A new method for storage of block samples: a pilot study

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A new method for storing mini-block samples was developed by the Norwegian University of Science and Technology. The method consists of storing samples inside a pressurised storage cell (PSC) in order to minimise the effects of stress relief. The pilot study consists of nine mini-block samples that were stored and tested at the sampling site. The samples were sealed with a rubber membrane and storage cell at the site, shortly after sampling. Thereafter, an isotropic pressure was applied and maintained constant throughout the storage period of up to 2 months while the excess water was monitored. The results indicate that the storage method reduces/minimises the effects of stress relief and ageing during the time delay between sampling and testing. The conducted tests indicate that samples stored inside the PSC result in geotechnical parameters that are close to the 0 d samples, which were tested less than an hour after the sampling.

KEYWORDS: clays; laboratory equipment; sampling

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NOTATION

A_u	Skempton's parameter for unloading
c_u	undrained shear strength
c_{ur}	remoulded shear strength from Swedish fall cone test
D	dilatancy parameter
e	void ratio
I_p	plasticity index
I_L	liquidity index
K_0'	coefficient of earth pressure at rest
M	constrained modulus
M_0	constrained modulus in overconsolidated stress range
p, p'	mean total and effective stress
p'_{ps}	mean effective stress at perfect sampling
p'_r	residual mean effective stress
$p_{storage}$	isotropic storage pressure
q	deviatoric stress
S_t	sensitivity
u, u_0	pore pressure and in situ pore pressure
u_{ps}	pore pressure at perfect sampling
u_r	residual pore pressure
V	volume
w	water content
w_L	liquid limit
w_p	plasticity limit
ϵ_a	axial strain
ϵ_v	vertical strain
ϵ_{v0}	volumetric strain at in situ effective stresses
σ_a, σ'_a	axial stress and effective axial stress
σ'_c	preconsolidation pressure
σ_h, σ'_h	horizontal stress and horizontal effective stress
$\sigma_{h0}, \sigma'_{h0}$	in situ horizontal effective stress
σ_r, σ'_r	radial stress and radial effective stress
σ_v, σ'_v	vertical stress and effective vertical stress
$\sigma_{v0}, \sigma'_{v0}$	in situ vertical effective stress

INTRODUCTION

Avoiding sample disturbance during sampling and maintaining an acceptable sample quality has been the topic of

research for several years (e.g. La Rochelle & Lefebvre, 1971; Lessard & Mitchell, 1985; La Rochelle *et al.*, 1986, among others). Block sampling has been proven to be the best method of sampling sensitive clay samples while maintaining high quality (e.g. Lacasse *et al.*, 1985; Hight *et al.*, 1992; Lunne *et al.*, 1997; DeGroot *et al.*, 2003; Tanaka, 2008; Emdal *et al.*, 2016). The block sampling technique (Sherbrooke-type of block samplers) ensures that the sensitive clay remains unaffected by shear distortion from the sampling tube (e.g. Lefebvre & Poulin, 1979; Hight *et al.*, 1992). However, extraction of a block sample from the ground changes the stress conditions of the soil from in situ to zero total stress. A saturated clay sample reacts to this change with a suction that compensates for the stress change and retains the mean effective stress or suction, at least a fraction of it (e.g. Amundsen *et al.*, 2020). With time, the suction will dissipate and the sample will experience a stress relief that may cause an additional sample disturbance. The effects of storage often include changes in mechanical and chemical properties of the samples.

Mechanical changes during storage are presented in Fig. 1, which show a summary of the previous studies where the peak undrained shear strength c_u and preconsolidation pressure σ'_c were investigated during a storage period of a few days to several months. Tube and piston samples show a significant decrease in both c_u and σ'_c during storage. Arman & McManis (1976) tested extruded tube samples stored for a year and observed significant decreases in both preconsolidation pressure and undrained shear strength of about 29 and 62%, respectively. Amundsen & Thakur (2018) tested quick clay samples that were stored inside their sampling tubes and observed that about 5 months of storage may result in a loss of about 17% of σ'_c and about 29% of c_u . In block samples, the reduction in c_u and σ'_c has been observed to be about 10–21 and 4–8%, respectively (Bozozuk, 1971; La Rochelle *et al.*, 1976). The data show that piston and tube samples are more affected by the storage time compared with block samples, presumably due to an extensive destructuration of soil structure during sampling and extrusion from the sampling tube (e.g. Ladd & Lambe, 1963; Baligh *et al.*, 1987; Ladd & DeGroot, 2003). However, most of the early studies on the effects of storage on the mechanical properties were limited to reference testing after a few days or weeks in storage, after the samples were

Manuscript received 17 May 2021; accepted 3 June 2021.
Published online at www.geotechniqueletters.com on 30 July 2021.

