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SAMPLE DISTURBANCE – SOFT CLAYS

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Abstract: This paper reviews the causes of sample disturbance and its impact on laboratory measured design parameters for soft clays. It is the most significant issue affecting the quality and reliability of laboratory test data. All key design parameters such as compressibility, yield stress and undrained shear strength are adversely influenced by sample disturbance. Each stage of the sampling process, from initiation of drilling to final preparation of laboratory test specimens, causes potential disturbance to samples and is described in the paper. Several practical solutions are presented, which if properly implemented can reduce the degree of sample disturbance. These include the use of weighted drilling mud, special tube sample geometry, fixed piston samplers, and proper sealing and handling of samples. Qualitative and quantitative methods of assessing sample quality are also presented together with examples from case studies.

1. INTRODUCTION

Figures 1a and 1b present stress history and undrained shear strength data for a soft clay site located north of Boston, Massachusetts. The site investigation was targeted at characterizing the thick soft clay deposit for design of a deep foundation system to support a highway superstructure. In particular, the key soil parameters required for design were the preconsolidation stress (σ'_p) and the undrained shear strength (s_u). The σ'_p data were from laboratory one-dimensional oedometer tests conducted on tube samples. The s_u data are from field vane (FVT) and torvane (TV) testing. The trends in the σ'_p and s_u data in figures 1a and 1b could be used as is for selection of design profiles. However, a simple inspection of the data in light of potential sample disturbance can reveal the poor quality and hence unreliability of the measured data. These data are used in Section 5 of the paper as an example to highlight the significance of sample disturbance for determination of design parameters in soft clays and methods that can be used to detect it.

This paper reviews the causes of sample disturbance and its impact on laboratory measured design parameters for soft clays. The paper first reviews the various stages of drilling, sampling and specimen preparation that can cause sample disturbance. Examples of the significance of sample disturbance for laboratory measurement of design parameters are given. Practical solutions that can help to reduce the degree of sample disturbance and methods for evaluating sample quality are presented. The data in figure 1 are examined in the context of the factors that cause sample disturbance and are evaluated using a simple sample quality assessment method. Data from other case studies are also presented. Some of the material presented in the paper is abstracted from Ladd and DeGroot [13].

