Geotech Geol Eng (2009) 27:207–215
DOI 10.1007/s10706-008-9223-2

ORIGINAL PAPER

Economic Sampling and Extraction of Undisturbed, High Quality Samples in Normally Consolidated Lacustrine Clays Using a Large Diameter Tube

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Received: 25 September 2007 / Accepted: 27 April 2008 / Published online: 23 May 2008
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Abstract This paper describes the development, design and use of a large diameter sampling tube. High quality test specimens are essential for the investigation of mechanical properties of a soil for high risk projects and when complex and expensive testing methods are to be used. Block sampling is recommended to give the highest sample quality for clayey soils, however, extracting blocks of normally consolidated lacustrine silty clay without excessive disturbance was challenging due to the inherent structure of the soft varved silty clay and difficulty in maintaining K_o conditions, as well as no vertical strain, in the sample. A new sample tube, with an inner diameter of 196 mm, an area ratio of 4% and an outer cutting-edge angle of 11° was designed to offer a larger cross sectional area than conventional thin walled sampling tubes, to provide the necessary side support and to prevent water ingress at the sides of the sample. The length-diameter aspect ratio was 1.275 to optimise the amount of clay sampled for subsequent testing and in an attempt to minimize the pressure in front of the tube. Samples were taken in initially newly excavated trenches at a depth of c. 1 m with this new sampler and with conventionally sampled soil specimens, prior to the main testing programme with samples from 6 m depth. A comparative study was then performed including preliminary unconsolidated unconfined compression tests followed by anisotropically consolidated undrained triaxial compression tests. It was important to establish whether this approach had led to an improvement in sample quality prior to embarking on an extensive triaxial stress path testing programme on this varved soil (Messerklinger, Non-linearity and small strain behaviour in lacustrine clay, 2006; Messerklinger and Springman, Geotech Test J 30(6), 2007; Messerklinger and Springman, Geotech Geol J, 2008). The results showed that the undrained shear strength of the specimens from the new sampler was consistently around 20% higher than that of specimens extruded from conventional thin walled tube samplers. This confirmed that samples with a significantly higher quality could be extracted from normally consolidated, fine grained, varved lacustrine deposits with this large diameter 'block' sampling tube.

Keywords Block sampling techniques · Varved lacustrine clay · High quality test sample

1 Introduction

It is well known that following any stress relief arising from excavation or drilling, sampling and extraction using standard sample tubes changes the stress and strain history considerably (e.g. Ladd and

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Lambe 1963; Baligh 1985; Baligh et al. 1987; Hight et al. 1992; Tanaka et al. 1996; Lunne et al. 1997; Clayton et al. 1998; Hight 2001; Ladd and DeGroot 2003). This modifies the mechanical characteristics of the soil and leads to the specification of different, and in general more conservative, material parameters (e.g. La Rochelle and Lefebvre 1971; Lefebvre and Poulin 1979; Lacasse et al. 1985). Therefore, the issue of sampling and extraction for objective laboratory investigations still remains a topic of concern and discussion (e.g. Jamiolkowski et al. 1985; Stallebrass et al. 1993; Clayton et al. 1998; Tanaka and Tanaka 1999; Jamiolkowski 2003; Long 2003, 2006; Ladd and DeGroot 2003; DeGroot et al. 2003; DeGroot and Lutenegger 2003).

Several advanced sampling methods for clays have been proposed in the literature. Namely, three significant 'block sampling' methods have been in use for over 25 years, stimulated by the need to obtain geotechnical parameters from highly sensitive marine or quick clays:

– Traditional block sampling method (Lefebvre and Poulin 1979),
– Sherbrooke 'block' sampler (Lefebvre and Poulin 1979), or
– Laval 'block' sampler (La Rochelle et al. 1981).