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Fig. 1. Change in normalised (a) peak undrained shear strength ($c_u/c_{u,ref}$) and (b) preconsolidation pressure ($\sigma'_c/\sigma'_{c,ref}$). $c_{u,ref}$ and $\sigma'_{c,ref}$ are averages of several tests with the least amount of storage time. Data are from Bozozuk (1971), Bjerrum (1973), Arman & McManis (1976), La Rochelle *et al.* (1976) and Amundsen & Thakur (2019)

transported to a laboratory. This study provides results that were obtained from samples that were tested on the site less than an hour after sampling, which eliminates a potential disturbance due to transport and handling. In addition, this paper presents a new method for sealing and storing of block samples that attempts to reduce/minimise the effects of stress relief and ageing of the soil during storage. The method consists of sealing the sample with a rubber membrane and applying an isotropic pressure. The pressurised rubber membrane minimises the amount of air near the surface of the sample and reduces oxidation of the minerals during storage, which is the major cause of ageing (Lessard & Mitchell, 1985). During storage, the pressure is maintained constant and the sample is allowed to drain the excess water, which presumably comes from the remoulded and disturbed clay at the surface of the samples. The samples were stored and tested at the site 2–65 d after sampling.

THEORETICAL BACKGROUND

When a soil sample is extracted from the ground, the total in situ stress reduces to zero. Hence, one would expect an elastic volumetric expansion of the sample. This expansion is, however, prevented by a negative pore pressure that develops in the soil (Ladd & Lambe, 1963; Skempton & Sowa, 1963). The difference in pressure transports porewater from the surface of the sample, which is destructured and remoulded, to the undisturbed clay in the core of the sample. This causes,

with time, swelling of the sample and dissipation of the negative pore pressure (e.g. Schjetne, 1971), and should be avoided, as it may cause a change in the strength and stiffness properties of the soil sample.

During sampling, the in situ anisotropic stress condition of a soil sample changes into an isotropic stress state. If the soil sample is otherwise undisturbed, the sampling is considered perfect (see Fig. 2). According to Ladd & Lambe (1963), the pore pressure after a perfect sampling should be

$$u_{ps} = -\sigma'_{v0}[K'_0 + A_u(1 - K'_0)] \quad (1)$$

where σ'_{v0} is the in situ vertical effective stress, K'_0 is the coefficient of earth pressure at rest and $A_u = (\Delta u - \Delta \sigma_h)/(\Delta \sigma_v - \Delta \sigma_h)$ is the pore-pressure coefficient, which is between -0.1 and 0.3 , and $1/3$ for an elastic response. Therefore, the theoretical mean effective stress, p'_{ps} , in a sample after the sampling should be

$$p'_{ps} = \frac{\sigma'_{v0}(1 + 2K'_0)}{3} = -u_{ps} \quad (2)$$

where an elastic response is assumed.

The low-plasticity clays and non-plastic soils will not follow a perfect sampling path during sampling, but rather a path of residual effective stress, p'_r (see Fig. 2) (e.g. Hight, 2001; Amundsen *et al.*, 2020).

MATERIALS

The samples that were used in this study were extracted from about 10 m depth at the Tiller research site. The area has been used for research purposes by the Norwegian University of Science and Technology (NTNU) for several years – for example, Sandven (1990); Gylland *et al.* (2013); Amundsen *et al.* (2017); among others. The samples consisted of a high-sensitive marine quick clay with sensitivity $S_r = 234$ and remoulded shear strength $c_{ur} \leq 0.1$ kPa. The material is normally to slightly over-consolidated ($OCR=1.7$).

The layering of the Tiller quick clay was investigated in detail by scanning a sampling tube prior to extrusion. Figure 3(a) shows the X-ray image of a sample from 10.0 to 10.8 m. After the scanning, the sample was opened and divided into 246 thin slices of about 3 mm in thickness; the natural water content was determined. The results show that the natural water content varies between 25 and 51%, with an average of 38.2%. The variations in water content match the layering that was captured by the X-ray image. The darker layers have a lower water content, indicating a higher silt content, and the lighter layers have a high water content, indicating a higher clay content. To confirm these observations, three layers of different water contents were chosen for further testing. The layers are marked in Fig. 3(a). Layer 1 has an average water content of 29.3%, layer 2 has 37.2% and layer 3 has 46.5%. First, the Atterberg limits were determined for the samples, followed by a determination of the grain-size distribution. The results in Fig. 3(c) show a clear correlation between the plasticity index, water content and clay content (% of the particles $< 2 \mu m$). Layer 1, with the lowest water content (29.3%), correspondingly had the lowest plasticity (4.9%) and the highest silt content (66%).