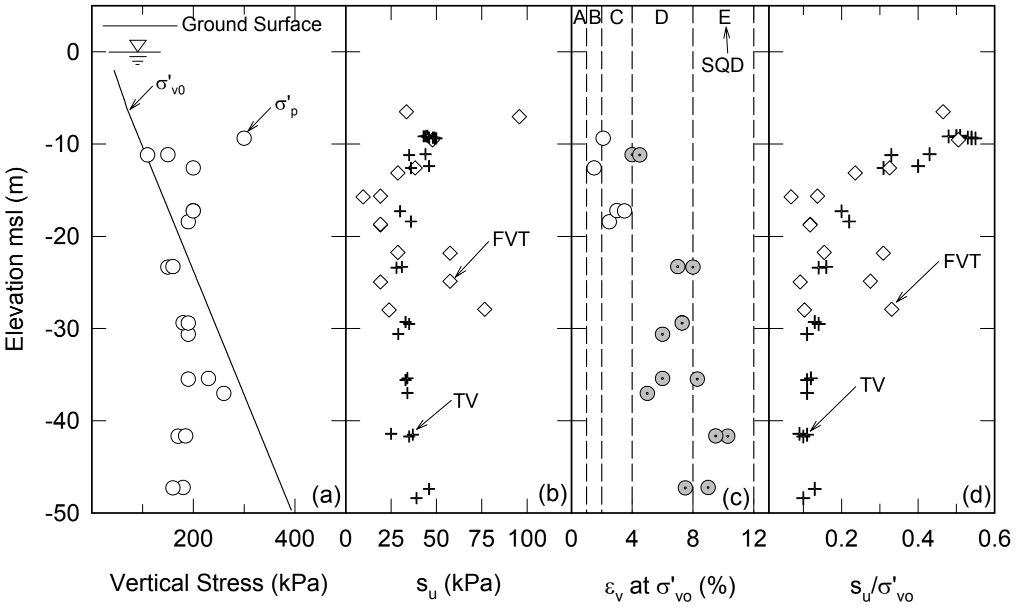


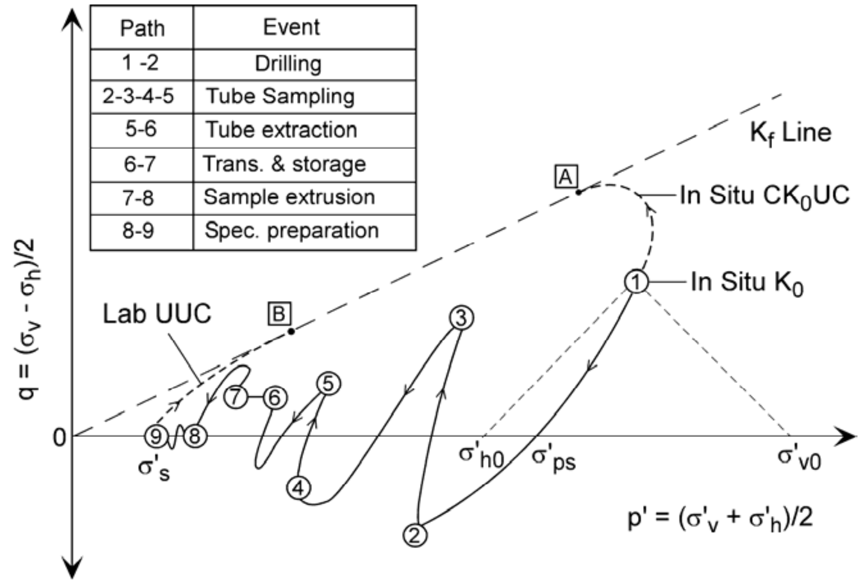
Fig. 1. Characterization data for soft clay, Saugus, Massachusetts:
a) stress history from oedometer testing, b) undrained shear strength, c) SQD sample quality,
and d) normalized undrained shear strength (after Mitchell et al. [21])

2. CAUSES OF SAMPLE DISTURBANCE

The most important effect of sample disturbance in soft clays is a soil destructuring, which is accompanied by a significant reduction in the sample effective stress (σ'_s). Figure 2 shows an example of how the reality of sampling and testing can vary unpredictably from the ideal. This figure shows the anticipated stress path experienced by a low overconsolidation ratio (OCR) clay starting from its in situ state of stress (Point 1) to its state of stress when ready for laboratory testing (Point 9). While design is for in situ stress states, disturbance caused by sampling and subsequent storage and handling can significantly alter the state of stress of samples. Clearly the state at Point 9 is very different from the in situ state at Point 1, and yet much of standard geotechnical engineering practice relies on strengths determined from samples starting from Point 9 (e.g., unconsolidated undrained triaxial compression [UUC] test). Figure 2 further shows the significant difference in potential effective stress paths for soil elements during undrained compression shear starting at Points 1 (in situ) and 9 (disturbed UUC test in the laboratory). Based on this simple depiction of what can happen during sampling, it should come as no surprise that there is often a gross mismatch between design performance based on laboratory derived strengths and field performance.

There are many factors involved in the process of drilling, sampling and specimen preparation that cause sample disturbance. The key stages of the process and its potential contributions to sample disturbance are as follows (with reference made to the points in figure 2):

Path 1–2. Borehole Drilling: Advancing an open borehole reduces the total vertical stress (σ_v), and hence subjects the clay at the bottom of the hole to potentially significant stress relief. The effective stress path from Point 1 to Point 2 in figure 2 passes through a point for which σ_v equals the in situ total horizontal stress (σ_{h0}). This stress state represents the theoretical "perfect sampling effective stress" (σ'_{ps}) as defined by LADD and LAMBE [14], i.e., the effective stress for undrained release of the in situ shear stress. However, if no drilling mud is used or its weight is too low, the soil at the bottom of the borehole can experience undrained extension unloading and in the worse case scenario can fail before it is even sampled.