Traditionally, block samples are carved out of the soil deposit at the bottom of a trench, whereas a 250 mm diameter cylindrical sample is cored from the bottom of a large scale borehole using a Sherbrooke sampler, with three circumferential cutters combined with downward directed water jets and three separate spring loaded base cutters. Some recent experience of downhole block sampling using a Sherbrooke device by the Norwegian Geotechnical Institute (NGI) and the University of Massachusetts (UMASS) has been summarised in DeGroot et al. (2003) with additional work from the Building Research Establishment (BRE), the Port and Harbour Research Institute (PHRI) and University College Dublin (UCD) discussed by Long (2006). The Laval sampler is a large scale sample tube (diameter 208 mm) with an overcoring device that is pressed into the deposit at the bottom of a borehole.

The major drawback of the two latter methods is the use of bulky sampling tools that require heavy non-uniform machines, which are very expensive and hence generally not feasible for commercial projects, and barely even for research purposes.

2 Block Sampling Method after Lefebvre and Poulin (1979) in Lacustrine Soils

The block sampling method after Lefebvre and Poulin (1979) was adopted in the first instance to sample normally consolidated varved lacustrine soils. A trench was excavated at the bottom of a 6 m deep excavation, and blocks of size 20 × 30 cm were carved out of the deposit, with a height of 20 cm. The base of the block was cut off with a steel plate with which the block was lifted out of the trench. The blocks were immediately packed in cling film wrap, waxed and placed in rectangular plastic boxes filled with damp sawdust.

During sampling, several disadvantages of this block sampling method were recognised:

– during carving around the desired samples, the normally consolidated and hence very soft clay stuck to the tools, even for the rather low plastic lacustrine clay sampled (Kloten clay: $I_P = 12\%$, $w_L = 27\%$, Messerklinger 2006), which was observed to have led to horizontal straining of the sample;
– when the extracted block was packed into cling film wrap and waxed, the sample was rotated successively. The blocks had a self weight of more than 20 kg and a soft consistency. Despite a careful approach, some deformations were applied to the block samples during turning and lifting. This observation was confirmed later in the laboratory, when a sample was unwrapped and cut;
– the intrinsic fabric of lacustrine deposits entails seasonal pairs of silt and clay layers sedimenting out (Bates and Jackson 1984; DeGroot and Lutenegger 2003; Messerklinger et al. 2004). The sample extraction took approximately 10 min. During this time, drainage along the silt layers to the side of the sample was possible, thus changing the water content, which was strictly discouraged by Skempton and Sowa (1963) for soft saturated clays. They contended that this is critical to being able to reproduce identical values of undrained shear strength despite changing total stress paths, provided also that the microstructure of the clay is not damaged significantly.

These observations led to the conclusion being drawn that the block sampling method after Lefebvre and Poulin (1979) is not a suitable method for high quality sample extraction from normally consolidated fine grained and varved lacustrine deposits.

The two other sampling methods, discussed in the introduction, are the Sherbrooke and the Laval sampler. Since the Sherbrooke sampler carves the sample from the deposit and extracts it without supporting its sides, while the Laval sampler uses a large scale tube, the latter method seemed to be the more promising one for the intended purpose.

Following the recommendations given in the literature, a new sampling tube was designed and constructed which has:

- no inside clearance (La Rochelle 1973; La Rochelle et al. 1981; Clayton et al. 1998);
- a small area ratio (Clayton et al. 1998; Tanaka and Tanaka 1999);
- a large sample diameter (Baligh et al. 1987);
- a small outside cutting-edge angle (La Rochelle et al. 1981; Clayton et al. 1998; Clayton and Siddique 1999; Tanaka and Tanaka 1999).

3 Design and Use of the New Sample Tube

A sketch of this newly designed sampling tube is shown in Fig. 1. A steel tube, with an outer diameter of 200 mm was manufactured and tested. The wall thickness of the tube is 2 mm, the area ratio (AR) is 4%, the diameter (B) over tube thickness (t) is ~100 and the outside cutting-edge angle (OCA) is 11°.

Additionally, a device to overcore the tube, whilst pressing the tube into the soil, was considered, similar to the Laval sampler. Overcoring was suggested by La Rochelle et al. (1981) as well as by Leroueil (2003), in order to minimise the pressure beneath the tube and to make sure that the soil that is replaced directly by the sampling tube is deformed towards the outside, rather than the inside, of the sample tube.

