Sample disturbances in block samples on low plastic soft clays

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ABSTRACT
The issue of sample disturbance is essential with regards to determining reliable and representative parameters for low plastic soft clays. Block sampling is considered to be the best sampling method to achieve high quality samples in soft clays. This study confirms this but also illustrates that it can be challenging to obtain excellent quality samples of low plastic soft clays even with a block sampler. The block sampler reduces sampling and handling induced disturbance to a minimum but cannot eliminate the total stress relief at sampling and the subsequent reduction of the effective stresses. This paper presents an extensive set of results from a testing programme carried out on block samples on low plastic soft clays from six different sites around central Norway. The results confirm that block sampling in general gives high quality samples in these low plastic brittle clays but they also illustrate that the quality tends to go down as the sampling depth increases. Hence there is still a challenge connected to high quality sampling at large depths, and sampling technique, sample storage and handling should be further addressed to reduce this.

Keywords: sample disturbance, sample quality, stress relief, sensitive soft clays, block sampling

1 INTRODUCTION

The applicability of engineering parameters for geotechnical design is linked to the quality of soil sampling and testing. Over the years, significant development has been made to improve sampling techniques. Despite this, sampling of low plastic soft clays remains challenging. The literature, e.g., Berre et al. (1969), La Rochelle and Lefebvre (1970), Bjerrum (1973), Leroueil et al. (1979), Lacasse et al. (1985), Nagaraj et al. (1990), Hight et al. (1992), Lunne et al. (1997), Tanaka (2000), Nagaraj et al. (2003), Ladd and DeGroot (2003), Leroueil and Hight (2003) and Karlsrud and Hernandez-Martinez (2013), Gylland et al. (2013), Amundsen et al. (2015a) and (2015b), confirms that low plastic soft clays such as Norwegian clays are prone to sample disturbance, especially when sampled using tube samplers. On the contrary, block sampling in such materials is considered to be a relatively gentle approach. In return, a more realistic soil behaviour can be captured in the laboratory, as illustrated in Figure 1 for a low plastic sensitive clay sample (Klett clay). It is believed that block sampling is among the best methods of collecting high quality samples of soft clays.

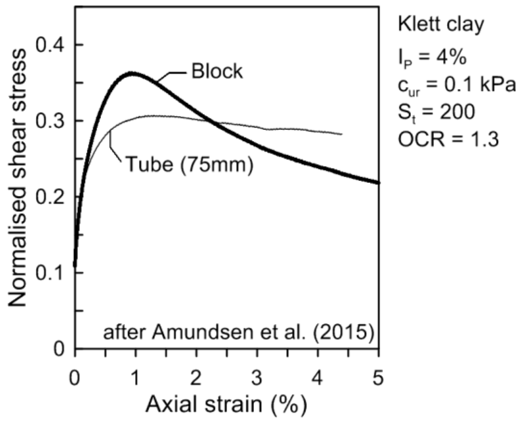


Figure 1 Illustration of sampling induced disturbances in Klett clay (Amundsen et al., 2015b). Here I_p refer to the plasticity index, c_{ur} is the remoulded shear strength measured using the Swedish fall cone, S_t is the sensitivity and OCR is the over consolidation ratio.

However, even block samples may fail to capture the true and unique response of low plastic clays if they are not sampled and handled properly. For instance, stress relief, transportation effects, storage time and testing procedures may lead to inaccurate response, e.g., Hvorslev (1949), Skempton and Sowa (1963), Ladd and Lambe (1963), Leroueil and Vaughan (1990) and Hight et al. (1992). This is illustrated in Figure 2 where a single block sample was tested by two different laboratories with a time difference of 4.5 hours, due to transportation and delayed testing. Despite similar testing procedures, the odometer results such as the preconsolidation stress (σ_c') and the constrained modulus (M) were found to be far lower for the sample (Lab 2) stored for 4.5 hours, see Figure 2.

For low plastic soft clays, the issue of sample disturbance is yet to be fully addressed. The reason could be that block samples generally give a better response than routine tube sampling. This observation leads to some interesting questions; to what degree is block sampling free from sample disturbances regardless of soil type? What should be the correct reference to distinguish a representative soil sample from a poor quality sample?

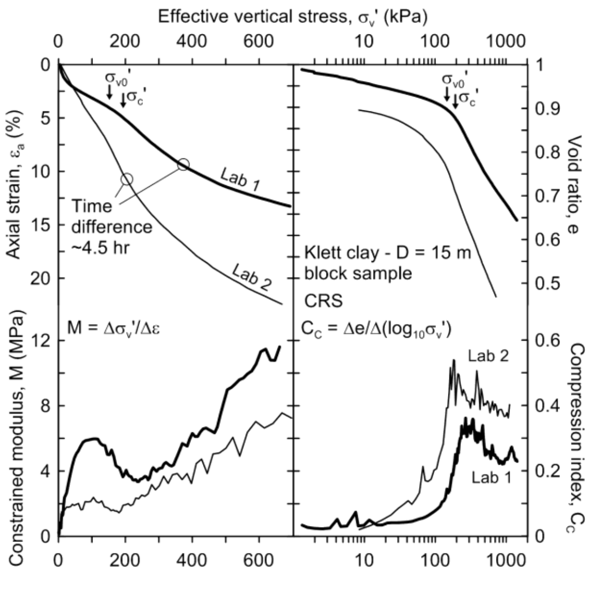


Figure 2 Non-unique response from a single block sample from Klett tested by two different laboratories (Amundsen et al., 2015a).