Path	Event
1 -2	Drilling
2-3-4-5	Tube Sampling
5-6	Tube extraction
6-7	Trans. & storage
7-8	Sample extrusion
8-9	Spec. preparation

Fig. 2. Hypothetical stress path during tube sampling and specimen preparation of center-line element of low OCR clay (from LADD and DEGROOT [13])

Path 2–3–4–5. Tube Sampling: Many researchers have studied the influence of tube sampling techniques and sampler design on the quality of soft clay samples (e.g., Hvorslev [8], Baligh et al. [2] and Clayton et al. [3]). Baligh et al. showed that for tubes with an inside clearance ratio greater than zero, the centerline soil experiences shear in compression ahead of the tube (Path 2–3), followed by shear in extension as it enters the tube (Path 3–4), and then compression inside the tube (Path 4–5). This straining of the soil, which can approach one per cent at the center-line (and even greater values at the edges) for the standard 76-mm diameter Shelby tube (table 1), causes destructuring and positive shear induced pore pressures for low OCR clays.

Table 1

Dimensions of sampling equipment

Sampler	D_1 (mm)	D_2 (mm)	D_3 (mm)	t (mm)	Angle (°)	AR (%)	D_2/t (–)	ICR (–)
Standard SPT[†]	34.9	50.8	34.9[†]	15.9[†]	60	111.9	3.2	0[†]
	60.3	76.2	60.3[†]	15.9[†]	60	59.7	4.8	0[†]
Shelby tube	72.1	76.2	74.6	1.65	≈ 44[‡]	11.7	46.2	3.5
Modified Shelby tube	74.6	76.2	74.6	1.65	5	4.3	46.2	0
Sherbrooke	–	250	–	–	–	–	–	–

Notes: See figure 3 for dimensions; [†]SPT with liners; $AR = (D_2^2 - D_1^2)/D_1^2$, $ICR = (D_3 - D_1)/D_1$; [‡]approximate angle since edge is beveled.

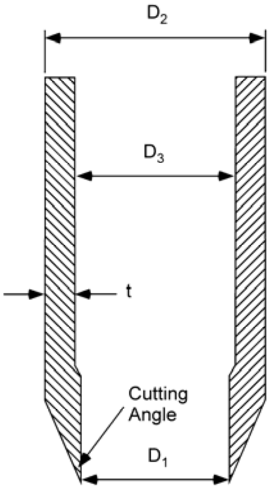


Fig. 3. Sample tube dimensions

Path 5–6. Tube Extraction: Debris and disturbed soil at the bottom of the borehole can enter an open tube sampler. After pushing, the strength of the clay at the bottom of the borehole and suction resists removal of the tube sample. These factors can result in significant disturbance of soil located at the top and bottom of the sample.

Path 6–7. Transportation and Storage: Excessive vibration/shock to the samples and large temperature changes, particularly freezing, during transportation can cause severe disturbance. During storage, consolidation of the positive shear induced pore pressure in the distorted zone at the perimeter of the tube causes a decrease in the overall effective stress in the sample.

Path 7–8. Sample Extraction: With time soil samples bond to the inside of tubes and in many cases subsequent extrusion can result in significant additional disturbance. The practice of extruding samples in the field eliminates this problem, but potentially increases the risk of handling disturbance in transporting the extruded samples from the field to the laboratory.

Path 8–9. Specimen Preparation: The test specimen may experience a further decrease in effective stress (to end up at σ'_s; Point 9) due to stress relief once removed from the tube and disturbance during trimming and mounting. According to LADD and DEGROOT [13] the pretest effective stress for reasonable quality samples of non-cemented clays is likely to be in the range of $\sigma'_s / \sigma'_{ps} \approx 0.25$ to 0.5 for relatively shallow soil of moderate OCR and in the range of $\sigma'_s / \sigma'_{ps} \approx 0.05$ to 0.25 for deeper soil with OCR < 1.5.

3. CONSEQUENCES FOR DESIGN

Sample disturbance adversely influences all-important engineering design properties of soft clays from compressibility to undrained shear strength. As shown in figure 2, the disturbance from sampling and handling results in a decrease in the sample effective stress. LADD and LAMBE [14] showed that this decrease can be well above 80% from the in situ effective stress and the reported laboratory stress–strain–strength properties at the sampling effective stress cannot possibly match the correct in situ properties. Even if samples are subsequently reconsolidated in the laboratory to in situ stresses, disturbed samples will undergo significant volumetric changes and further destructuring, again resulting in unrealistic stress–strain behaviour.