After consideration of early sampling experience with this very sticky soil, it was thought that any attempt to carve the soil would not work and consequently the idea of an overcoring device was set aside. Instead, the sample tube was designed with a length of 250 mm, which is short compared to the Laval sampler tube, in order to minimize the pressure in front of the tube.

This short, large diameter sample tube has the additional advantages that:

- the external force, necessary to press the tube truly vertically into the soil, is relatively small, which minimised any tendency for any one-off or repeated lateral movements;
- since lateral extent of the excavation was not an issue, several short samples could be taken next to each other without interference, giving more test specimens with the same layering, which is particularly important for the varved structure of lacustrine soils;

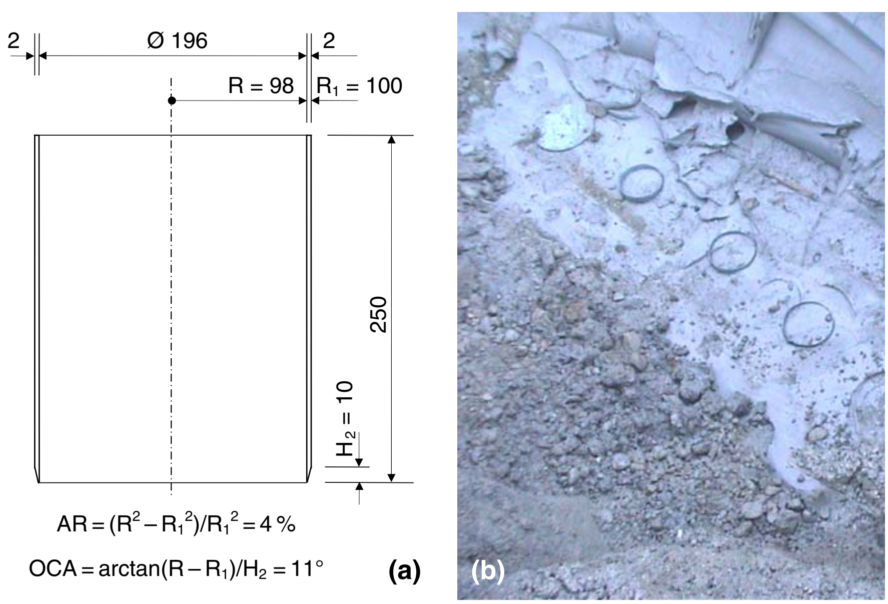


Fig. 1 (**a**) Design of the new sample tube (dimensions in millimetres). (**b**) Sampling Kloten clay with the new large diameter tubes

– Baligh et al. (1987) investigated tube penetration using the Strain Path Method, which they stated to be the dominant source of disturbance:

  - shear distortions were only seen near sampler walls with virtually none seen in the central core of a soil specimen for tubes with B/t = 40;
  - the greatest disturbance is reflected in the vertical strain inside the sample;
  - hence samples taken in tubes with B/t = 100 will experience even less disturbance, which also implies that samples taken at a spacing of at least the radius of this large diameter tube will deliver acceptable sample quality (see spacings of greater than sample diameter in Fig. 1b);

– taking the full sample tube out of the deposit is easier:

  - in contrast to standard tube sample extraction or Laval sampling, no vacuum or rotation was applied in order to separate the sample from the deposit;
  - the sample tube together with the sample inside was separated from the deposit by carefully digging the surrounding soil away until it was possible to cut the tube off from the underlying soil with a steel wire, this is only suitable for comparably short sample tubes;
  - the sample weighed less (total <14 kg) and was easier to handle;

– since smaller portions of soil will be extruded in the laboratory, no additional storage of the sample between extrusion and test performance is needed;

Contrary to the suggestions of La Rochelle et al. (1981), it was decided to keep the soil sample in the steel tube until test sample preparation, in order to overcome the distortions due to packing and to minimize any side-drainage.

A device was constructed to extrude the soil from the sampling tube (Fig. 2a and b), consisting of two parts, a circular steel plate which a diameter of 195 mm and a steel ring with an inner diameter of 198 mm (Fig. 2a). The plate is placed on the bottom and the ring on the top side of the sample tube. The sample is then extruded from the tube in a press.