These questions are examined in this paper using six low plastic soft clays from six different sites in central Norway. In doing so, the paper presents data from 50 mm diameter Constant Rate of Strain (CRS) oedometer tests on specimens taken from block samples with 160 mm and 250 mm in diameter. The results are discussed in this paper in light of existing sample quality assessment methods and the factors that may influence their sample quality.

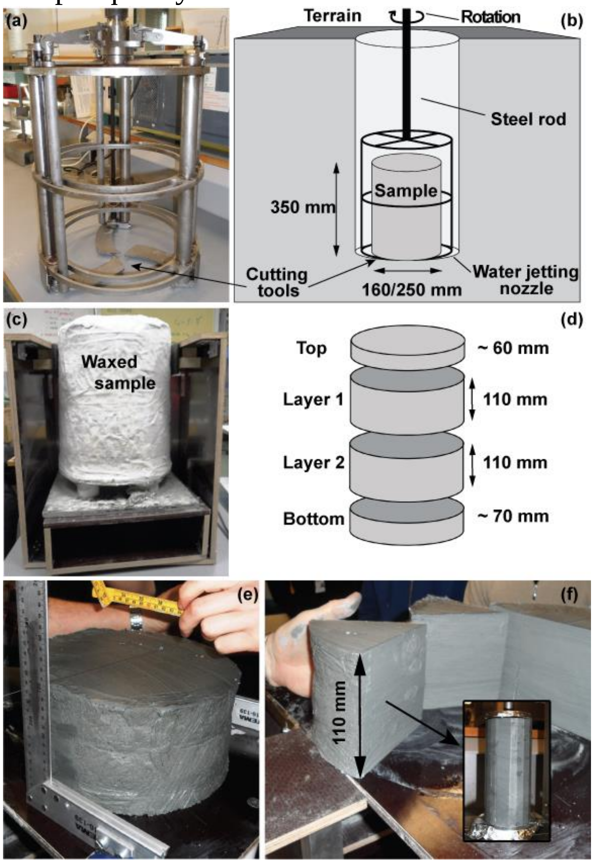


Figure 3 (a) Sherbrooke block sampler at NTNU, (b) schematic view of a block sample being carved, (c) waxed sample, (d) schematic view of a sliced sample, (e) a block sample slice and (f) a piece of clay from block sample (photo: Amundsen).

2 BLOCK SAMPLING AND SAMPLING DISTURBANCE

The samples in this study were taken by two block samplers, an original Sherbrooke (250 mm) (Lefebvre and Poulin, 1979) and a downsized Sherbrooke block sampler (160 mm) developed at NTNU.

The Sherbrooke block samplers do not use a sampling tube, but cores out an annulus around the block of soil to be sampled, Figure 3b. The cutting knives are shown in Figure 3a and b. When the sample is extracted from the ground, it may be waxed and stored or trimmed and tested directly after sampling, shown in Figure 3c, d and f.

Table 1 Indicators and methods of sample quality estimation from literature (Amundsen et al., 2015b).

Year	Method	Parameter	"Very good to excellent" quality	"Very poor" quality
Triaxial and oedometer tests:				
1979-1988	Volumetric strain (ε_{v0}) at *in situ* effective stress (σ_{v0}') (Andresen and Kolstad, 1979), (Lacasse and Berre, 1988)	ε_{v0}	<1%	>10%
1996	Specimen Quality Designation (SQD) (Terzaghi et al., 1996)	ε_{v0}	<1%	>8%
1997	Change in void ratio ($\Delta e/e_0$) (Lunne et al., 1997), which depends on the overconsolidation ratio (OCR)	$\Delta e/e_0$	<0.04(OCR 1-2) <0.03(OCR 2-4)	>0.14 OCR 1-2) >0.10(OCR 2-4)
2013	Oedometer stiffness ratio (Karlsrud and Hernandez-Martinez, 2013)	M_0/M_L	>2.0	<1.0
Uniaxial compression tests:				
1979	Strain at failure (ε_{vf}) in an unconsolidated and undrained (UU) test on soft clay (Andresen and Kolstad, 1979)	ε_{vf} (UU)	3-5%	10%
1980	Unconsolidated and undrained shear strength, s_u (UU), measured in the laboratory (Ladd et al., 1980), (Ladd and DeGroot, 2003)	s_u (UU)	Relative assessment based on information about stress history and predicted strength using SHANSEP	
Suction and shear wave velocity measurements:				
1963-2002	Residual effective stress (σ_s') and the effective stress for a "perfect sample" (σ_{ps}') (Ladd and Lambe, 1963), (Hight et al., 1992), (Ladd and DeGroot, 2003)	σ_s'/σ_{ps}'	≈0.25-0.50 (OCR>1.5) ≈0.05-0.25 (OCR<1.5)	
1996-2000	Soil suction (u_r) (Tanaka et al., 1996), (Tanaka, 2000)	u_r/σ_{v0}'	≈ 1/5 to 1/6	
2007	Shear wave velocity (V) (Landon et al., 2007), V_{vh} is measured in the field and V_{SCPTU} is from SCPTU.	V_{vh}/V_{SCPTU}	≥0.60	<0.35
2010	Combination of normalized shear wave velocity (L_{vs}) and normalized soil suction (L_u) (Donohue and Long, 2010)	L_{vs} L_u	L_{vs} < 0.65 L_u < 0.4	L_{vs} > 0.8 L_u > 0.6
1985-2014	Radiography (Ladd and DeGroot, 2003)	Visual identification of sample disturbance.		