Figure 4 presents an example of this behaviour for constant rate of strain (CRS) consolidation tests conducted on two samples of Boston Blue Clay. One sample was collected using a regular Shelby tube (table 1) with a free piston and without drilling mud, the other sample was collected with a special Shelby tube (table 1) with a fixed piston and barite weighted drilling mud. The differences in the compressibility and preconsolidation stress are significant. Another example is shown in figure 5 for anisotropically consolidated (CAU) triaxial compression tests reported by LUNNE et al. [20] on samples reconsolidated to σ'_{v0} and σ'_{h0} (based on an estimate of the in situ

K_0) prior to undrained shear. The samples were collected using three types of samplers: the NGI 54 mm diameter sampler, a standard 75 mm diameter fixed piston, thin-walled tube sampler, and the Sherbrooke block sampler. There are clear differences in measured stress–strain behaviour and undrained shear strength that would have an important impact on selection of design parameters.

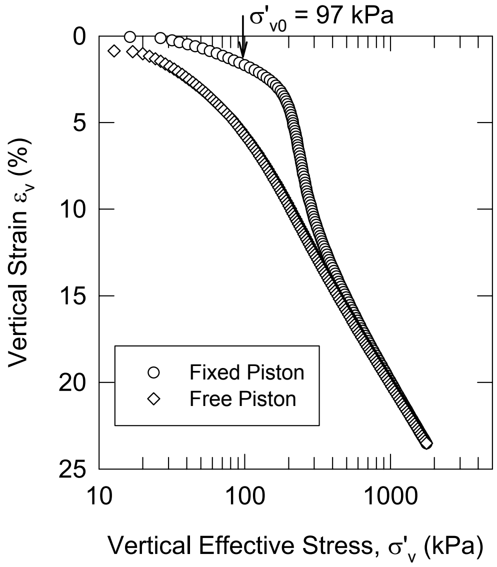


Fig. 4. Comparison of CRS data for fixed piston and free piston samples of Boston Blue Clay, Newbury, Massachusetts (depth of 9.8 m)

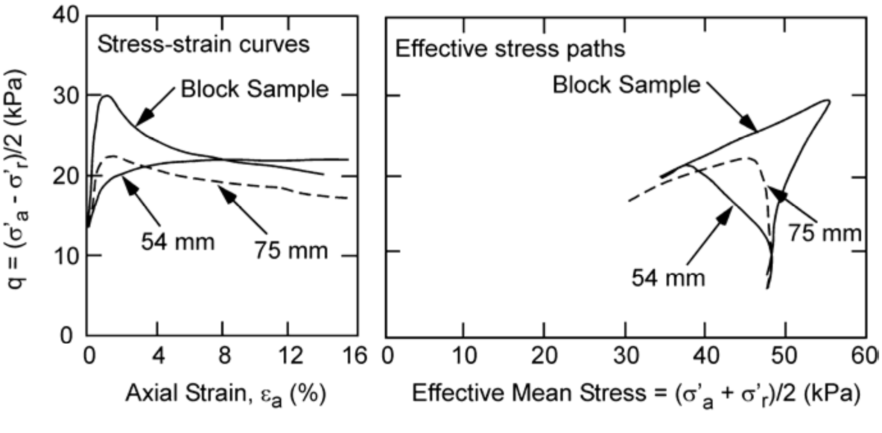


Fig. 5. CAU triaxial recompression test results for specimens of Lierstranda Clay, Norway, collected with three different samplers (LUNNE et al. [20])

4. PRACTICAL SOLUTIONS

The influence of sample disturbance on design parameters is significant as demonstrated by the examples presented in section 3. This section offers a number of practical solutions that can help to reduce the degree of sample disturbance experienced by soft clays. These solutions follow the drilling and sampling sequence given in section 2 and figure 2. Most of these solutions are relatively easy to implement in practice with little additional time and cost. In fact, several of the solutions have been known for several decades (e.g., HVORSLEV [8]) and yet are nevertheless still often not used in practice.

Path 1–2. Borehole Drilling: Stress relief is unavoidable because of the necessity of advancing an open borehole for most sampling methods. However, the magnitude of stress relief during drilling can be managed by using a weighted drilling mud. Ideally a drilling mud is used to keep Point 2 in figure 2 as close as practical to σ'_{ps}. LADD and DEGROOT [13] give a procedure for computing a suitable weight drilling mud given certain soil properties and borehole geometry. Typical recommended mud weights range from $1.2\gamma_w$ to $1.3\gamma_w$. The drilling mud can be developed using a combination of recirculation of cuttings and/or commercial drilling products. Mud weights can be enhanced by adding heavy weight products such as barite (barium sulfate), which has a specific gravity of 4.2. Mud weights should be checked with a mud balance. Careful attention also needs to be given to keeping the drilling mud at or near the top of the borehole, particularly during removal of long sections of drill rods.

