BIG – Branschsamverkan i grunden

Forskningsprogram för effektiv och säker grundläggning av vägar och järnvägar

Projekt A2018-22

Towards high quality deep soft soil samples

Technical Report

CHALMERS UNIVERSITY OF TECHNOLOGY

KTH

TRAFIKVERKET

STATENS GEOTEKNISKA INSTITUT

LULEÅ TEKNISKA UNIVERSITET

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Georgios Birmpilis, Jelke Dijkstra

CHALMERS

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B2018-01 Technical Report: Towards high quality deep soft soil samples

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Department of Architecture & Civil Engineering
Geology & Geotechnics
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Göteborg, Sweden 2020

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B2018-01 Technical Report: Towards high quality deep soft soil samples
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Abstract

Sample quality is directly linked to reducing uncertainties in soil properties that are critical for the reliable prediction of the performance of geostructures, and the associated costs for construction and maintenance. High quality samples in soft soils are commonly retrieved using specialised samplers that retrieve large samples. Most of those methods, however, are limited to relatively shallow depths. This project will investigate if miniature samples cored from the standard STII sampler, which has been reliably used in deep clay deposits, are a viable alternative for obtaining high quality test results, whilst enabling sampling from deeper deposits. In this research the focus is on strength and stiffness properties as obtained from triaxial testing. This required the further development of a bespoke test setup to subsample and subsequently test the miniature samples in triaxial conditions. The, so-called, X-Clay apparatus is a miniature Bishop-Wesley cell with added features to handle small samples without disturbing them during handling, mounting and testing. The results of a large pool of standard and miniature tests showed that miniature sampling provided good to excellent quality when assessed from the change in void ratio during consolidation to the in-situ anisotropic stress state. Nevertheless, subsequent testing in undrained loading indicates that the deviation of strength and stiffness characteristics is larger for miniature samples. After correcting the strain rate from 0.01%/min to 0.05%/min the results for the evaluated (undrained) strength are comparable to the standard sample size. In contrast, the results for the evaluated undrained stiffness underpredicts, by a large degree, those of the large samples. There are some advantages of testing miniature samples over standard sample sizes for long-duration and drained loading paths that are not affected by pronounced excess porewater pressures effects. Most notably drained loading paths will be accelerated, and thus could be used as a complementary procedure in standard soft soil testing routines in case effective stress properties need to be obtained with the highest degree of confidence.

Keywords: Sample disturbance, miniature triaxial test, sensitive clay

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1 Introduction

1.1 Background

Sample quality is directly linked to reducing uncertainties in soil properties that are critical for the reliable prediction of the performance of geostructures. As outlined in prior Trafikverket projects preceding this work (Wood and Dijkstra, 2015; Karlsson et al., 2015), potentially large gains are obtained for using high quality samples in geotechnical problems in soft soils that are governed by the Serviceability Limit State -reduction in expenses for foundations and deep excavations-. Those include, but are not limited to, settlements and vibrations of railway foundations and deformations surrounding deep excavations. Large diameter samplers are used to minimise effects from the cutting shoe and internal friction within the tube. Furthermore, methods that cut the sample free before sampling, such as the Sherbrooke or mini-block sampler show great promise in sensitive clays (*e.g.* Lefebvre and Poulin, 1979; Rochelle et al., 1981; Long, 2006; Lunne et al., 2006; Emdal et al., 2016). High quality block samples, such as those obtained using the mini-block sampler used in (Karlsson et al., 2015; Karlsson et al., 2016), are cumbersome for large depths over ca. 15 m. This project will investigate if miniature samples cored from the standard STII sampler that produces samples with a diameter of 50 mm are a viable alternative for obtaining high sample quality test results whilst enabling sampling from deeper deposits. Since, high quality deep samples cannot be benchmarked by the use of the mini-block sampler, shallow samples (<10 m) of proven high quality are used as a proxy to test the validity of the miniature sampling technique. In this research the focus is on strength and stiffness properties as obtained from triaxial testing. Hence, miniature samples with 10 mm diameter and 20 mm height are tested using a newly developed miniature triaxial apparatus and subsequently compared to the mini-block data from prior research (Karlsson et al., 2015; Karlsson et al., 2016). This new device is developed to minimise the scaling effects and difficulties associated with small samples (membrane, sample geometry, stress control).

1.2 Aim and objectives

The aim is to assess the feasibility of testing miniature samples (10 mm diameter, 20 mm height) cored from the standard Swedish STII sampler as an alternative for normal sized (50 mm diameter, 100 mm height) triaxial samples from high quality block samples.
The following objectives were set:

- Develop a methodology to obtain miniature samples from the STII sample tubes;
- Adapt a custom-designed triaxial cell with increased precision on stress and strain control to facilitate the testing of miniature samples;
- Perform a complete series of triaxial compression tests to examine the scale effect of the miniature sample to undrained and drained stiffness and strength properties of sensitive clay.

1.3 Limitations and changes along the way

A main limitation of the proposed method is that it requires samples from homogeneous clay profiles. For clays with inclusions of coarser material or varved clays the scale effect of miniaturisation is overly limiting.

One of the main challenges was to develop a methodology to obtain and handle miniature samples of natural soft clays. The difficulty related to the very small threshold of forces and strain that can be tolerated by the sample without disturbance, during the (sub)sampling subsequent moving and mounting procedure.

Additionally, the demands on the accurate control and measurement precision was high due to the small amplitude of forces, displacements and volume changes. In order to tackle this challenge, non-standard instrumentation had to be implemented. The cell itself must conform with the uniqueness of the sample and the mounting details. Therefore, it was designed and manufactured entirely in Chalmers' workshops. Finally, the bespoke design of the set up included a in-house programmed software based on a feedback correction algorithm.

All these novel set ups and methodologies were synchronised and calibrated to form the unique miniature triaxial set up.

1.4 Originality & Timeliness

The main originality in this project was the unique sampling and mounting procedure of intact miniature samples on the triaxial pedestal, in order to benefit from the advantages of the miniature scale. This is an adjustment of the testing procedure for samples obtained using the standard and well established Swedish STII piston sampler. As such, miniaturisation can address sample quality related issues, while respecting the standardised geotechnical practices applied by the wide majority of industry stakeholders in Sweden.

Moreover, the developed apparatus was designed to be compatible with state-of-the-art non-invasive X-ray techniques, that require down-scaling of sample environment, test equipment and instrumentation . Results regarding the internal deformation of characteristic Swedish sensitive clays by the use of X-ray non-invasive techniques are reported in Birmpilis (2020).

2 Methodology

2.1 Introduction

Two types of triaxial apparatuses were employed for the test series. For the standard sample sizes the GDS Bishop Wesley cell modified for soft soil testing as described in Olsson, 2013 was used. In the initial stage of the tests the samples were consolidated to the *in-situ* stresses using a K_0 of 0.6. In all standard size tests side drains have been employed to accelerate consolidation. The miniature samples were probed in the custom-made XCLAY miniature triaxial cell.

2.2 Test site

All the material used in the present investigation was sampled from the Utby test site, located in Utby to the east of Gothenburg (Figure 2.1). An homogenous clay deposit is found from 6 – 10 meters depth which for all STII samples would classify as a high plasticity clay CH with high sensitivity following the British Standard 5930. Table 2.1 presents the relevant geotechnical soil properties as determined from the classification tests.

The 50 mm Swedish STII piston sampler was described in detail by SGI (1961). The piston sampler is jacked into the soil to the required depth before cutting samples (whilst holding the piston in place). Three 170 mm tall samples are cut into plastic tube (liner). The upper and lower tubes are considered to be influenced most by the sampling process in terms of mechanical disturbance. Therefore, the middle tube is preferred for its highest quality. The main advantages of this sampler is that after the extrusion from the tube the samples can be directly tested without additional trimming, and that the samples if sealed appropriately have less stress relaxation and oxidation effects than mini-block samples.