Soil disturbance can occur during sampling, transportation and storage, as well as during handling and preparation before testing. The mechanisms related to soil disturbance are stress changes, mechanical disturbance, changes in water content, void ratio and pore water chemistry.

DeGroot et al. (2005) pointed out that the most important effect of sample disturbance in soft clay is soil destructuring, which is accompanied by a significant reduction in the effective stress. The stress relief is unavoidable and its impact depends on the sampling depth and soil properties.

Table 1 provides an overview over different indicators that have been proposed in the literature. Of these, only two methods are used in Norway and they are briefly discussed below.

2.1 *Change in the void ratio, $\Delta e/e_0$*

The change in sample void ratio (Δe), caused by reapplying the in situ effective stress (σ_{v0}'), is recognized as a useful indicator of sample quality. Lunne et al. (1997) proposed this criterion for sample quality evaluation using the $\Delta e/e_0$ value, where e_0 is the in situ void ratio of a soil, as indicated in Table 2. The criterion is based on triaxial tests on a medium plastic soft clay (I_P = 14-20%) from Lierstranda with an assumption that block samples give the best sample quality compared to piston samples. This is discussed in detail by Amundsen et al. (2015a).

2.2 *Oedometer stiffness ratio, M_L/M_0*

The ratio M_0/M_L has been proposed as a new sample quality evaluation criterion by

Karlsrud and Hernandez-Martinez (2013). The maximum constrained modulus in the overconsolidated stress range (M_0) and the minimum constrained modulus after preconsolidation stress (M_L) show the effect of sample disturbance, as illustrated in Figure 4. The sample disturbance causes a reduction in the M_0 modulus and an increase in M_L due to a denser soil structure caused by a large volumetric change during reloading.

Table 2 Sample quality assessment on basis of $\Delta e/e_0$ (Lunne et al., 1997) and M_0/M_L (Karlsrud and Hernandez-Martinez, 2013) values from oedometer tests.

Sample quality	$\Delta e/e_0$ OCR 1-2	$\Delta e/e_0$ OCR 2-4	Ratio M_0/M_L
1 - Very good to excellent	<0.04	<0.03	>2
2 - Good to fair	0.04-0.07	0.03-0.05	1.5-2
3 - Poor	0.07-0.14	0.05-0.10	1-1.5
4 - Very poor	>0.14	>0.10	<1

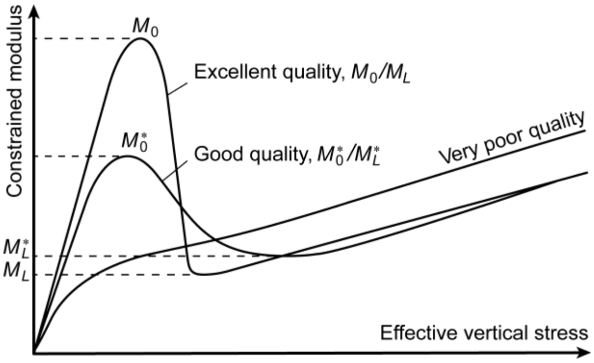


Figure 4 Definition of constrained modulus relationships from oedometer tests (Amundsen et al., 2015b).

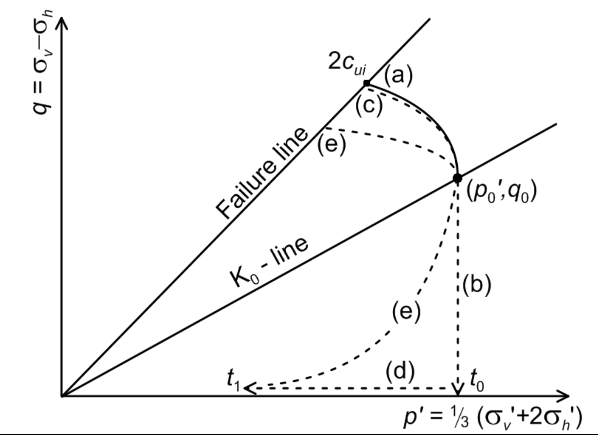
2.3 Stress relief

Stress relief of the sample refers to the undrained removal of the in-situ stresses during sampling and extraction from its parental soil deposit. Due to stress unloading, the clay will have a tendency to swell. If the swelling is prevented, as in undrained unloading, negative pressure, or suction, (u_k) will develop in the pore water. The suction will result in additional effective stresses in the sample, which is isotropic. Therefore, the magnitude and the nature of the effective stresses in the soil samples are different from the in-situ condition. The concept of stress relief in a saturated clay block sample, with Skempton's pore pressure parameter $B=\Delta u/\Delta\sigma=1.0$, is schematically presented in Table 3.