Path 2–3–4–5. Tube Sampling: Research has clearly shown the benefits of using modified tube geometry to decrease the shear induced strains during tube sampling. For soft clays it is recommended to use large diameter (≥ 76 mm) tubes, with a sharp edged (about 5 to 10°, depending on soil stiffness) small area ratio ($AR < 10\%$) and approximately zero inside clearance ratio ($ICR \approx 0$). Figure 6 shows, drawn to scale, a standard 76 mm diameter US Shelby tube that has been modified to these recommendations by simply cutting off the standard end and machining a 5° cutting angle (by cutting the lip off the standard Shelby tube end the *ICR* goes to 0; table 1). Tubes should ideally be made of noncorrosive materials (e.g., stainless steel) and be clean and free from any dents or burrs. A light coating of lubricant (e.g., silicone oil) can be used to lubricate the inside of the tube.

Of all possible sampling methods, research has shown that block sampling, such as that with the Sherbrooke sampler (LEFEBVRE and POULIN [19]), is considered the best method of collecting high quality samples of soft clays (e.g., LACASSE et al. [11], LUNNE et al. [20], HIGHT et al. [7], TANAKA [24]). The Sherbrooke sampler does not use a sampling tube but rather carves samples out of the bottom of a borehole that are approximately 250 mm in diameter by 300 to 350 mm in height. While the Sherbrooke sampler is a specialized piece of equipment, it is feasible to use it with standard drilling equipment (e.g., DEGROOT et al. [4]). Even though block sampling is considered a state-of-the-art sampling method, its use should be considered for large, complex projects. Examples of the successful use of the Sherbrooke block sampler on commercial design projects are given by LADD et al. [15] and HERMANN and JENSEN [5].

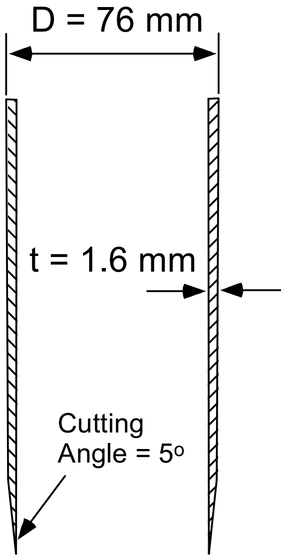


Fig. 6. Schematic of modified Shelby tube drawn to scale: $ICR = 0$, $AR = 4.3\%$, $D/t = 46$

Path 5–6. Tube Extraction: The use of a stationary (fixed) piston while tube sampling is essential for high quality sampling. The piston prevents debris from entering the tube before reaching the bottom of the borehole and controls the entry of soil during sampling. The piston head also serves to create suction inside the tube at the top of the sample to better retain it during tube extraction. Fixed piston samplers use either actuating rods or hydraulics to control the piston head. The actuating rods are more cumbersome to use than the hydraulic system, but they do allow direct observation of the position of the piston head at the ground surface during sampling.

Path 6–7. Transportation and Storage: The ends of tube samples should be sealed with wax and capped (usually plastic caps that are sealed with duct or electrical tape) in the field prior to transport. Wax sealing is best done using a 50:50 mixture of paraffin wax and petroleum jelly (LA ROCHELLE et al. [17]). It is important that the wax mixture be brought just to its melting point and not overheated. Block samples should be sealed using multiple layers of the same 50:50 mixture together with a couple of layers of plastic wrap dipped in the wax mixture and a final layer of cheese cloth to provide additional support. Samples should not be subject to excessive temperature changes, particularly freezing temperatures. Tube and block samples should be transported upright in boxes that provide damping of shocks and vibrations. This can be done by placing the samples on foam padding, surrounding the samples with wood chips or Styrofoam pellets, and using vibration control mounts for the boxes (e.g., figure 7). Once at the laboratory, samples should be stored in a room with humidity and temperature control.