Depth (m)	*Sampler* (-)	ρ (t/m^3)	w_p (%)	w_N (%)	w_L (%)	PI (%)	S_t (-)	τ_{fu} (kPa)
5	STII	1.55	25	81	63	38	30	10
6	STII	1.59	22	71	55	33	26	9
	Block		34	69	52	18	27	12
7	STII	1.58	20	72	55	35	27	10
8	STII	1.54	23	71	60	37	28	14
9	STII	1.58	19	75	61	42	29	17
10	STII	1.58	25	70	60	35	5	3

Table 2.1: Soil characterisation

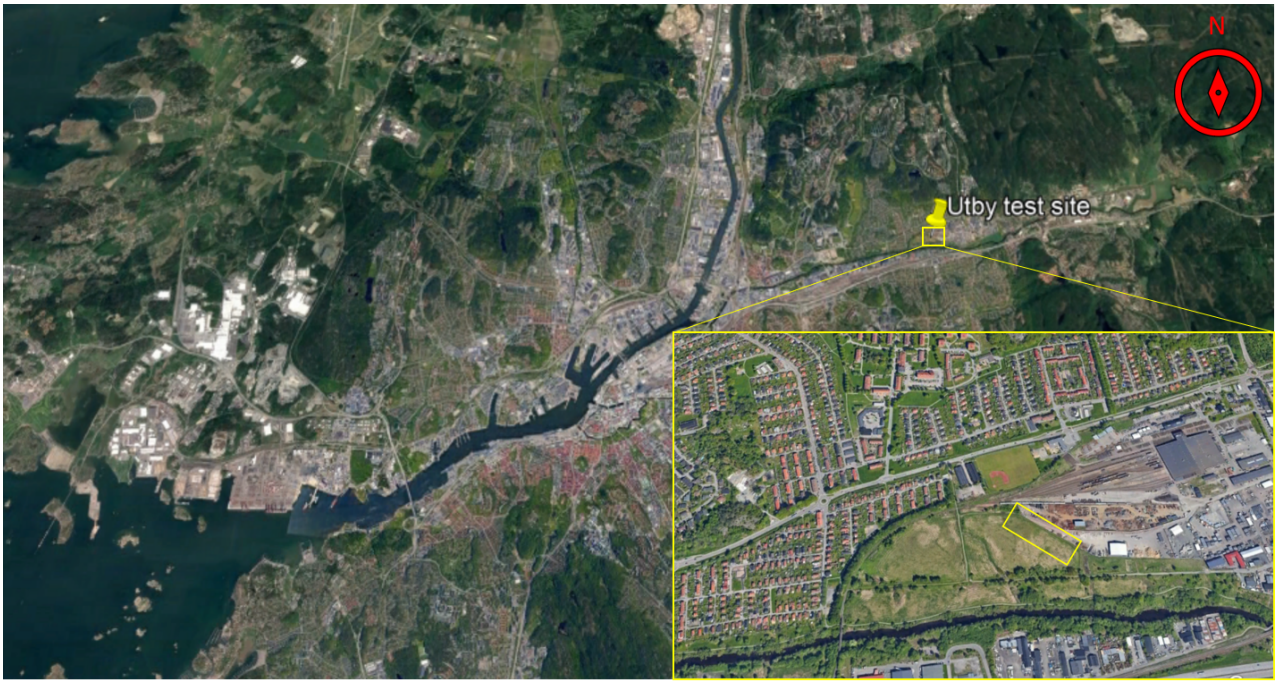


Figure 2.1: *The Utby test site, located in the outskirts of Gothenburg.*

2.3 Test setup: XCLAY triaxial cell

A bespoke apparatus was developed for advanced triaxial testing of miniature samples: the XCLAY triaxial cell shown in Figure 2.2next to the standard GDS triaxial cell. In case of soft soil probing, advanced total stress and pore pressure control are de facto requirements, for handling a large range of loading paths and effective stress control at low effective stress levels in soft soils with low strength and stiffness.

2.3.1 Mechanical design

The XCLAY triaxial cell is of the Bishop-Wesley kind. Bishop and Wesley (1975) developed an elegant hydraulically operated triaxial apparatus in the 1970s. The major advantage of the apparatus is the ease of performing stress and strain probing by controlling the axial stress, cell pressure and back pressure. As such the Bishop-Wesley design is used as a starting point for the present miniature triaxial apparatus. A schematic diagram of the apparatus is shown in Figure 2.3. The main components of the apparatus are:

- The lower body, which contains the piston system that actuates the moving pedestal. The frictionless piston system consists of a stainless steel ram, which can slide linearly in a smooth brass fitting, with the help of lubrication. Two Bellofram rolling diaphragms (manufactured by MARSH BELLOFRAM, MPN:4-100-81-CBJ) that seal the piston from the cell pressure and the liquids in the lower chamber. The back pressure is regulated through the piston in the bottom of the sample using a precision syringe pump.

- The cell contains the sample. A plexiglass tube of 5 mm thickness and 50 mm outer diameter is selected to provide optical transparency. Paraffin oil is used to apply cell pressure on the sample. A maximum total outer diameter of 70 mm of the cell, including

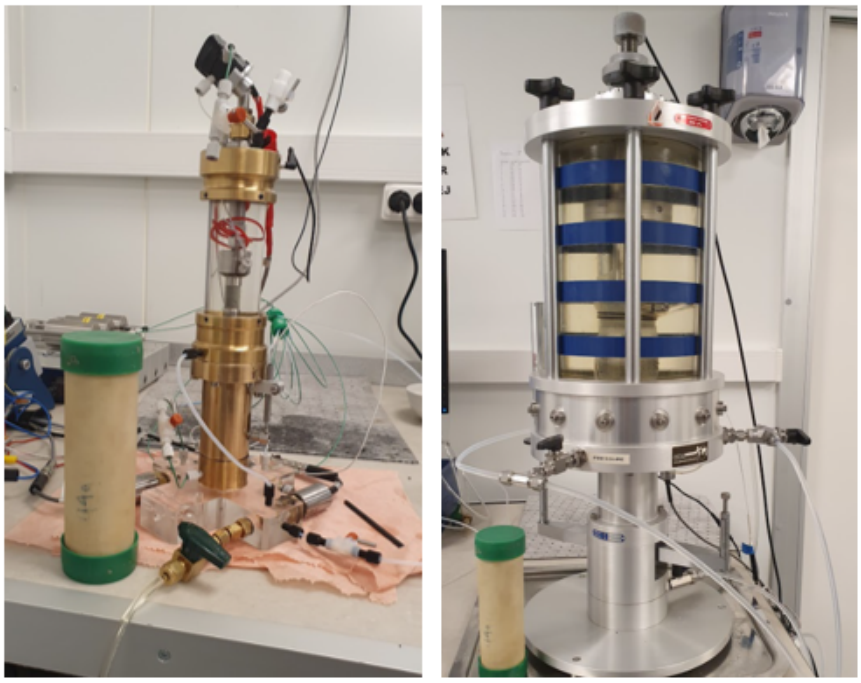


Figure 2.2: *The XCLAY miniature triaxial cell besides the standard size GDS Bishop-Wesley triaxial cell.*

the top and bottom cell-cap, is required for the use of the cell in high resolution absorption based tomography.

- The mounting ends which position the sample. The top cap and pedestal stage are equipped with a thin ring shaped protrusion (0.2 mm thickness, 0.3 mm penetration length) that penetrates the sample, sealing the connection (magnified window in Figure 2.3). A submerged miniature load cell (FUTEK Miniature S Beam Load Cell LSB200), with 19 mm height and 17.5 mm length provides measurements of the axial load inside the cell, hence the deviatoric component of the load is measured directly.

2.3.2 Control

One of the advantages of the present experimental setup is the custom and automated control of the syringe pumps. A configuration of high precision neMESYS Mid Pressure Syringe Pumps (Cetoni GmbH) was used to regulate the pressures in the lower chamber, the triaxial cell and the porewater pressures in the sample (back pressure). The syringes in this system are modular which allows to optimise the control volume for the required application (back pressure, cell pressure).