METHODOLOGY

The samples in this study were taken by using a downsized version of the Sherbrooke block sampler (160 mm wide and 300–350 mm high), also called the mini-block sampler, made at the NTNU (Emdal *et al.*, 2016).

Fig. 2. Sampling-induced stress changes of a saturated block sample in (a) $\sigma'_h - \sigma'_v$ stress space and (b) $p' - q$ stress space and (c) dissipation of pore pressure with time. Perfect sampling: p'_{ps} is the mean effective stress and u_{ps} is the negative pore pressure. Sampling: p'_r is the residual mean effective stress and u_r is the negative residual pore pressure or suction. Storage: $p_{storage}$ is the isotropic storage pressure (source: adapted from Amundsen *et al.* (2020))

The pressurised storage cell (PSC) was developed and built at the NTNU. Figure 4(a) shows the cross-section of the PSC that consists of a footing (1) with a pedestal (2), where the mini-block sample is placed (160 mm wide, cut to 300 mm high). The sample is covered with filter paper (3) on the top and bottom. The rubber membrane (4) seals the sample with O-rings (5) to the top cap (6) and pedestal (2). Thereafter, the sample is covered with the cylinder (7) and locked to the pedestal (2) with six screws (9). The cylinder is locked using a lid (8) with two outlets, one for the water (10) to fill up the cell and the second outlet for the pressure control system (11). The drainage tube (12) allows the excess water to drain and be monitored during storage. The storage pressure was set to be less than half of the in situ mean effective stress (about $0.4 p'_0$) and was maintained constant during storage. Storage pressure attempts to maintain the isotropic stress that a sample experiences after sampling (see Fig. 3), which are lower than the in situ stress conditions.

Sealing and applying pressure on a sample inside the storage cell was conducted at the site, shortly after sampling. The PSC was stored inside the field laboratory (developed and made by the Norwegian Public Road Administration or NPRA), which was placed at the Tiller research site throughout the storage period. In an attempt to evaluate the effect of the PSC, a set of mini-block samples was stored without a PSC. Samples were sealed using several layers of household plastic film (PF). After the storage periods, block samples were opened and tested at the NPRA field laboratory. None of the samples was transported, except for PF4 and PSC4; however, none of the advanced tests was conducted on those samples.

Fig. 3. (a) X-ray image of a 54 mm piston sample of quick clay with its natural water content; (b) grain-size distribution; (c) correlation between the plasticity index, water content and the % of particles $< 2 \mu\text{m}$

The conducted tests were as follows: water content (w), remoulded shear strength (c_{ur}), pore water chemistry, constant rate of strain (CRS) oedometer tests and anisotropically consolidated triaxial tests that were sheared undrained (CAUC). The soil specimens were cut out and trimmed to 20 mm high and 50 mm wide for oedometer tests, and 100 mm high and 54 mm wide for the triaxial tests. The oedometer tests were conducted with a strain rate of $1.0\%/h$, and the triaxial tests were consolidated isotropically with 1.0 kPa/min and anisotropically with about 0.08 kPa/min . The specimens were sheared with $1.5\%/h$ after about 1 d of consolidation.

RESULTS AND DISCUSSION

Three sets of samples were analysed, a reference sample, samples that were stored inside the PSC and samples that were sealed with a plastic film (PF-samples). A summary of the samples that were tested in this study is shown in Table 1. The reference block sample was tested shortly after sampling at the NPRA field laboratory, about $0.5\text{--}2 \text{ h}$ after the sample was extracted from the ground. Six samples were stored at the site for $2\text{--}43 \text{ d}$ prior to testing at the site and two samples were transported to the laboratory prior to storage of $61\text{--}65 \text{ d}$. The volumetric strain $\Delta V/V_0$ of the

Fig. 4. (a) Cross-section of the PSC developed and made at the NTNU; (b) a mini-block sample, sealed with a rubber membrane and O-rings, after storage inside the PSC