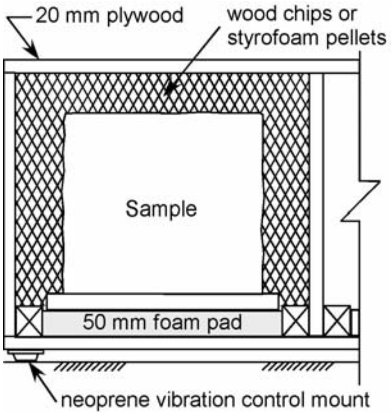


Fig. 7. Schematic of container used for transport of block samples (DEGROOT et al. [4])

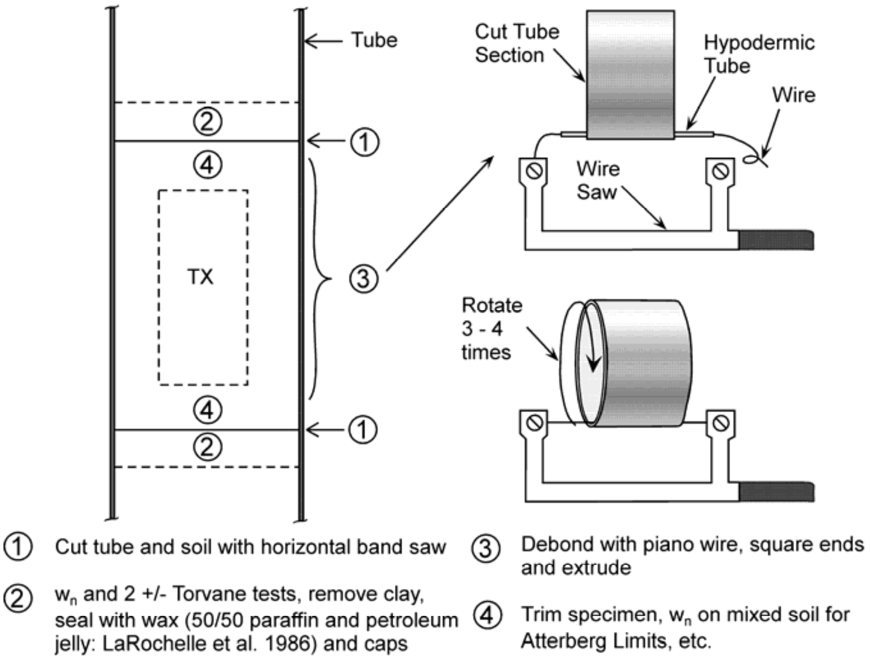


Fig. 8. MIT procedure for obtaining test specimen from tube sample (LADD and DEGROOT [13])

Path 7–8. Sample Extraction: The potential bonding between the inside of tubes and the soil can result in severe disturbance during laboratory extraction. Therefore, samples should not be extruded from tubes (except if done immediately after sampling) without first breaking any bonding at the soil–tube interface. Once a location within a tube is selected for testing, the tube should be cut adjacent to the desired sample location using a horizontal band saw or by hand (e.g., hack saw). A hypodermic tube can be used to feed a thin wire into the soil/tube interface and rotated several times around the perimeter to break the soil/tube bond (figure 8). With experience, the whole process only takes a few minutes.

Path 8–9. Specimen Preparation: Soil within 1 to 1.5 times the tube diameter from the top and bottom of the tube should not be used for consolidation and strength testing because of greater disturbance near the sample ends (LACASSE and BERRE [10]). Test specimens should be carefully trimmed in a humid room using sharp cutting tools and wire saws. Subsampling in the laboratory using tubes can create additional disturbance and therefore should not be used. Sample sides should be trimmed during specimen preparation to also remove potentially disturbed perimeter material. Trimming in a humid room should prevent moisture evaporation from samples but it is also important to control sources of swelling during specimen set-up (e.g., HIGHT [6]).