The system is computer controlled following the flow chart shown in Figure 2.4. The input for the syringe pumps are setpoints for the final displacement and the displacement rate of the syringe piston. Through a PID (Proportional–Integral–Derivative) error control loop, the user can define the desired stress path of the sample during the consolidation and the shearing stage. In order to apply linear stress paths (in the $p' - q$ space) in the temporal range required by the test a PD control is more suitable. In a PD system, The Proportional (P) control is the

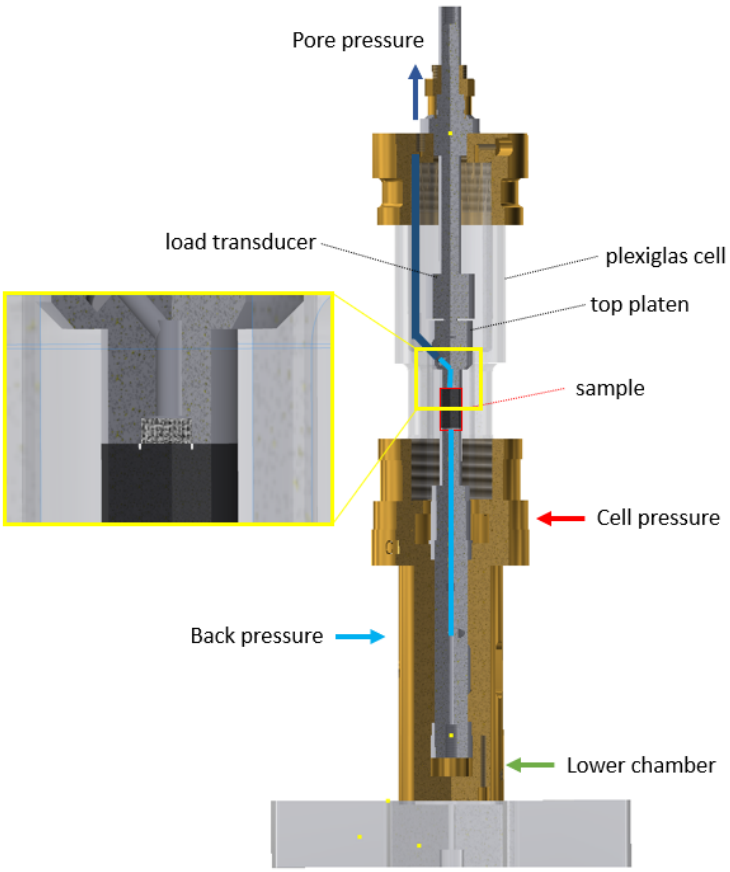


Figure 2.3: *Three quarter section view of the XCLAY miniature triaxial apparatus.*

Table 2.2: Performance characteristics of neMESYS Mid Pressure Syringe Pump.

Module characteristics	
max. Plunger Rate	6 mm/s
min. Plunger Rate.	1 nm/s
min. Plunger Travel	3.7 nm
max. Linear Force	1000 N

action which restores the error amplitude and the Derivative (D) control is the action keeping the system in balance avoiding large oscillations.

Strain rate control is also available. The capability of nanometre scale incremental resoultion of the syringe pumps (Table 2.2) makes the error correction control of the system extremely versatile and adaptable to the desired stress path control.

2.3.3 Subsampling and mounting

The miniature sample of soft clay is too delicate to be handled by hand. For this reason, both for the sampling and the mounting processes of intact specimens of natural clay on the pedestal of the XCLAY device an *untouched by hand* procedure was adopted (Figure 2.5). A stainless steel cutting ring of 10 mm inner diameter is cut into a standard STII piston sample collected

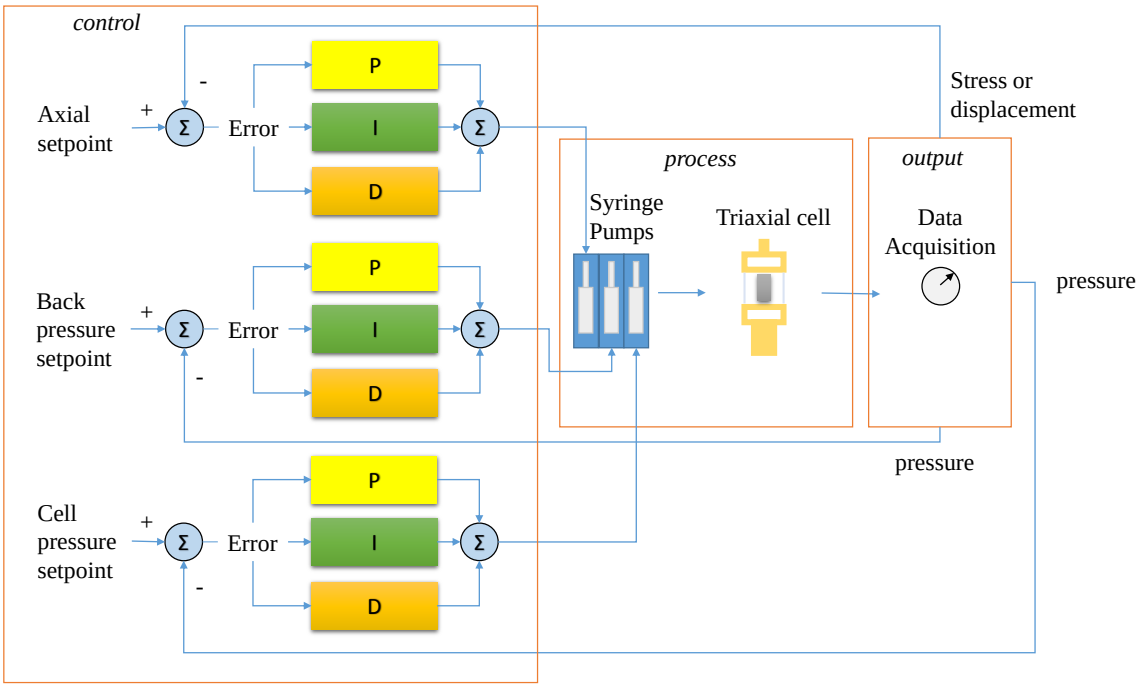


Figure 2.4: *Flow chart of the triaxial system, showing the relationship between computer control, mechanical process and data acquisition.*

from the field (50 mm diameter) with a constant penetration rate of 0.6 mm min^{-1} (Figure 2.5a). The selected penetration rate is a trade off between generation of excess pore water pressures from overly fast penetration and undesired drying effects that might result from a prolonged procedure. Subsequently, the cutting tube is cut free from the master sample. Then, the miniature sample is placed on the pedestal of the XCLAY apparatus by sliding the bottom of the cutting ring, left empty for this purpose, onto the top of the pedestal (Figure 2.5b-2.5c). In the last step the miniature sample is extruded and aligned by sliding the ring down around the base of the pedestal (Figure 2.5d). The interface between the miniature sample and the end platens on the pedestal needs to be sealed to prevent the cell liquid from entering the pore water pressure and back pressure channels. To seal the interface a sharp and thin protruding ring -part of the end platen- (height: 0.3 mm, inner diameter: 4.2 mm, thickness: 0.1 mm) surrounding the undersized porous disk penetrated in the sample during mounting.

2.3.4 Membraneless operation

Due to the small size and the low stiffness of the clay sample, the addition of a membrane was considered unsuitable. Therefore, a membraneless configuration using the paraffin method (Iversen and J.Moum, 1974) was used (Figure 2.6). Paraffin oil is immiscible with the porewater in the clay sample and so, in combination with the low permeability of the clay, penetration of the paraffin into the sample does not occur at the pressure levels applied (< 200 kPa). An investigation was made to validate that the paraffin method is reliable for the clay samples used. X-ray Computed Tomography (XCT) was employed to investigate the pore water response in the sample. Figure 2.7 shows a vertical slice of an XCT image of a sample with an iodine-containing non-ionic radiocontrast agent dissolved in the porewater. It was demonstrated that

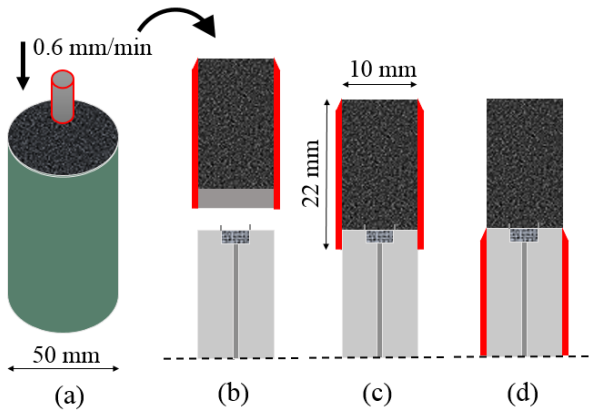


Figure 2.5: *Sampling and alignment of the miniature sample on the XCLAY triaxial pedestal.*

