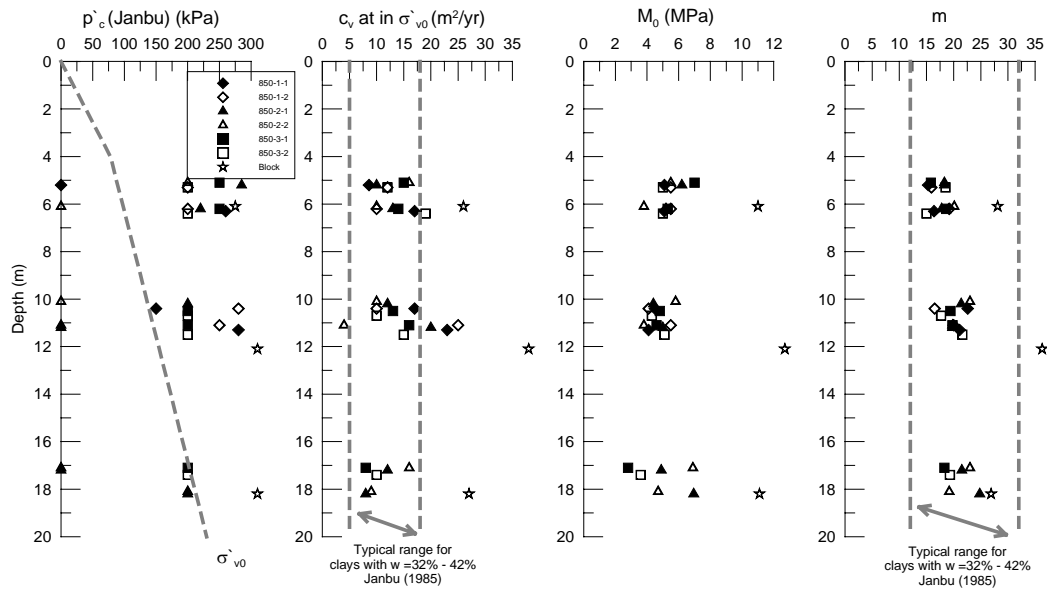


Fig. 8. Various parameters from CRS tests. (a) preconsolidation pressure, (b) coefficient of consolidation, (c) constrained modulus and (d) modulus number

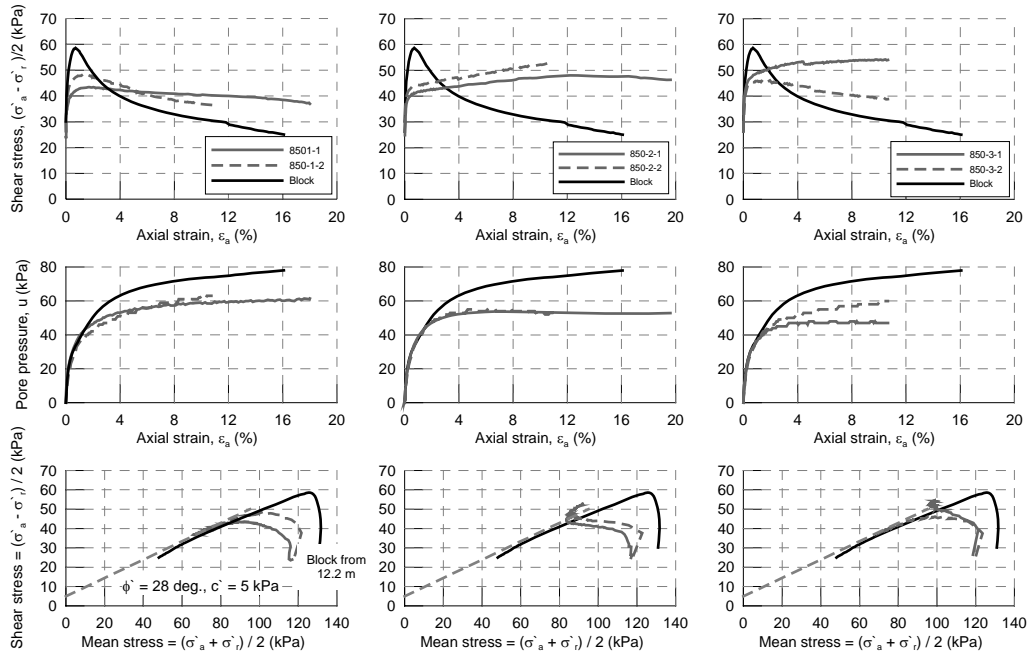


Fig. 9. CAUC triaxial tests on piston tubes samples at about 11.3m with companion block sample at 12.2 m

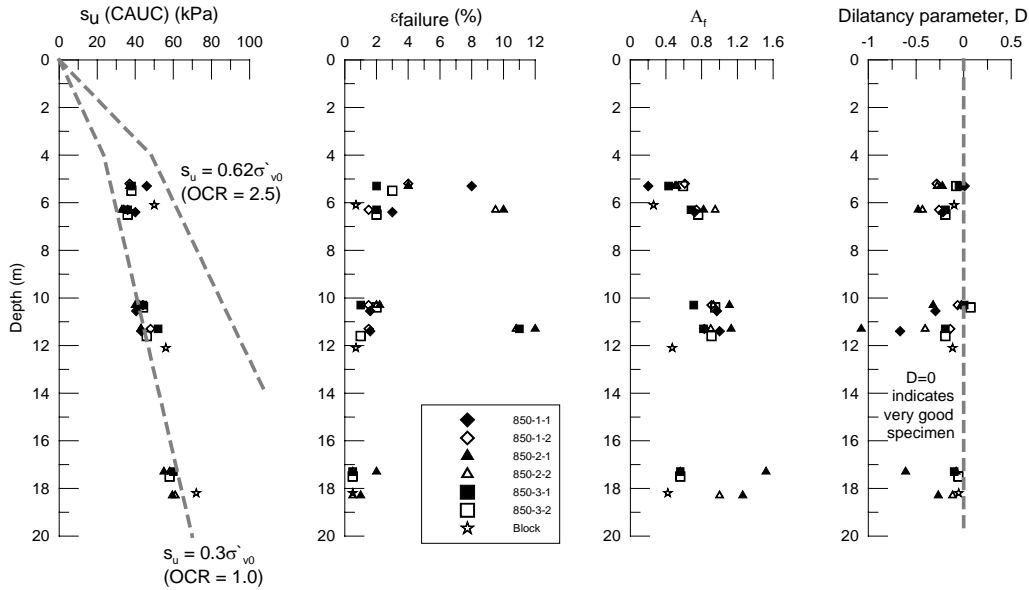


Fig. 10. Various parameters derived from CAUC tests. (a) undrained shear strength, (b) strain to failure, (c) pore pressure parameter at failure and (d) dilatancy parameter