To obtain an indication of the relative sample quality achieved, a comparative study on samples taken with the new sample tube and with two standard sample tubes was performed. One of the standard tubes had an inner diameter of 100 mm, an AR of 8% and an OCA of 16° and the other had an inner diameter of 65 mm, an AR of 13% and an OCA of 16°. The walls of both standard samplers were 2 mm thick.

A lacustrine clay deposit from a traffic intersection in Birmensdorf, on a bypass west of Zurich, was selected for this investigation. A trial pit was dug to a depth of 1.0 m. Then several sets of these three different sample tube types were carefully pressed vertically into the deposit, before the sample tubes (also containing the soil) were extracted by excavation with the shovel and were separated from the deposit with a steel wire.

The mechanical and mineralogical characteristics of the lacustrine Birmensdorf clay, used in this investigation, are given in more detail in Fleischer (2000), Panduri (2000), Plötze et al. (2003), Trausch Giudici (2004), and Messerklinger (2006).

4 Laboratory Investigations

4.1 Unconsolidated Unconfined Compression Test

It was decided to perform unconsolidated unconfined compression (UUC) tests to evaluate the sample quality (Fig. 3). This type of test provides no radial support to the test specimen and consequently the 50 mm diameter and 80 mm high specimens were expected to react more sensitively to sample disturbance (e.g. Lacasse et al. 1985).

For the test specimen preparation, the soil sample was extruded carefully from both the block samples and the tube samples using the extrusion device for the block samples (Fig. 2) and an equivalent standard extrusion device for the tube samples. Standard size test specimen (UUC test: 50 mm diameter and 80 mm height; CAUC tests: 50 mm diameter and 100 mm height) were cut and trimmed on a soil lathe using cheese wire and were placed in the test apparatus.

From the test results (Fig. 3) can be seen that significantly greater peak deviator stresses (which are also the total axial stresses, σ_a) were mobilised for the