The block sample is removed from its in-situ conditions, shown in Table 3(a), to an isotropic state, $\sigma_h=\sigma_v=0$ (b). When the sample is reconsolidated and sheared (c) to failure immediately after unloading (t=0, no storage time), the undrained shear strength (c_u) should be close to the in-situ strength (c_{ui}). This is illustrated in experimental results by Skempton and Sowa (1963) on a remoulded medium plastic clay, see Figure 5. A small reduction in negative pore pressure during "sampling" was observed, which had reduced the undrained shear strength by about 1.5% compared to the "ground" sample.

Table 3 Sampling induced stress changes.

(a) In situ σ_{v0}; u_0; σ_{h0}	$\sigma_{v0}' = \sigma_{v0} - u_0$ $\sigma_{h0}' = \sigma_{h0} - u_0 = K_0' \sigma_{v0}'$ $p_0 = 1/3(\sigma_{v0} + 2\sigma_{h0})$ $p_0' = p - u_0$
(b) Sampling 0; u_k; 0 p'; p'	Undrained, ΔV=0 $u_k = -1/3(\sigma_{v0}' + 2\sigma_{h0}')$ $p' = -u_k$ and $p = 0$
(c) Test (t = 0 or t_0) Cons.: σ_{v0}'; 0; σ_{h0}' Failure: σ_v; u; σ_h	No swelling, ΔV=0 Consolidation: $\Delta V \approx 0 \rightarrow$ good quality Undrained shear: $c_u \approx c_{ui}$
(d) Stored block sample (t > 0 or t_1)	Sample disturbance due to the loss of suction $t_1 \rightarrow u_{k,1}$ ($\lvert u_{k,1}\rvert < \lvert u_k \rvert$) $\rightarrow$ Swelling: $\Delta V > 0$
(e) Test (t > 0 or t_1) Cons.: σ_{v0}'; 0; σ_{h0}' Failure: σ_v; u; σ_h	Consolidation: $\Delta V > 0 \rightarrow$ poorer quality Undrained shear: $c_u < c_{ui}$ $u\,(t>0) > u\,(t=0)$
Sample quality assessment	$\frac{\Delta e}{e_0} = \frac{\Delta V}{V_0} \cdot \frac{1+e_0}{e_0}$



If the block sample is stored (t>0), the suction in the sample reduces with time and swelling occurs (ΔV>0), see Table 3(d). The swelling after sampling influences the potential change of volume during consolidation to in-situ stresses, which is used as an indicator of sample quality; the $\Delta e/e_0$-criterion. Therefore, a decrease in the suction may cause a significant reduction in sample quality as well as undrained shear strength (c_u<c_{ui}), even if the sample is consolidated back to its original stress state, shown in Table 3(e). A disturbed sample is described by a reduction of undrained shear strength and an increase of pore pressure at failure, $u\,(t>0) > u\,(t=0)$.

The effect is also illustrated in Figure 5 with tests on a low plastic quick clay from Ellingsrud. Bjerrum (1973) concluded that the internal swelling which had occurred after 3 days had reduced the undrained shear strength by 15 %.

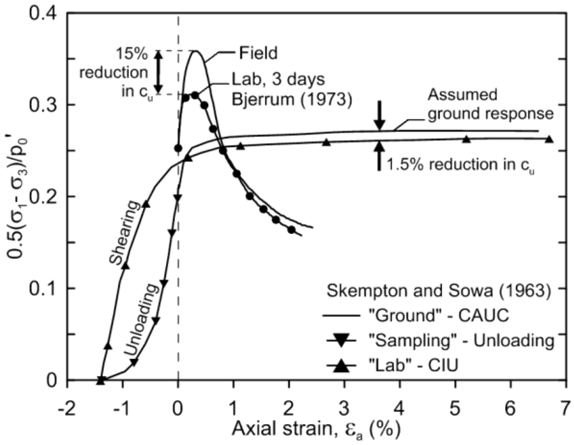


Figure 5 Stress paths for medium plastic clay (S_t=2) after Skempton and Sowa (1963) and for Ellingsrud clay (S_t=70) after Bjerrum (1973).

Adams and Radhakrishna (1971) conducted a series of tests on block samples, from deep open excavation, which showed that specimens that were allowed to take on water and lose suction experienced significant reduction in strength.

Measuring the pore pressure changes in a sample during and after sampling is key to understanding how quickly a block sample may be subjected to stress relief. This is however not a straightforward task. An attempt has been made by Schjetne (1971) to measure the pore pressure changes during sampling in a soft clay with a hypodermic needle piezometer built into a piston sampler. The results showed that sampled quick clay had lost most of the pore pressure quickly and swelled inside the tube due to free water in the remoulded material along the tube walls.

Figure 6 shows loss of suction with storage time in two reconstituted samples of kaolin and illite (Kirkpatrick and Khan, 1984). The remaining suction in a sample will not be a perfect u_k value due to non-elastic behaviour during unloading. Tanaka and Tanaka (2006) noted that the remaining suction has a tendency to decrease with decreasing plasticity index (I_p).