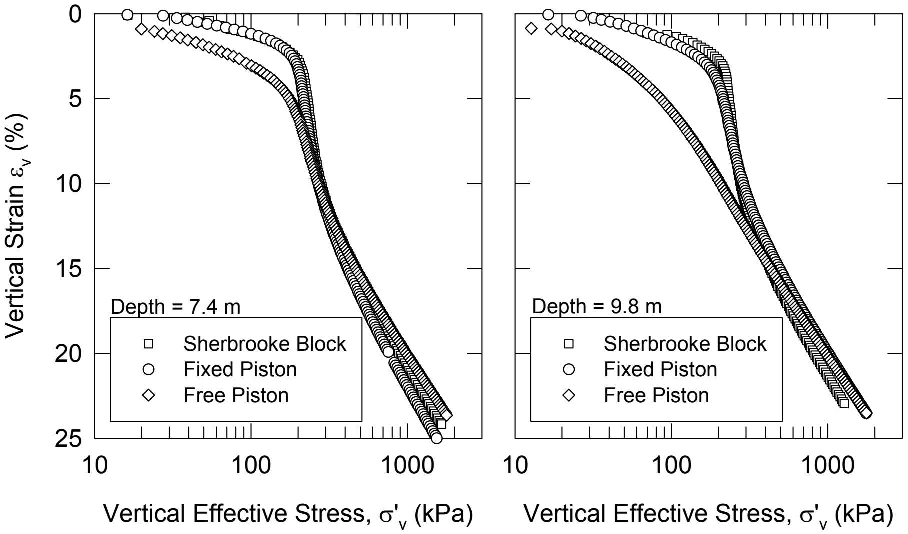


Fig. 9. Comparison of CRS data for free piston, fixed piston and Sherbrooke block samples of Boston Blue Clay, Newbury, Massachusetts

Summary: Figure 9 plots data from CRS tests conducted on samples of Boston Blue Clay collected with three different sampling methods. The free piston samples were collected using a standard 76 mm Shelby tube (table 1) in a borehole without drilling mud, the fixed piston samples were collected using a modified Shelby tube (table 1) using a fixed piston sampler in a borehole advanced with a barite based drilling mud, and the block samples were collected using the Sherbrooke block sampler using a barite based drilling mud. The samples were sealed, transported and trimmed in accordance to the recommendations given above. The difference in quality between the free piston samples and the fixed/block samples is significant. However, of even greater significance is the fact that the fixed piston samples produced compression curves nearly identical to the high quality block samples. These results show that it is possible to collect very good to excellent quality samples with equipment that is readily available to most drillers (the only custom item for the fixed piston sampling was the machining of the ends of the standard Shelby tubes to produce the 5° cutting angle and zero *ICR*).

5. QUANTIFICATION OF SAMPLE DISTURBANCE

Whenever evaluating consolidation and strength data it is essential to evaluate sample quality although this is not common in practice. Radiography is a critical step in any important test program and provides valuable visual information on sample quality and selection of test specimens from sample tubes. Qualitative methods of evaluating sample quality include measurement of soil suction to get σ'_s (LADD and LAMBE [14], POIRIER et al. [22]), volumetric strain ($\varepsilon_{\mathrm{vol}}$) during laboratory reconsolidation to σ'_{v0} (ANDRESEN and KOLSTAD [1]), and shear wave velocity (SHIBUYA et al. [23], LANDON et al. [16]). Currently, the simplest and most effective of these methods is the measure of $\varepsilon_{\mathrm{vol}}$ at σ'_{v0}. ANDRESEN and KOLSTAD [1] first developed this method with a ranking system that assigns a description of sample quality ranging from poor to excellent. TERZAGHI et al. [25] adapted this method and coined the term *Specimen Quality Designation* (SQD) with sample quality ranging from A (best) to E (worst) as listed in table 2. Terzaghi et al. suggest that reliable estimates of engineering parameters such as σ'_p and s_u require samples with SQD equal to B or better. Recently, LUNNE et al. [20] updated Andresen's and Kolstad's sample quality method to use the measure of $\Delta e/e_0$ for reconsolidation to σ'_{v0} as listed in table 2. The $\varepsilon_{\mathrm{vol}}$ or $\Delta e/e_0$ measurements are objective and easy to perform on laboratory specimens and should be reported for every consolidation and CU strength test conducted on clays.

Figure 10 shows the value of the SQD method for assessing sample quality. The normalized preconsolidation stress based on CRS tests conducted on various quality samples of Boston Blue Clay is plotted versus $\varepsilon_{\mathrm{vol}}$ at σ'_{v0}. The σ'_p values from the high quality Sherbrooke block samples were chosen as the reference values and other estimates for the different sampling methods were normalized by these values. The decrease in σ'_p with a decrease in sample quality is large and has obvious consequences for design.