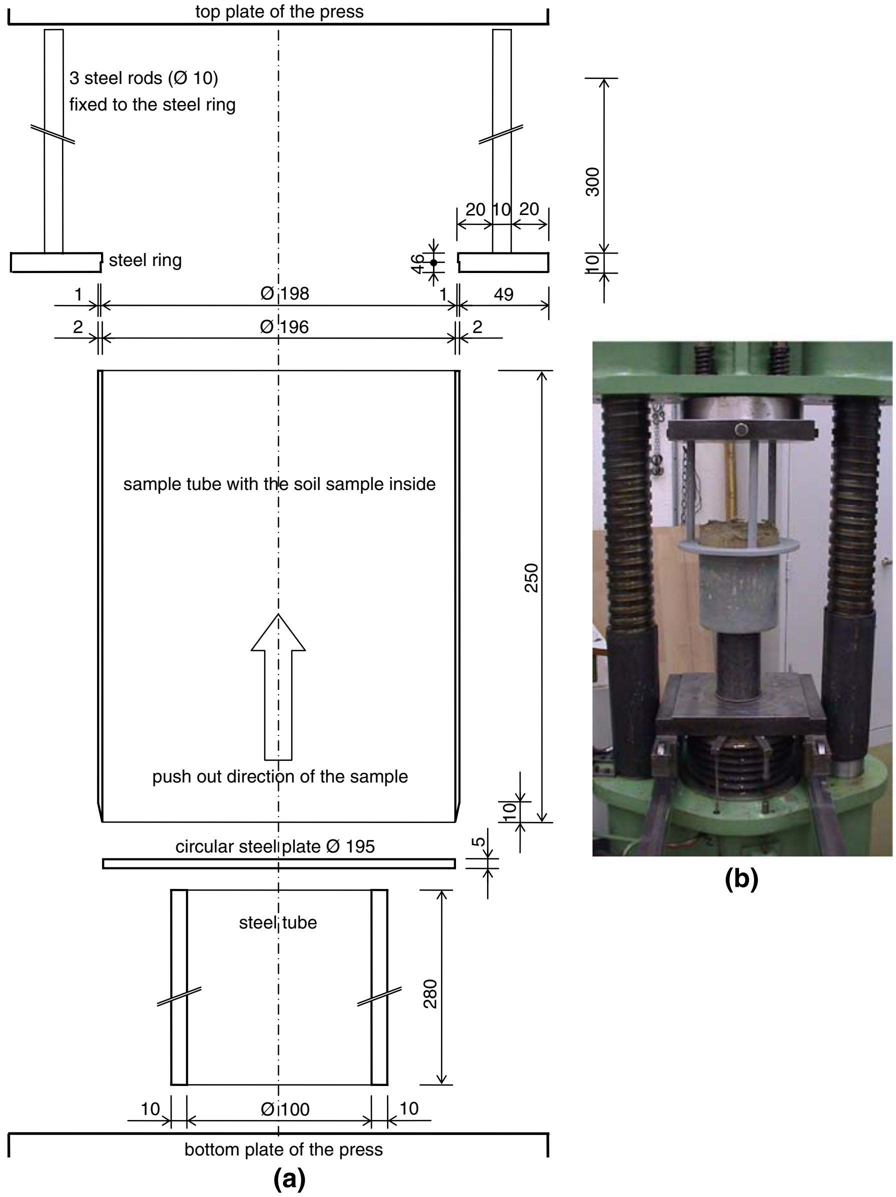


Fig. 2 Extrusion of the soil sample from the tube: (**a**) sketch of the extrusion setup with the steel tube and the circular steel plate on the bottom side of the sample tube and the extrusion device on the top side (dimensions in millimetres), (**b**) picture of the extrusion setup

specimens trimmed from the largest tubes with lower area ratio and cutting edge angle. Furthermore, the deviator stresses were also somewhat higher for the specimens from the 100 mm diameter tubes, with the same OCA but lower AR than those from the 65 mm diameter tubes.

Although the UUC test is not a highly sophisticated means of investigation to determine accurate values of undrained shear strength (e.g. Ladd and DeGroot, 2003) and the effective stresses cannot be determined, it still has validity for comparison of data from the same testing method for the different quality samples. This method was also adopted by Santagata and Germaine (2002) to investigate the influence of loss of effective stress due to sampling. They showed that minimising the loss of effective stress due to sampling was essential to maintain high quality samples. Data from the present investigations show likewise that the shear resistance increases significantly when the same soil is less disturbed, having been sampled with tubes of larger diameter.

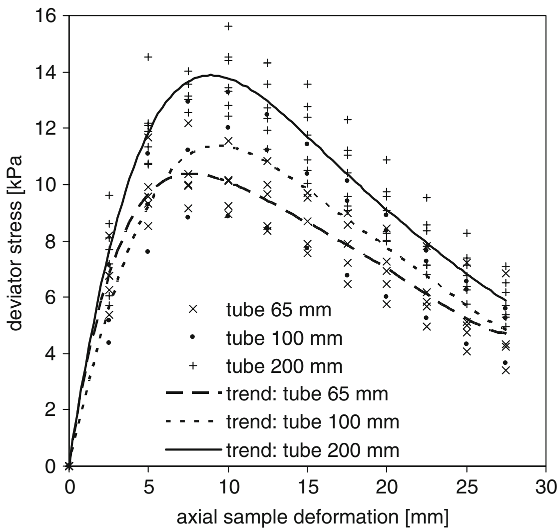


Fig. 3 Results of the unconsolidated unconfined compression tests on natural Birmensdorf clay with specimens from three different sample tube diameters

4.2 Anisotropically Consolidated Undrained Triaxial Shear Tests in Compression

Subsequently, anisotropically consolidated undrained triaxial compression (CAUC) tests were performed to confirm whether the results of the UUC tests would be repeated under significantly more controlled test conditions. Details of the sample preparation and data evaluation methods are described further in Messerklinger (2006).