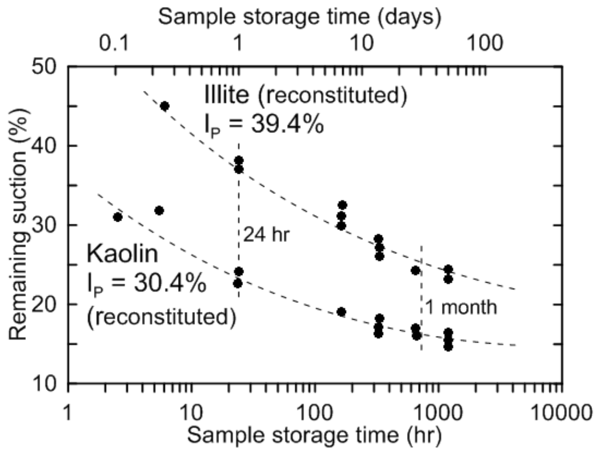


Figure 6 Normalized loss of suction versus sample storage time on reconstituted samples (Kirkpatrick and Khan, 1984).

In engineering practice it is rare that samples are tested on the same day that they are extracted. This is a problem also for block samples.

Table 4 Material properties of tested low plastic soft clays in central Norway.[1]

Sites (sample diameter)	Water content w (%)	c_{ur} (kPa)	Plast. index I_P (%)	OCR
Møllenberg (250 mm)	40.3	0.1	5.9	2.3
Rissa (250 mm)	36.1	0.7-1.5	8.5	2.1-2.2
Tiller (160 mm)	43.1	0.1-1.1	8.7	1.9-2.2
Byneset (160 mm)	37.0	0.3	6.5	1.5-2.0
Dragvoll (160 mm)	38.8	0.1	4.4	1.4-1.9
Klett (160 mm)	34.5	0.1	4.0	1.2-1.4

[1]Here c_{ur} is the remoulded shear strength measured using the Swedish fall cone and OCR is the overconsolidation ratio.

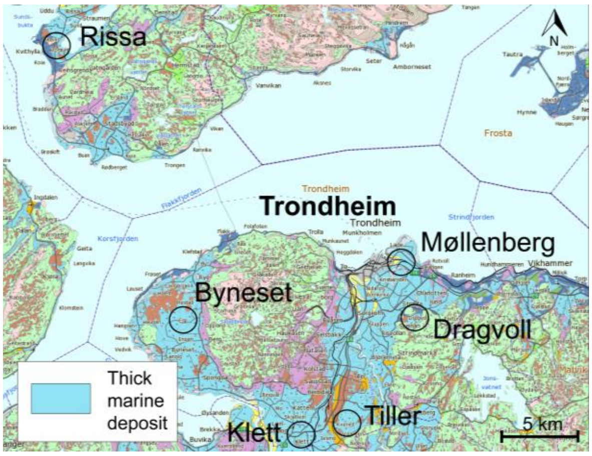


Figure 7 Sampling site locations near Trondheim, central Norway (geological map, NGU).

2.4 Testing and results

NTNU collected low plastic soft clay block samples from six different sites in central Norway. Table 4 summarises some selected geotechnical material parameters of six clays, Møllenberg (Amundsen, 2011), Rissa (Amundsen, 2012), Tiller, Byneset, Dragvoll (Bryntesen, 2014), (Helle et al., 2015) and Klett, most of which are highly sensitive in nature, with an S_t value up to 387.

Over the years, these clay deposits have been extensively tested by NTNU. The handling and testing procedures were more or less identical for all presented sites. Moreover, given the scope of this paper, only selected results are presented and discussed.

2.5 Geological history of sites

From the geological history of the marine deposits near Trondheim, no exceptional loading events are known, only normal sedimentation processes. Groundwater level is about 0-1 m below ground level at all investigated sites, but some fluctuations may have induced changes in the stress history.

Rissa and Møllenberg sites may have experienced some erosion due to their location close to a slope.

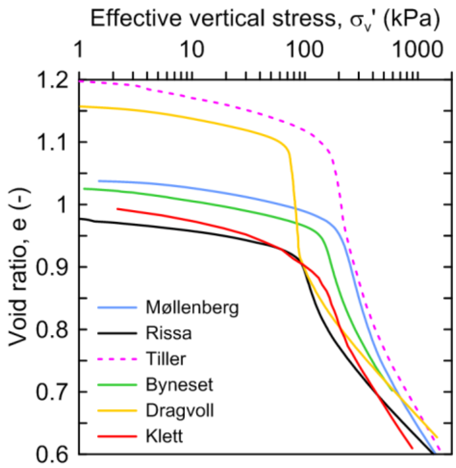


Figure 9 Typical e-logσ_v' relations for low plastic soft clays.