Table 2

Quantification of sample disturbance based on specimen volume change during laboratory reconsolidation to σ'_{v0}

Specimen quality designation (SQD) (TERZAGHI et al. [25])		$\Delta e/e_0$ criteria (LUNNE et al. [20])		
Volumetric strain (%)	SQD	OCR = 1 – 2 $\Delta e/e_0$	OCR = 2 – 4 $\Delta e/e_0$	Rating*
< 1	A	< 0.04	< 0.03	Very good to excellent
1–2	B	0.04–0.07	0.03–0.05	Good to fair
2–4	C	0.07–0.14	0.05–0.10	Poor
4–8	D	> 0.14	> 0.10	Very poor
> 8	E			

* Refers to use of samples for measurement of mechanical properties.

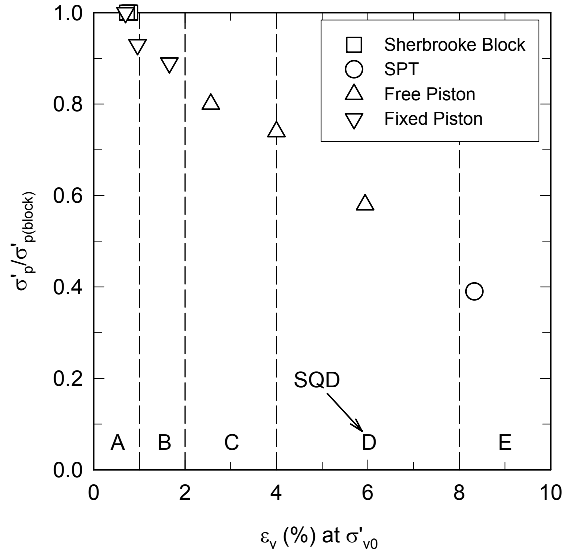


Fig. 10. CRS preconsolidation stress normalized by Sherbrooke block sample values versus volumetric strain at σ'_{v0} for different samplers, Boston Blue Clay, OCR < 4, Newbury, MA

Figure 1 also highlights the value of using simple quantitative methods of assessing sample quality. Figure 1c plots ε_{vol} (= ε_v) versus depth corresponding to the oedometer tests from which the σ'_p values in figure 1a were determined. All samples below elevation –20 m have SQDs of D and E which based on the recommendation of TERZAGHI et al. [25] would not produce reliable estimates of σ'_p. Corroborating evidence regarding the poor quality σ'_p data is the fact that all values below elevation –20 m are less than σ'_{v0}. This alone suggests an apparent underconsolidated soil. However, the geological history of the region (KENNEY [9]) indicates the soil should not be underconsolidated and only a slight 1.5 m artesian condition exists in the underlying glacial till. The apparent underconsolidation is probably a result of sample disturbance causing a large decrease in the measured σ'_p. For strength data, it is also useful to plot normalized values (i.e., s_u/σ'_{v0}) as is done in figure 1d for the field vane and laboratory torvane data. The FVT data are highly scattered and many tests had unusually low undrained strength ratios, i.e., s_u(FVT)/ σ'_{v0} only about 0.1. The s_u(TV) data show very little scatter and the s_u(TV)/σ'_{v0} ratios clearly show a transition from the crust to the softer clay at depth. However, the ratios for the deep clay are also very low. The poor quality tube samples (hence very low lab values of σ'_p and s_u) and unreliable FVT data are believed to be largely due to making a hollow stem auger borehole without a proper weight drilling mud.

6. SUMMARY

All aspects of drilling, sampling, and laboratory preparation can cause adverse disturbance to soft clay samples. This can result in misleading and unreliable laboratory measured stress–strain–strength behaviour, which can amount to either unsafe or overly conservative design. There are, however, a number of practical and relatively simple steps that can be taken to reduce the adverse effects of sample disturbance. Drilling should be conducted using an appropriately weighted drilling mud, samples should be collected using large diameter thin-walled, sharp edged fixed piston samplers. Samples should be protected from shock and excessive temperature changes during transport and stored under high humidity, controlled temperature conditions. Laboratory test specimens should be cut from tubes and debonded from the tube prior to trimming. It is essential to evaluate sample quality for all design parameter tests; $\varepsilon_{\mathrm{vol}}$ at σ'_{v0} during laboratory reconsolidation is a simple yet effective indicator of sample quality.

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