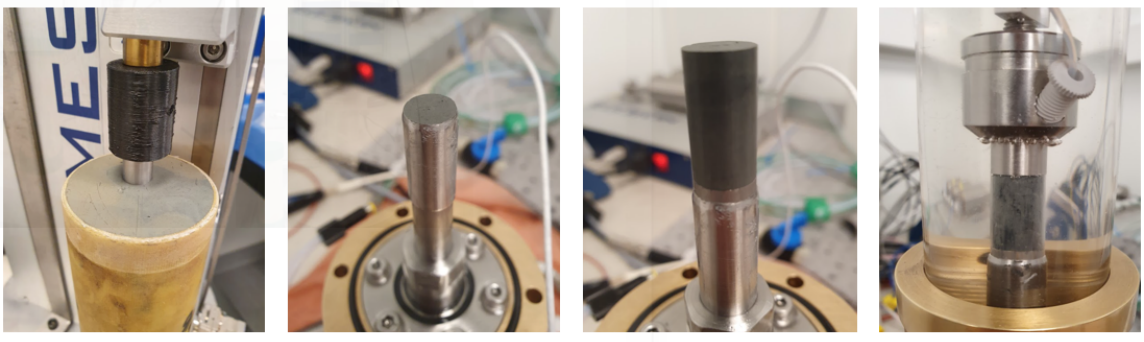


Figure 2.6: *The mounting procedure from sampling to complete mounting.*

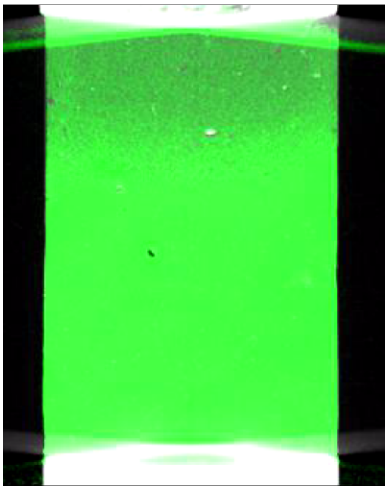


Figure 2.7: *XCT on a satrated clay sample with dissolved contrast agent. The paraffin surrounding the sample does not penetrate.*

the paraffin surrounding the sample does not penetrate the clay, and the radiocontrast agent does not diffuse into the paraffin.

2.4 Selection of loading rate

The effect of strain rate on undrained shear strength of saturated fine-grained soils is experimentally well investigated (*e.g.* Bjerrum, 1967; Vaid and Campanella, 1977; Crooks and Graham, 1976; Lefebvre and LeBoeuf, 1987; Sheahan et al., 1996; J. Yin and Cheng, 2006). The findings indicate that an increase in the strain rate results in an increase of the undrained shear strength. This rate effect is combination of the intrinsic material rate effects and the porewater effects. In Scandivavia, the standard rate of engineering strain is 0.01%/min (Larsson, 1977). During undrained compression there is no volume change in the sample, however, the pore pressure distribution in the sample is affected by the change in the specimen geometry and the local variations in the void ratio (*e.g.* within a shearband). Furthermore, similitude indicates that scaling down the sample size might affect the porewater response, *e.g.* for miniature penetrometers smaller probes require larger loading rates to obtain representative strengths, (Lehane et al., 2009). In the current study different rates are investigated for the miniature samples: 0.01%/min, 0.05%/min and 0.01%/min. Due to the miniature sample size the strain rates correspond to sub-micron displacements in the time window of the control loop of the software. Such length changes are close to the measurement limit of the LVDT used to measure the axial displacement for the control loop. Therefore, the PID loop algorithm parameters were calibrated for the tests at higher strain rates (0.1%/min) first.

2.5 Test Programme

Tables 2.3 & 2.4 summarise the testing programme for both the miniature and the standard sample size.

Table 2.3: Overview of testing of miniature samples.

Sample	Depth (m)	Test	Rate (%/min)
1	8	K_0CU	0.1
2	9	K_0CU	0.1
3	9	K_0CU	0.1
4	9	K_0CU	0.1
5	9	K_0CU	0.1
6	9	K_0CU	0.1
7	8	K_0CU	0.05
8	8	K_0CU	0.1
9	8	K_0CU	0.1
10	9	K_0CU	0.1
11	9	K_0CU	0.1
12	9	K_0CU	0.1
13	7	K_0CU	0.05
14	7	K_0CU	0.05
15	9	K_0CU	0.01
16	9	K_0CU	0.01
17	9	K_0CU	0.01
18	8	K_0CU	0.01
19	8	K_0CU	0.01
20	7	K_0CD	0.005

Table 2.4: Overview of testing of standard size samples.

Sample	Depth (m)	Test	Rate (%/min)
1	9	K_0CU	0.01
2	9	K_0CU	0.01
3	9	K_0CU	0.01
4	9	K_0CU	0.01
5	10	K_0CU	0.01
6	10	K_0CU	0.01
7	8	K_0CU	0.01

3 Test Results

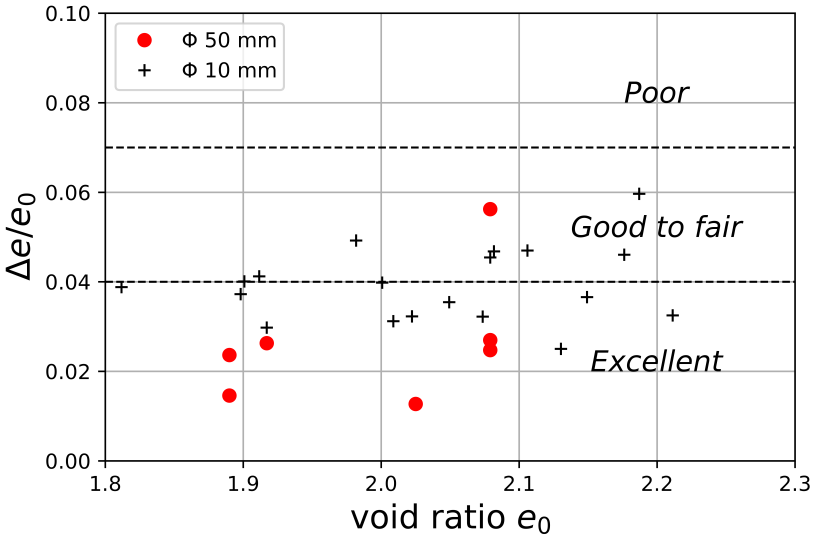


Figure 3.1: *Sample disturbance factor (sdf) chart for the tested samples.*

A sample disturbance factor was determined from the change in void ratio Δe during consolidation of the sample to the in-situ stress level. This value was subsequently normalised with the in-situ void ratio e_0 as determined from the water content of the sample. This sample disturbance factor

$$sdf = \frac{\Delta e}{e_0} \tag{3.1}$$

was first proposed by Lunne et al., 1997 as it is more sensitive than only considering the volume change (*e.g.* the volumetric strain ε_v). The void ratio change Δe is calculated from the volumetric strain measured during consolidation to $\sigma'_{h;0}$ & $\sigma'_{v;0}$, where $\sigma'_{h;0} = K_0\sigma'_{v;0}$ For the miniature triaxial set up discrepancies of the volume measurements were observed due to the minute volumes of water expelled by the sample during the consolidation stage. This might be further affected by the presence of microbubbles in the system. In that case, the volumetric strain was calculated by the axial strain with the use of Poisson ratio ν=0.2 (equation 3.2).

$$\nu = -\frac{\delta\varepsilon_{radial}}{\delta\varepsilon_{axial}} \tag{3.2}$$

It should be noted that all the miniature samples, of varying age, demonstrate good to excellent quality (Figure 3.1) when using the sample disturbance factor.