Table 1. Overview of the mini-block samples from the Tiller site used in this study

Sample	Storage: d	Borehole	Depth: m	σ'_{v0} : kPa	p'_0 : kPa	p_{storage} : kPa	$\Delta V/V_0$: %
Ref.	0	MBH09	10.45–10.80	102	68	0	—
PF1	2	MBH05	9.40–9.75	93	62	0	—
PF2	11	MBH09	9.50–9.85	97	65	0	—
PF3	31	MBH08	10.35–10.60	101	67	0	—
PF4*	65	MBH08	10.70–11.05	104	69	0	—
PSC1	3	MBH09	11.50–11.85	112	75	30	0.010
PSC2	9	MBH09	9.85–10.25	97	65	28	0.155
PSC3	43	MBH09	11.85–12.20	115	86	33	0.423
PSC4*	61	MBH08	11.05–11.40	108	72	30	—

All samples, except for PF4 and PSC4, were stored and tested at the sampling site. σ'_{v0} : in situ vertical effective stress; p'_0 : in situ mean effective stress ($K'_0 = 0.5$); p_{storage} : isotropic storage pressure; $\Delta V/V_0$: volumetric strain; PF, sealed with a plastic film; PSC, pressurised storage cell

samples PSC1–3 was monitored throughout the storage of 3, 9 and 43 d and the results are shown in Fig. 5. The short-term storage of 3 and 9 d resulted in a negligible volumetric strain of 0.10 and 0.15%. The storage of 43 d resulted in a larger volumetric strain of 0.42%, but the sample still classified as of high quality (Lunne *et al.*, 1997). Sample PSC4 was allowed to drain water during storage, but the volumetric strain was not measured. It was noted that the drainage tube was not dry when the sample was opened and tested.

Figure 6 shows the measured water content, remoulded shear strength, pH and sum of cation concentrations in all nine samples. The shaded area in the figure represents the range of values of 0 d samples. Note that the measured values are in the upper range shown in Fig. 4. The results indicate that all mini-block samples, that were stored either

Fig. 5. Volumetric strain $\Delta V/V_0$ of the mini-block samples stored in the PSC with a p_{storage} isotropic pressure. PSC, pressurised storage cell

Fig. 6. Variation in (a) water content (w); (b) remoulded shear strength (c_{ur}); (c) pH and (d) sum of cation concentrations during the storage of mini-block samples. Samples were either tested immediately after sampling or sealed and stored. PF, sealed with a plastic film; PSC, pressurised storage cell

in the PSC or sealed with a PF, show no changes in water content or remoulded shear strength as the measured values are within the range of scatter of natural variation. This is in agreement with the negligible volumetric strain that was measured during storage (see Fig. 5).

According to Lessard & Mitchell (1985), it is expected that both block and extruded tube samples that are stored for more than 2 months show the signs of ageing when they are not properly sealed. Typical signs of ageing are an increase in remoulded shear strength, pH and sum of cations (Lessard & Mitchell, 1985). The measured remoulded shear strength was constant for all samples, regardless of the storage period and conditions (see Fig. 6(b)). The pH values and the sum of cation concentrations show some minor changes in the PF-samples after 2 months of storage, especially at the periphery of the sample (see Fig. 6(d)). The samples that were stored in the PSC (see Fig. 6), showed no changes during storage. This indicates that clay samples can be sealed with the use of a PF as long as the storage period is a few months.

The comparison between test results of the reference sample, PSC-samples and PF-samples is shown in Figs. 7–9. The results indicate that the storage of the mini-block samples inside the PSC has halted the decrease of c_u , which would have reduced by 6–13%. The σ'_c reduces by 16–23% in the samples sealed with a PF; however, the PSC-samples remain close to the range of 0 d samples during storage. It appears that the PSC is able to preserve c_u and σ'_c during storage. Note that some of the c_u values (PSC) are slightly above the range of values of 0 d samples as shown in Fig. 9(a). The increase in c_u is only 2% and therefore assumed to be within the natural variation in the soil. The PF-samples, on the contrary, show a clearer change in c_u during storage. Other parameters derived from the triaxial and oedometer tests, such as dilatancy parameter D and constrained modulus M_0 , which are usually affected by the sample disturbance (e.g. Lunne *et al.*, 1997; Karlsrud & Hernandez-Martinez, 2013), have not been significantly

influenced by the storage in the PSC compared with the storage in a PF (see Fig. 9). M_0 reduced by about 22–33% in the PF-samples and exhibited a more contractile behaviour prior to failure ($D < 0$).