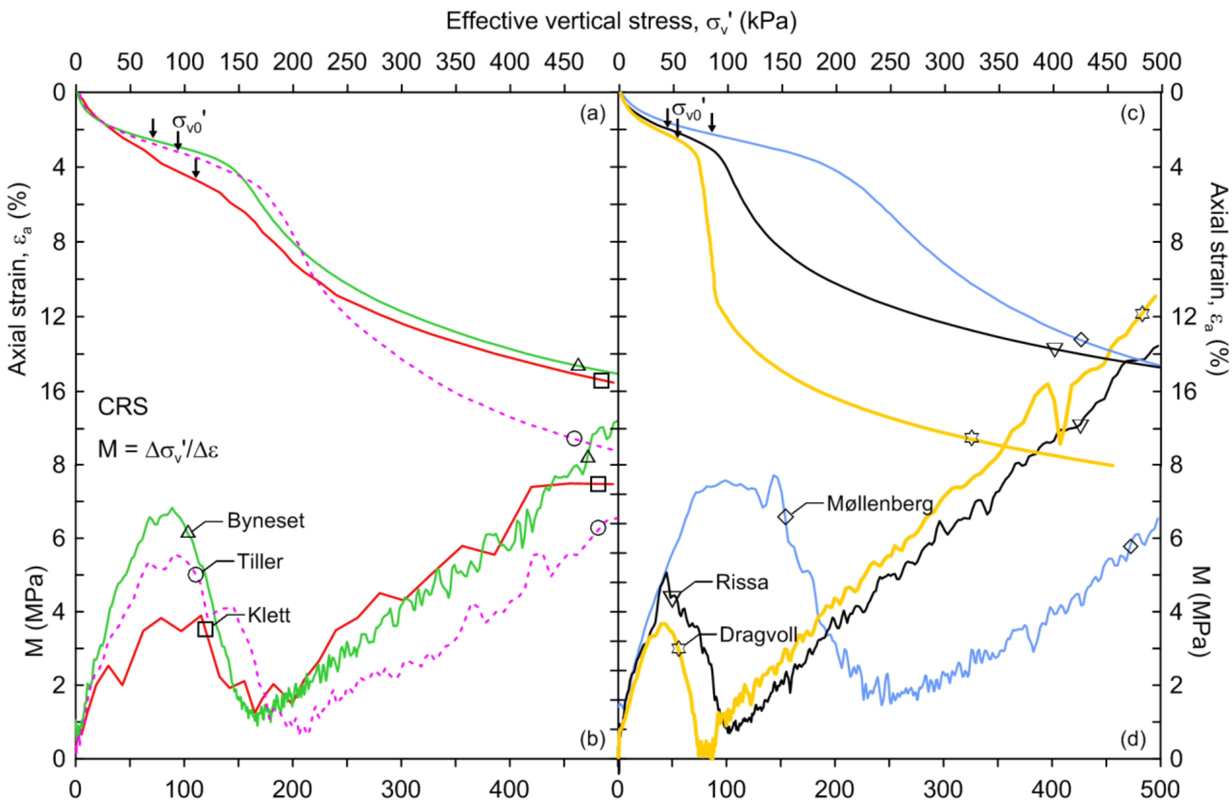


Figure 8 Typical oedometer test results on block samples from low plastic soft clays.

2.6 *Oedometer tests*

Figure 8 shows typical results of constant rate of strain (CRS) type oedometer tests performed on the clay samples from each of the investigated sites. All specimens, extracted using block sampling, were trimmed to a cross sectional area of 20 cm^2 and a height of 2 cm. The material properties of these specimens are given in Table 5.

Table 5 Results of CRS tests on low plastic soft clays in central Norway.

Site:	Møll.	Rissa	Tiller	Byn.	Drag.	Klett
Samp. (mm)	250	250	160	160	160	160
Depth (m)	8.66	4.02	9.83	7.95	6.23	9.99
w (%)	40.4	35.8	42.5	36.0	41.1	35.7
σ_{v0}' (kPa)	87.9	45.9	93.5	76.5	53.8	110
σ_{c0}' (kPa)	200	96	180	150	75	150
OCR	2.3	2.1	2.0	2.0	1.4	1.4
ε_{v0} (%)	2.3	2.0	3.6	2.5	2.5	4.8
$\Delta e/e_0$	0.045	0.040	0.065	0.049	0.047	0.096
M_0 (MPa)	7.3	4.1	5.1	6.6	3.4	3.5
M_0/M_L	4.4	4.9	6.1	5.7	9.2	2.8

Typical e-logσ_v' curves of the soil samples are presented in Figure 9. Their distinguishing features are the sharp bend at the preconsolidation stress (σ_c'). The approach to estimate σ_c', proposed by Janbu (1963) and adopted in Norway, is to use ε-σ_v' plots as shown in Figure 8a and Figure 8c.

The constrained modulus ($M=d\sigma'/d\varepsilon$), introduced by Janbu (1963), is shown in Figure 8b and d. For a low stress level on the loading branch, the resistance against deformation is large, with a maximum M_0. While the stresses increase, the resistance eventually decreases to M_L due to partial collapse of the grain skeleton. The diagram in Figure 4 contains the definitions of the mentioned constrained module.

2.7 *Heterogeneity and loss of suction*

Sampling of normally consolidated clays is challenging. When the clays are also low plastic, it makes it even more difficult. Schjetne (1971) made an attempt to measure the stress changes in a low plastic clay (I_P=3%) during sampling. He concluded that a low plastic soft clay lost most of its suction and swelled inside the cylinder before testing.