3.1 Comparison of small and large samples

The test results of the miniature and standard tests are compiled in Figure 3.3 in the $p' - q$ stress space normalised by the *in-situ* mean effective stress p'_0. The axial strain ε_{axial} to the deviatoric stress q curves are plotted in Figure 3.4. All stresses are also normalised to the

in-situ effective stress p'_0. Cambridge stress invariants are adopted, *i.e.* in triaxial space: $p = (\sigma_1 + 2\sigma_3)/3 = (\sigma_v + 2\sigma_h)/3$, $q = (\sigma_1 - \sigma_3)$ and ' denotes effective stress. The shearing stage was run until excess pore pressures were stabilised, suggesting that critical state was reached. The excess pore water pressure profiles measured at the bottom of the sample are plotted in Figure 3.5.

It is observed that there are discrepancies observed between the $p' - q$ curves for the miniature and the standard samples. While the difference in the mean of the maximum deviatoric stress between the two sample sizes is reasonably small, the evolution of excess pore water pressure generation appears to be dissimilar. In Figure 3.5, it is shown that the miniature samples develop higher excess porewater pressures at already smaller strain magnitudes (for the case of 0.1%/min, as shown by Figure 3.7). Moreover, the failure appears more brittle (Figure 3.2) expressed as a clear continuous shear band, immediately after the peak deviatoric stress, without the typical bulging observed in standard size specimens. The shape of the sample in failure is influenced by the boundary conditions of the test, *e.g.*, the friction with the end platens and the use of a membrane with a certain stiffness. Therefore, the measured post-peak porewater pressures are considered unreliable, which also impacts the validity of the calculated p'. The latter affects the interpretation of the critical state friction angle from M.

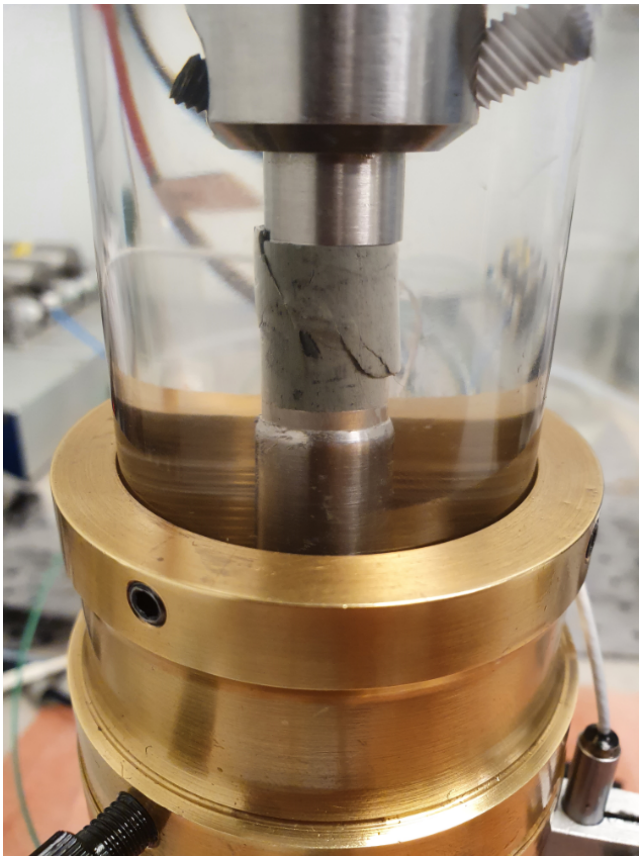


Figure 3.2: *Failure band in miniature sample.*

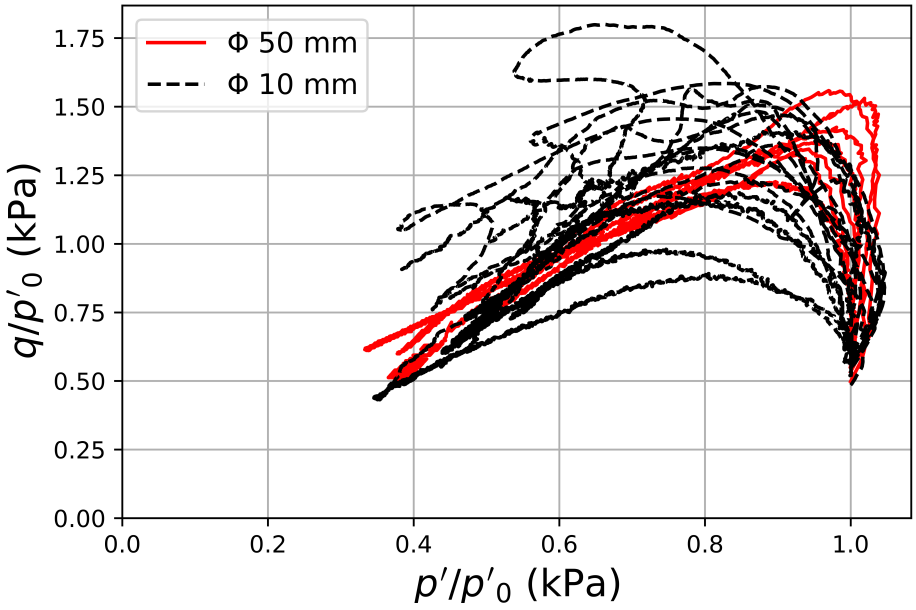


Figure 3.3: *Mean effective stress (p') to deviatoric stress (q) for miniature and standard size samples. The stresses are normalised with the mean effective in-situ stresses.*

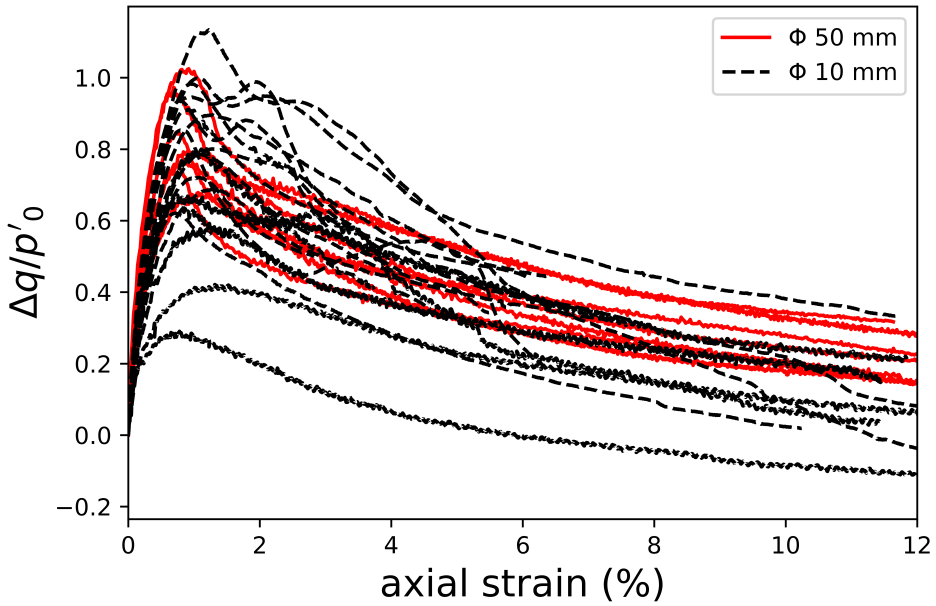


Figure 3.4: *Axial strain (%) to shear deviatoric stress (Δq) for miniature and standard size samples. The stresses are normalised with the mean effective in-situ stresses.*

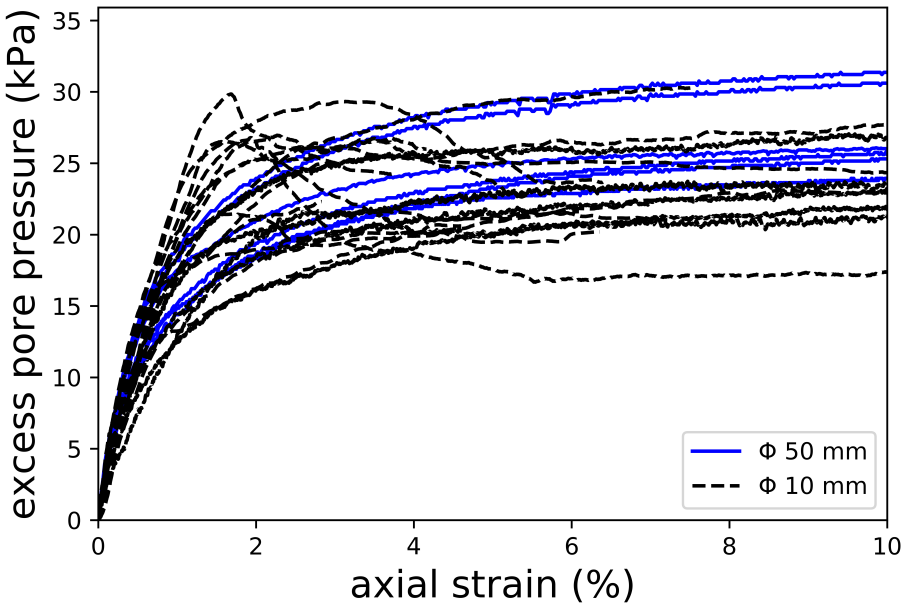


Figure 3.5: *Axial strain (%) to shear deviatoric stress (Δq) for miniature and standard size samples. The stresses are normalised with the mean effective in-situ stresses.*