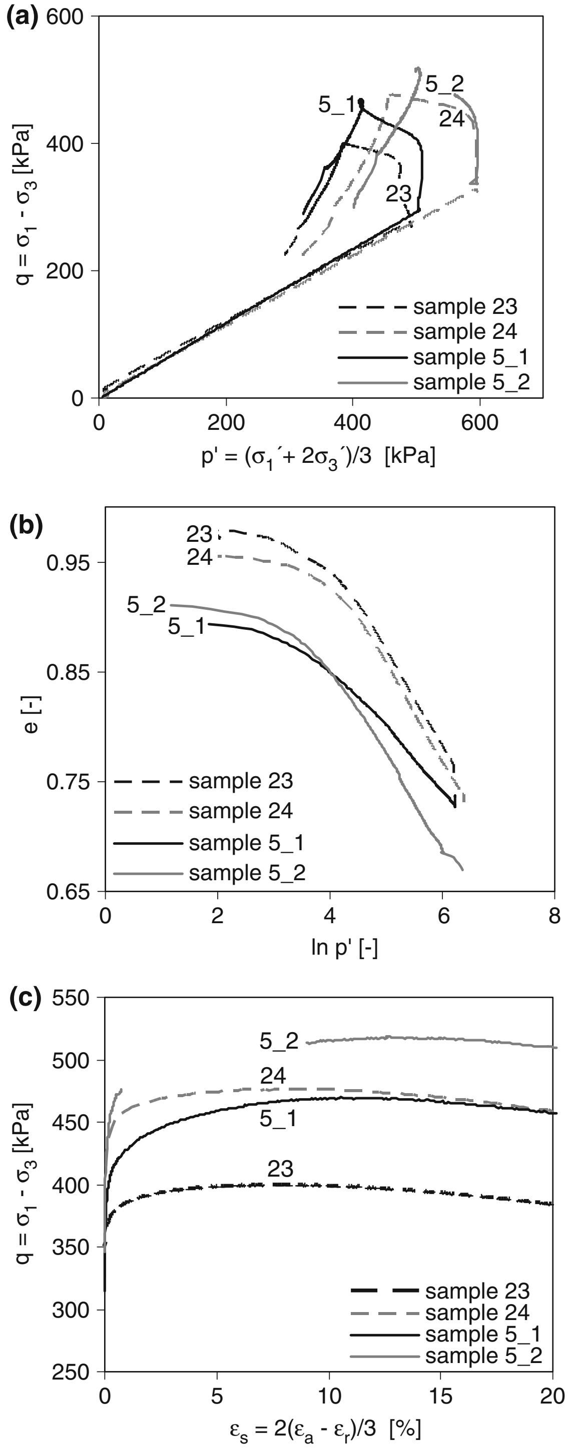
Tests B5_1 to B5_2 were performed on samples from a 200 mm diameter tube and tests 23 and 24 were performed on samples from a 65 mm diameter tube. The samples B5_1 and 23 were consolidated anisotropically along the same path to the same stress state, and subsequently sheared undrained under strain control in compression at the same cell pressure and strain rate. This was also done with samples B5_2 and 24, but at a higher stress level (Fig. 4a). This allowed comparative data to be obtained for the two datasets.

Comparison of the stress paths in the mean effective stress—deviator stress (p′−q) diagram (Fig. 4a), with $p' = (\sigma'_a + 2\sigma'_r)/3$ and $q = (\sigma'_a - 2\sigma'_r)$ and σ'_a, σ'_r representing the axial and radial effective stresses respectively, shows that both larger diameter samples have a steeper stress path following consolidation up to the peak value of the deviator stress. Long (2006) notes that this is generally the case for the post consolidation effective stress path until failure for high quality samples, while the stress path displays loss of mean effective stress at more or less constant deviator stress before failure for low quality samples. The stress path is close to horizontal in p′−q space near to failure for the 65 mm diameter tube samples, which results, ultimately, in a lower undrained shear strength.