The block samples that were sealed with a PF showed a reduction in the peak undrained shear strength of about 6–13% after 2 months of storage. The reduction in strength is more significant when the Tiller quick clay was stored inside the sampling tubes, which resulted in an 18–29% reduction after 1–3 months of storage (see Fig. 1 and Amundsen & Thakur, 2019). The reduction is even greater, by about 41–48%, when comparing a 0 d block sample with a sample stored in a 54 mm tube. This illustrates the significance of high-quality sampling and the importance of testing the clay shortly after sampling.

The quality of the tested samples, according to the $\Delta e/e_0$ criterion (Lunne *et al.*, 1997), is summarised in Figs. 9(c) and 9(f). The results indicate that the storage of the PF-samples deteriorates their quality. However, the samples that were stored in the PSC exhibited quality that is closer to that of 0 d samples. This indicates an improvement of the sample quality when samples are stored in the PSC.

Some of the observed changes can be caused by natural variation in the clay; however, the number of tests that were conducted on stored samples indicates that there is a systematic decrease in mechanical properties during the storage of mini-block samples, as shown in Fig. 9. The results are similar to an observation reported by Bjerrum (1973) where the c_u reduced by 15% after 3 d in a 95 mm sampling tube, and an extensive study conducted by Amundsen & Thakur (2019) where the c_u decreased by 18% after a month in 54 mm sampling tubes. This indicates that the support of the sampling tube or high-quality block sampling is not enough to preserve the mechanical properties of the normally consolidated high-sensitive marine clays of low plasticity and that a constant pressure is necessary to preserve the mechanical properties of the clay. More research is, however, needed to determine the optimum magnitude of

Fig. 7. Effect of storage on triaxial test (CAUC) results of mini-block samples. Samples were sealed either with a plastic film (marked PF) or with the pressurised storage cell (marked PSC)

the storage pressure and the maximum storage time. Equipment and technique can be modified to make PSCs easy to transport without risking the quality of the samples. The conducted tests show that the proposed method of storing samples is able to minimise the effects of stress relief and storage.

CONCLUSION

A new method has been developed for storage of mini-block samples using a PSC. In the storage cell, the sample is sealed with a rubber membrane and stored under drained

conditions with a constant isotropic storage pressure of about 40% of the in situ mean effective stress.

The results indicate that water content, remoulded shear strength, pH and sum of cations are constant or within the range of natural variation, during storage of up to 2 months in the PSC. Some minor/negligible changes are observed in samples that were sealed with a PF, which indicate that the ageing process has begun in the soil. It is, therefore, concluded that block samples can be stored inside the PF only for a few months before measurable ageing of the clay occurs.

Fig. 8. Effect of storage on oedometer test (CRS) results of mini-block samples. Samples were sealed either with a plastic film (marked PF) or with the pressurised storage cell (marked PSC)

Fig. 9. Effect of storage on (a)–(c) triaxial test (CAUC) results and (d)–(f) oedometer test (CRS) results. Samples were sealed either with a plastic film (marked PF) or with the pressurised storage cell (marked PSC)

The triaxial and oedometer tests conducted on the PSC-samples indicate that strength and consolidation parameters were close to the 0 d samples. The PSC-samples seem to have avoided a 6–13% decrease in undrained shear strength, 16–23% for the preconsolidation pressure and 22–33% for the constrained modulus. The sample quality, assessed by using the $\Delta e / e_0$ criterion (Lunne *et al.*, 1997), has also improved in the mini-block samples that were stored inside the PSC.

The observed results indicate that the confining isotropic pressure in the PSC provides the support that is needed to preserve some of the effective stress during storage and minimise the stress relief, which has proven to be beneficial with regards to sample quality and material properties. The conducted study is a limited pilot study, but the results are promising. Further research is required to propose recommendations for storage procedures, such as the drainage, optimal storage pressure and maximum storage time.

ACKNOWLEDGEMENTS

G. Winther, E. Husby, P. Østensen, K. I. Kvisvik and E. Andersen, engineers at NTNU Geotechnical Division are gratefully acknowledged for their skills and knowledge that made the experimental work possible. The authors acknowledge support from the inter-governmental research programme 'Natural hazards: Infrastructure, Floods and Slides (NIFS, www.naturfare.no, 2012–2015)'. The first author was supported by the Research Council of Norway, grant number 246629.

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