3.1.1 Response

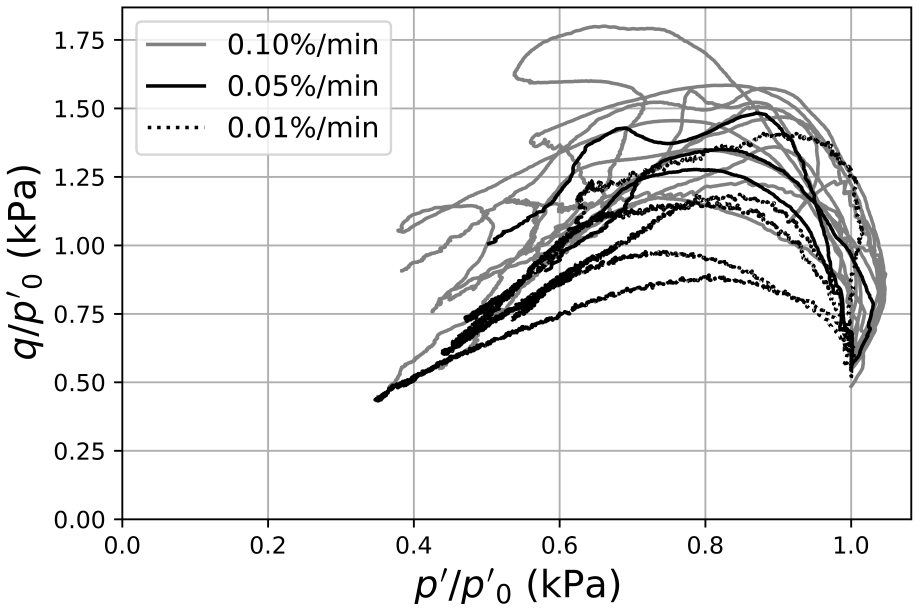


Figure 3.6: *Mean effective stress (p') to deviatoric stress (q) for miniature size samples. The stresses are normalised with the mean effective in-situ stresses.*

Prior to interpretation of the results, the expected rate dependency effect (Graham et al., 1983; Lefebvre and LeBoeuf, 1987; Zhu and J.-H. Yin, 2000; Z.-Y. Yin et al., 2010) on the the

response of the test should be examined. The miniature tests are plotted according to their shear rate in Figure 3.6 in the normalised stress space $p' - q$. Figure 3.7 shows the development of excess pore water pressures for the miniature tests performed at different shear rates. As mentioned earlier, rate dependency has an effect on the undrained shear strength. So, the high strain rate, *i.e.*, 0.1%/min, generates larger shear resistance when compared to the results for 0.01%/min (Figure 3.8). Nevertheless, the somewhat larger variance of the results hinder a direct comparison.

Moreover, the tests performed at 0.1%/min strain rate resulted in a fast and abrupt failure. This is also observed in the plot of excess pore pressure profiles, shown in Figure 3.7.

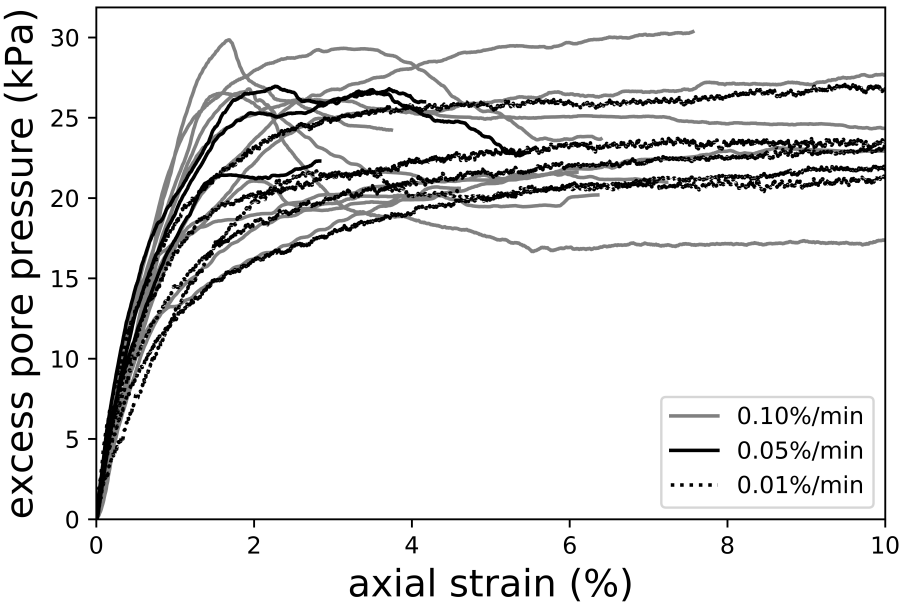


Figure 3.7: *Axial strain to excess pore pressure for miniature and standard size samples.*

3.1.2 Interpretation of soil properties

The undrained and drained strength and stiffness properties are subsequently evaluated from the results reported. In standard geotechnical engineering practice an anisotropically consolidated undrained triaxial test in compression (where porewater pressures are measured during the test) provides data on the undrained Young's modulus E_u, the undrained shear strength s_u and the slope M of the critical state line which is directly linked to the internal friction angle at critical state (an effective stress soil property). The undrained shear strength (s_u) is derived from the peak deviatoric stress q_f (at failure) as:

$$s_u = q_f/2 = (\sigma_1 - \sigma_3)/2 \tag{3.3}$$

The critical state slope is defined at large strains, when excess porewater pressures are stabilised:

$$M = q/p' \tag{3.4}$$

where $q = (\sigma'_1 - \sigma'_3)$, $p' = (\sigma'_1 + 2\sigma'_3)/3$

Figure 3.8 presents an histogram of the undrained shear strength that is normalised with the *in-situ* mean effective stress. As demonstrated the mean value of s_u deviates as function of strain rate. The miniature test with 0.05%/min rate, appear to fall closest to the values of the standardised test.

Another common strength parameter is the slope M of the critical state line. In this case, it is observed that the slope of the critical state line is generally overestimated by the miniature test, with the exception of the results for the tests sheared at a rate of 0.01%/min.