Evaluation of a comparative void ratio e at a specific value of p′ (say 10 kPa) of the four test specimens prior to anisotropic consolidation (Fig. 4b), shows that the two specimens cut from larger diameter tube samples with lower area ratios have smaller values (0.8897 and 0.9002 respectively) than the two specimens from the 65 mm diameter tube samples (0.9771 and 0.9543). The magnitude of change in initial void ratio lies in a range between 5% and 10%. This clearly indicates that this varved soil undergoes more loosening during the sampling process when tubes of smaller diameter are used. This tendency of looser samples from the 65 mm diameter tube samples even remains after consolidation (e at undrained shearing, Table 1).

Changes in void ratio Δe during the reconsolidation phase up to the past pre-consolidation vertical effective stress σ'_p are also indicative of greater disturbance in the tube samples. Lunne et al. (1997) suggest using the criteria $\Delta e/e_o$ during this anisotropic consolidation phase back to σ'_p and values less than 4% imply very good to excellent sample quality and between 4% and 7% good to fair quality, which was also recommended by Long (2006). It is nonetheless challenging in this case to calculate these values since the limitations in the testing method meant that it was not possible to establish true e_0 values and establishing σ'_p on a logarithmic scale is known to be dependent on the method adopted and on velocity of loading, so there are too many sources of error in determining Δe and e_o and hence $\Delta e/e_o$.

The peak deviator stress (q_{peak}) and the corresponding shear strain increment applied during the shear path after consolidation ($\Delta\varepsilon_s$ at q_{peak}), as well as the residual deviator stress (q at $\Delta\varepsilon_s = 20\%$) is presented in Table 1. Together with the plot of deviator stress q against shear strain ε_s of the two pairs of tube and block samples (Fig. 4c), Table 1 shows that higher peak and residual deviator stresses are mobilised for the larger diameter samples at the



◀ **Fig 4** Results of undrained triaxial compression tests on natural samples of Birmensdorf clay, taken with the new sample tube (sample 5_1 and 5_2) and with conventional 65 mm diameter sample tubes with (sample 23 and 24): (**a**) anisotropic consolidation and undrained shearing effective stress paths; (**b**) compression curves of the anisotropic consolidation paths (e-ln p′); (**c**) deviator stress against shear strain of the undrained shear path (shear strains are set zero at the start of the shearing path)

same magnitudes of shear strains. The magnitude of this difference is around 20%. These results are comparable to those given by the UUC tests discussed previously.

Table 1 Summary of the shear failure stress/strain states

Sample	q_{peak} (kPa)	$\Delta\varepsilon_s$ at q_{peak} (%)	e During shearing (-)	q at $\Delta\varepsilon_s = 20\%$ (kPa)
23	400	6.8	0.6916	384
24	477	8.0	0.6733	458
5_1	470	12.2	0.6153	457
5_2	518	12.6	0.5861	510

5 Conclusion

The purpose of this investigation was to find an economic yet effective method of extracting high quality samples from test pits and excavations in normally consolidated fine grained lacustrine deposits for subsequent laboratory stress path testing. A new sampling tube was designed after testing and evaluating the suitability of the existing advanced block sampling methods for clays, as proposed in the literature.

The comparative study of shear tests conducted on specimens taken with the new sample tube and with conventional tube samples showed that:

- the relative sample quality, measured by the increase in undrained shear strength improved significantly (∼20%),
- the magnitude of increase (of undrained shear strength) of sample quality is in the same range as can be expected using the Laval or the Sherbrooke sampler (e.g. Tanaka and Tanaka 1999),
- but compared to these two advanced sampling techniques, the new sample tube allows for the special needs of sampling varved lacustrine clay deposits,
- and additionally allows an easy and consequently inexpensive high quality sample extraction, which is currently restricted to locations in pits and excavations above the water table.

Acknowledgements We gratefully acknowledge the help from Mr. Schwarz from the company Heierli AG for providing the opportunity to test the new sample tubes at the construction site of the highway intersection in Birmensdorf (CH). The first author is grateful for support from the Swiss National Science Foundation, Grant Nos. 200021-100 362 and 200021-100 362/1. The first author also thanks Mr. F. Sommerauer from the company Sommerauer in 5121 Hollersbach 7 (A) for supporting this research by manufacturing the new sample tubes and the corresponding sample extraction device.

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