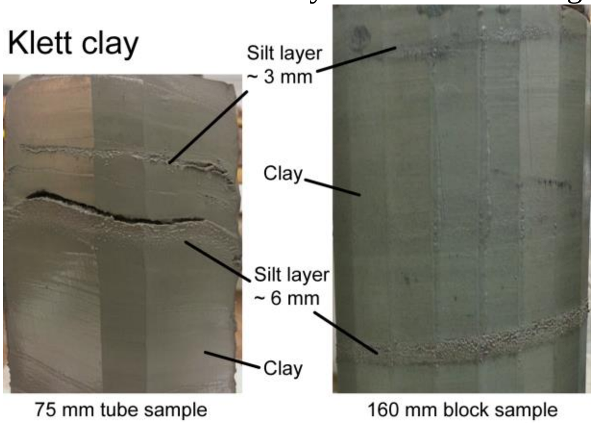


Figure 10 Example of silt layers in Klett clay.

This fact demands an understanding of how quickly the suction may be lost. The answer to this issue lies in the sizes of and the interparticle bonding between clay particles. Permeable materials have a lower tendency to exhibit suction and higher tendency to lose it during and after testing (Fredlund et al., 2012). Kirkpatrick and Khan (1984) tested kaolin which had about 30% left of its suction after three hours of storage. The permeability of kaolin is about hundred times lower than for example Dragvoll or Klett clay. In addition, clays may have layers of highly permeable material, such as silt. Internal drainage of pore water through thin silt layers can reduce the soil suction tremendously, which seems to be the case with the Klett clay. An example of silt layering in the Klett clay is illustrated in Figure 10.

Temperature changes and other chemical reactions will also influence the quality of a sample; however, this aspect is not addressed herein. A descriptive study is necessary in order to determine how this influences the quality of a block sample.

3 CONCLUDING DISCUSSION

A detailed sample quality assessment was carried out and it was found that the quality varied regardless of the type of block sampler and how careful the samples were tested.

Figure 11a compares the magnitude of $\Delta e/e_0$ for samples retrieved at six different sites with low plastic soft clays.

According to the $\Delta e/e_0$ criteria of Lunne et al. (1997), the quality of most samples in Figure 11 may be judged as “good to fair” and “poor”. The “poor” quality samples have been retrieved from a depth of 7 to 15 m and the “good to fair” samples from 4 to 10 m.

The $\Delta e/e_0$-value is, at least in part, caused by stress relief followed by a loss of suction. It is clear from Figure 11a, where sampling procedure and handling were identical, that the sample disturbance increases with depth or with magnitude of stress relief, and consequent swelling, experienced by a sample. Another contributing part to the $\Delta e/e_0$-value is the disturbance induced by the sampler during extraction, transport and handling. This disturbance is dominant for tube sampling, but minimal for block sampling.

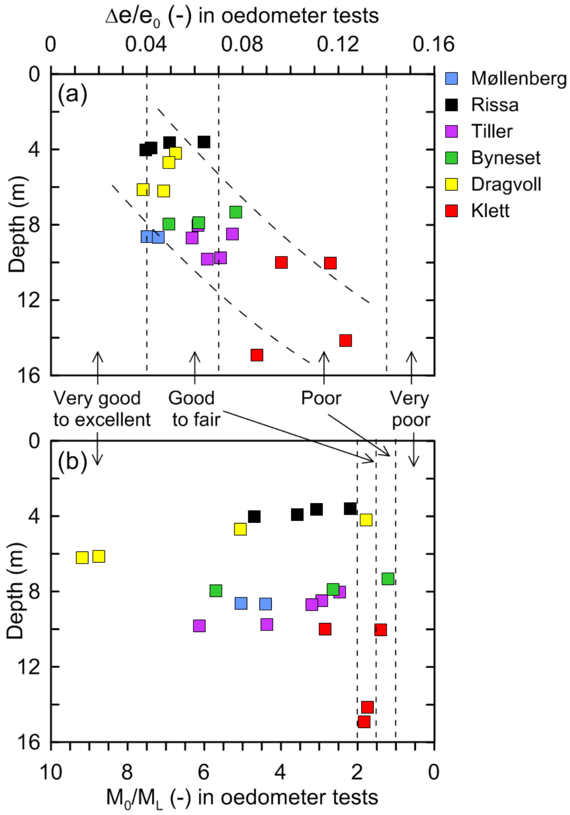


Figure 11 Profile of (a) $\Delta e/e_0$ and (b) M_0/M_L ratios for block samples in low plastic clays.

An advantage of tube samplers is that the stress relief may be delayed by the support of the tube. However, for low plastic soft clays, this effect has diminished before testing is performed (Schjetne, 1971).

If one accepts the $\Delta e/e_0$-criterion, then it is fair to say that one is not guaranteed a high quality sample by using block sampling. In order to ensure good quality sampling, stress relief should be avoided or at least reduced.

Figure 11a has been replotted according to the new M_0/M_L-criterion in Figure 11b. It shows that most of the oedometer tests in this study are classified as of highest quality according to this classification. This is discussed in detail in the following sections.

3.1 *Stiffness parameters, M_0 and M_L*

The behaviour of the soil changes dramatically when the vertical load exceeds the preconsolidation stress. Samples of high porosity and water content may get a low M_L-value. This may further result in a high M_0/M_L-ratio and a sample quality labelled as perfect. In other words, the M_0/M_L-ratio describes brittleness of the material.