Finally, the stiffness is evaluated as the secant modulus of undrained stiffness $E_{50;u}$, which is defined as the ratio of the difference in deviatoric stress at the 50% of the peak strength to the corresponding axial strain using the following equation (the secant stiffness is more reliably determined when compared with the tangent stiffness at small magnitudes of strain):

$$E_{50;u} = \frac{\Delta q_{50}}{\Delta \varepsilon_{axial}} \tag{3.5}$$

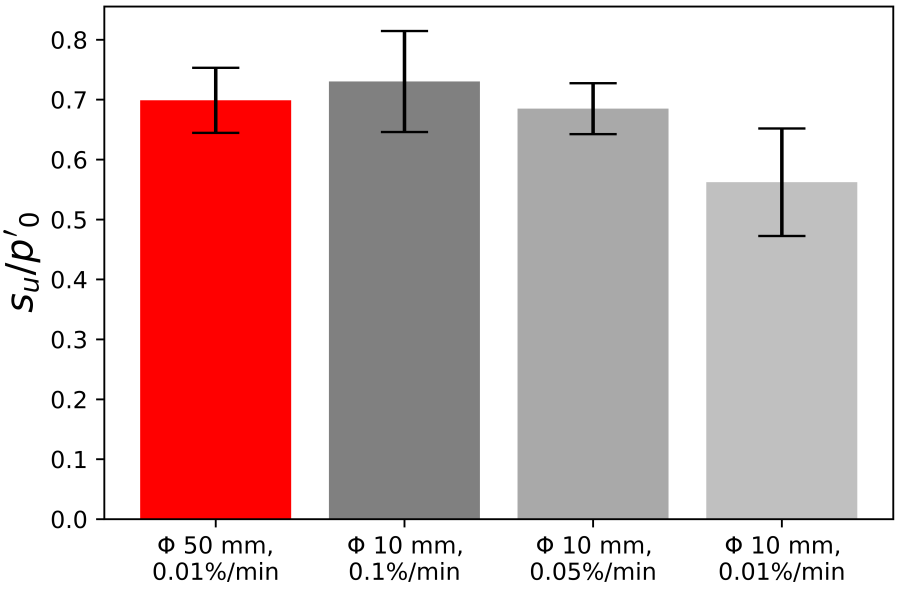


Figure 3.8: *The histogram of the normalised undrained strength for the standard sample size, at the following shear rates: 0.1, 0.05, 0.01 %/*min*. The error bars represent the standard deviation.*

3.2 Discussion of results

- The largest reduction in test time stems from the shorter drainage lengths that lead to shorter consolidation times and due to scaling of the shear rate. Whilst in theory a 5^2 reduction of test time when compared to the large sample sizes (without side drains) in the current test series the consolidation time was halved, due to very stringent end of consolidation criterion (zero excess porewater pressures). Note that for large samples

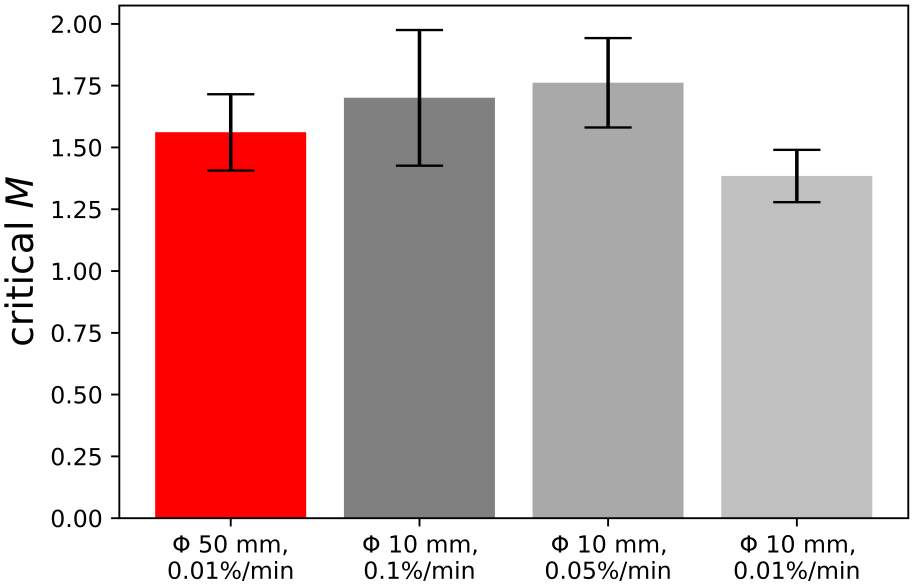


Figure 3.9: *The histogram of the critical state slope for the standard sample size, at the following shear rates: 0.1, 0.05, 0.01 %/*min. *The error bars represent the standard deviation.*

of sensitive clay, where on average 24 h consolidation time is used, this is not always reached. Furthermore, the final strain magnitude was substantially larger at 25%

- The sample quality metric based on volume change during consolidation to in-situ stress indicates sample qualities that are comparable to those for the large samples.

- When comparing the stress-strain results it becomes apparent that larger differences are observed in-between samples tested in comparable conditions. Although this large scatter was unexpected for the generally homogeneous soft clay deposits in the Nordic countries, this is partly associated to natural heterogeneities in the clay sample. The length scale of the heterogeneities does not scale when the sample size is reduced. Hence, the impact of these heterogeneities on the stiffness or hydraulic conductivity will lead to the magnitude of the deviations measured in the axial load and excess porewater pressures.

- The boundary conditions required for membraneless testing -the end effects- can affect the sample shape at failure, however, this does not appear to influence the evaluated values for the (un)drained strength much, since the tests on standard samples are also affected by rough end platens.

- When compared to the standard sample size, the miniature samples showed large differences in the generation of excess porewater pressures. The failure mechanism does not scale in a similar manner as the sample size, hence larger and more pronounced localisation effects lead to more erratic porewater pressure measurements.

- Rate effects that are present for natural sensitive clays further complicate the interpretation. Tests with varying rates indicate that for the same (engineering) strain rate, *i.e.*, 0.01%/min, both the undrained shear strength and the slope of the critical state line are

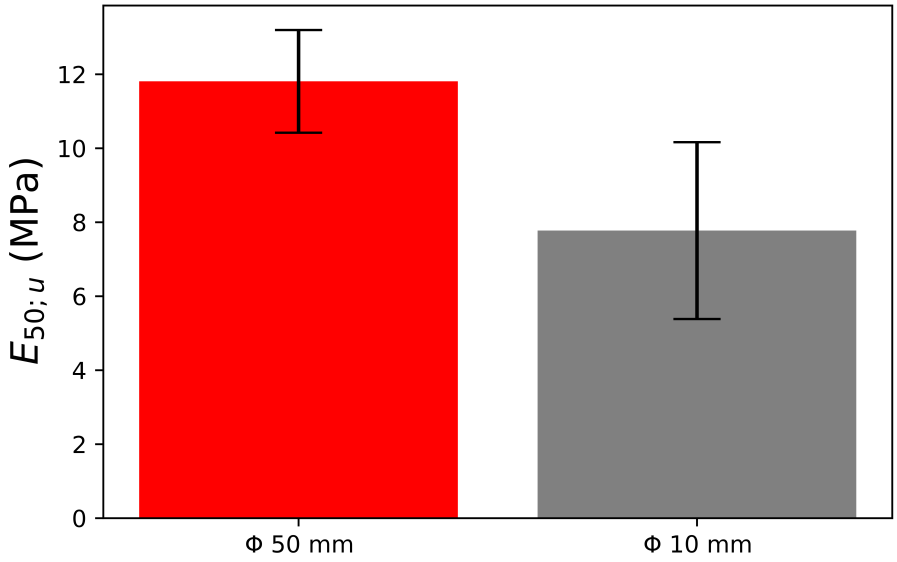


Figure 3.10: *Secant modulus of undrained stiffness $E_{50;u}$ (at 50% of strength) for* 9 m *depth sample for standard and miniature sample sizes.*

underestimated significantly and show a larger scatter, for the case of miniature samples. Clearly, in smaller samples tested at conventional strain rates the mobilised magnitude and distribution of porewater pressures is leading to lower strength.

- The 0.05%/min rate produces results for the evaluated (undrained) strength that are closest to the standard test dimensions with a smaller scatter in the results than for the large samples.

- The undrained stiffness was systematically lower in the miniature samples, regardless of sample quality. This indicates that the induced scaling effects that lead to a more pronounced generation of porewater pressures more strongly affect the mobilisation of undrained stiffness. This result indicates that for the natural clay tested the small samples are not a viable alternative for assessing undrained stiffness with a larger degree of confidence.

- It appears that drained loading paths are potentially more suitable for test miniaturisation as this avoids porewater pressure effects. Furthermore, the scaling allows shorter test durations during consolidation and probing, due to the reduced drainage length. The results of a drained triaxial test loaded in compression are shown in Figures 3.11 & 3.12. The test was performed 5 times faster than the standard strain rate used in Sweden (*i.e.*, 0.005%/min instead of 0.001%/min).