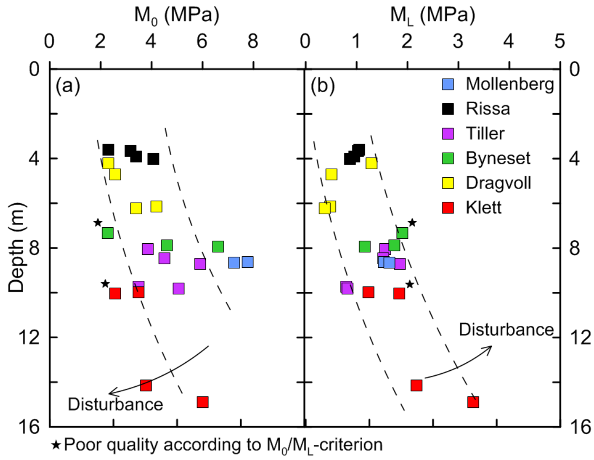


Figure 12 Profiles of (a) M_0 and (b) M_L for block samples in low plastic clays.

The soil stiffness, M_0, is naturally dependent on effective vertical stress and OCR. Soil disturbance causes a destructuring of the soil skeleton and it results in a reduction of the M_0 modulus and an increase of the M_L modulus. This is illustrated in Figure 12.

3.2 *The $\Delta e/e_0$ versus M_0/M_L criteria*

Figure 13 illustrates the M_0/M_L versus $\Delta e/e_0$ with some OCR values. It is clear that M_0/M_L decreases with increasing $\Delta e/e_0$ or sample disturbance. However, the criteria limits do not match well for low plastic soft clays. Clays with a higher OCR value give the best quality according to both criteria, but the scatter is much larger for clays with low OCR. The difference between Dragvoll and Klett is the sampling depth, see Figure 13.

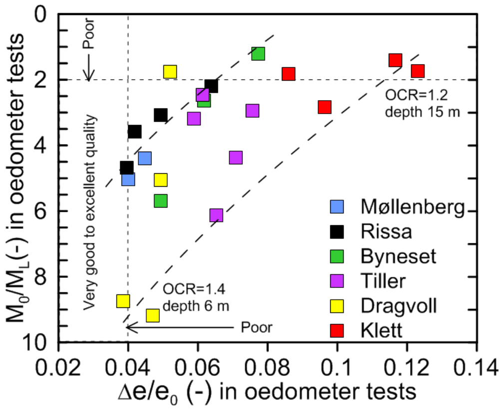


Figure 13 Change in void ratio versus stiffness ratio from oedometer tests.

One primary reason for conducting an oedometer test is to determine a reliable preconsolidation stress. The understanding is that if one does not have a good sample, it is hard to estimate σ_c'. In the results shown in Figure 8 and Figure 9 it is definitely possible to estimate σ_c' even though some of the samples are classified as of "poor" quality according to the $\Delta e/e_0$-criterion. On the other hand, the M_0/M_L-criterion labels the same samples as excellent. The M_0/M_L-criterion takes the sharp bend of the oedometer curve into account and therefore may be more suitable to assess the quality of estimated preconsolidation stress in low plastic soft clays. It however does not indicate the quality of constrained modulus M_0 and may judge a sample as excellent based on an extremely low M_L value.

3.3 Closing remarks

In this paper, an attempt has been made to highlight the challenges related to the handling of block samples. The results show that it is not given that block sampling will produce a high quality sample. Due to stress relief, loss of suction, handling and storage time one may expect poorer sample quality, especially for low plastic soft clays. The key to overcome this issue is to develop a storage procedure for the sample so that loss of suction is minimized. This is the topic of ongoing research at NTNU, and more detailed results may be expected in the future.

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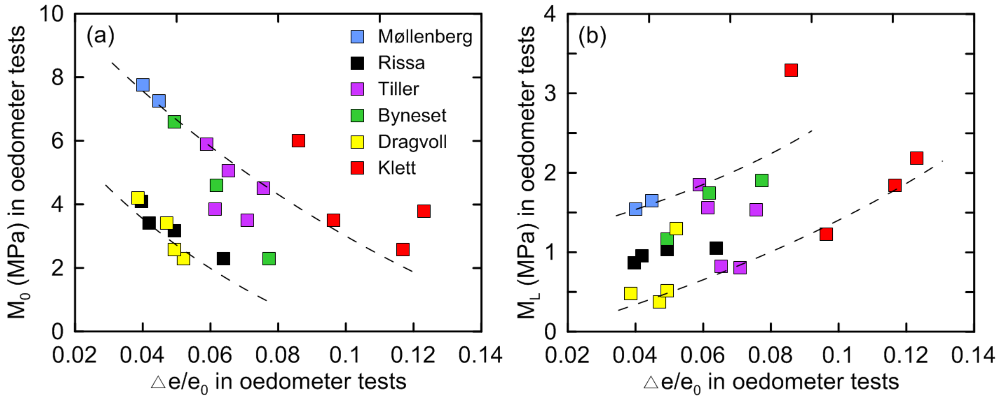

Figure 14 Stiffness M_0 and M_L from oedometer tests versus $\Delta e/e_0$-ratio.

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