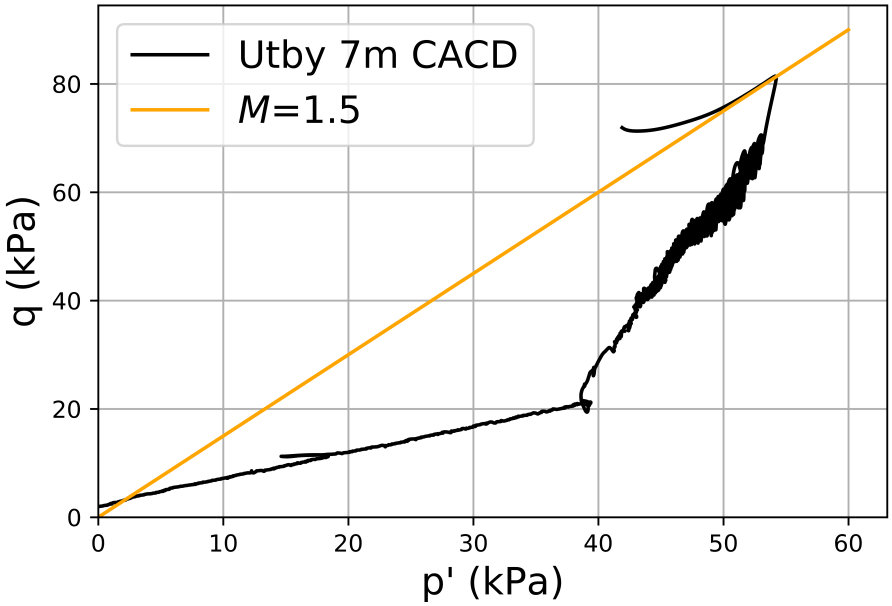


Figure 3.11

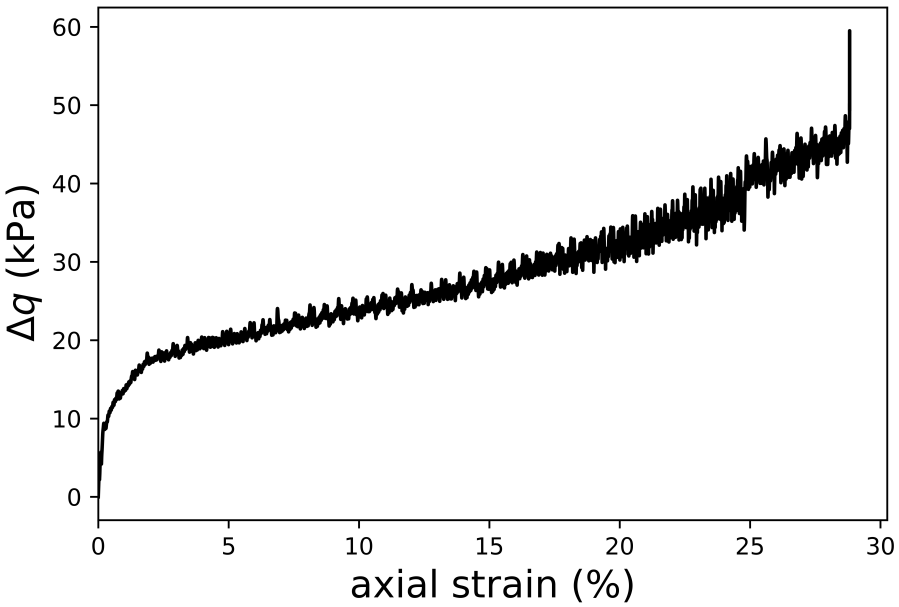


Figure 3.12

4 Conclusions & Recommendations

4.1 Conclusions

The research set out to investigate the feasibility of obtaining high quality results from standard STII piston samples by coring miniature samples. A natural Swedish sensitive clay from Utby was used, for which a large data set of test results on standard sized samples from the STII and mini-block sampler are available.

A bespoke test setup to subsample, and subsequently test, the miniature samples in triaxial conditions was developed. The so-called X-Clay apparatus is a miniature Bishop-Wesley cell with added features to handle small samples without further disturbance during handling, mounting and testing.

The turn around time for miniature undrained triaxial testing is on average reduced by 1 – 2 d. Miniature drained triaxial tests, however, can be performed in a similar amount of time as an undrained test on a regular sample size (days instead of weeks).

A series of anisotropically consolidated undrained triaxial tests were performed on miniature samples with reduced height, *i.e.* a reduction from 100 mm to 20 mm, and diameter, *i.e.* a reduction from 50 mm to 10 mm. All samples tested indicated high quality following the Lunne (or NGI) metric. This sample quality assessment metric proved to be a poor indicator of sample quality for triaxial testing of both miniature and standard sized samples.

Although, the miniature tests show scatter that relate to more erratic excess porewater pressure response, the scatter in the evaluated undrained shear strength is comparable to that found for the large samples from STII and mini-block after increasing the strain rate.

The results indicate that in undrained loading paths the generation of excess porewater pressures are strongly affecting the results. The current data indicate that for best comparison with the high quality data on large samples, the loading rate needed to be increased from 0.01%/min to 0.05%/min.

Whilst the strength properties agree well, the post-peak softening behaviour and the undrained stiffness remain strongly affected by the more pronounced generation of excess porewater pressures. In this regard miniature testing reduced the reliability of the results when compared to STII and mini-block samples. This partly due to the scaling errors arising from sample inhomogeneities and partly from the testing procedure.

In conclusion, the current test campaign suggests that small samples are not a viable alternative to reduce sample disturbance effects, and their associated uncertainties for undrained triaxial tests on STII samples, without increasing the number of tests.

Finally, the current miniature test setup shows promising results for drained loading paths, where excess porewater pressure effects are absent, and effective stress parameters are directly measured. The latter are more suitable for subsequent advanced analyses using Finite Element Analyses.

4.2 Recommendations

4.2.1 Scientific

Some of the scientific and technical issues encountered can be overcome by investigating the following:

- The natural deviation of the miniature samples can be tackled by the larger number of tests available from the same volume of material obtained from the field. The shorter test duration partly mitigates the additional expenses incurred.

- Some of the discrepancies observed between the two group of tests, with different sample size, could be overcome by the selection of an intermediate sample size. This approach would combine the benefits of the subsampling procedure to minimise sample disturbance and a reduction of the impact of the natural heterogeneities on the results.

- The new apparatus has a high potential for drained probing of natural soft soils under different controlled stress paths with significantly reduced test duration and sampling costs. This aids the development of the next generation of representative constitutive models for natural sensitive clays.

4.2.2 Engineering Practice

Given the data gathered and lessons learned in the current project it seems prudent to recommend the following for engineering practice. The findings in this report indicate that for the determination of strength and stiffness on (deep) samples obtained with the STII sampler:

- Normal sized samples 50 mm diameter x 100 mm height are preferred for the most reliable determination of (undrained) stiffness.

- Miniature tests are a viable option -without added uncertainties from sample disturbance- when limited soil material is retrieved (*i.e.* one middle tube only) and anisotropic (undrained) strength is of main interest.

4.2.3 Applied research for engineering practice

- For undrained loading paths it is recommended to investigate intermediate sample sizes cut from the STII samples as well as other sampling techniques based on large diameter piston samplers (diameter > 100 mm). Both approaches are expected to improve the quality of the samples and hence the data from the subsequent laboratory tests when compared to mini-block samples, whilst enabling samples from deep deposits. In some cases this can lead to substantial reduction in foundation costs.

- The miniature testing procedure shows most promise for drained loading paths (monotonic and/or cyclic). Therefore, further investigation is recommended with an explicit focus on drained loading. Obtaining reliable experimental data on the drained response of soft soils is becoming increasingly more important, given that over the years the need for more advanced laboratory tests to obtain drained soil properties for aiding the design of

foundations and deep excavations in soft soils has increased. This is partly due to their need in more advanced numerical analyses, and partly out of necessity for modelling the rate-dependent response of soft soils, such as those in Gothenburg. Problems have recently arisen in some major projects where drained triaxial tests have been performed, most notably a series of drained triaxial tests performed for Centralen and Rosenlund in Gothenburg by two independent laboratories. The tests show premature undrained failure after a sudden build-up of excess pore water pressures during drained shearing, resulting in unreliable measurements for the internal friction angle (an essential soil property). To prevent this type of unwanted test anomalies, a refined test protocol for the execution of drained triaxial tests on natural sensitive clays need to be developed using a combination of back-analysis, numerical modelling and experimental testing.

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