Studia Geotechnica et Mechanica, Vol. XXIX, No. 1–2, 2007

LABORATORY TESTING OF UNDISTURBED SOFT CLAY SAMPLES TO DETERMINE ENGINEERING DESIGN PARAMETERS

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Abstract: This paper reviews laboratory methods for measuring the stress–strain–strength–flow behaviour of soft clays for determination of design parameters. It describes three levels of testing from simple classification tests to advanced testing for measurement of design parameters. The paper traces some of the major practical contributions of experimental research to our understanding of soft clay mechanical behaviour. Recommendations are given for implementation of these research results in practice with the goal of improving the engineering state-of-the-practice, which often lags well behind the research state-of-the-art. Significant advances in the understanding of clay behaviour have been realized in the past few decades including such issues as the influence of anisotropy, stress history, rate effects, and sample disturbance. Of these issues, sample disturbance remains by far the most difficult one to deal with in practice and in fact is often ignored. It is recommended that evaluation of sample disturbance be considered an essential aspect of any site characterization program.

1. INTRODUCTION

Soft clays challenge geotechnical engineers because of their high compressibility and low undrained shear strength. Soft clay deposits often have highly varied geological histories, thus making systematic quantification of their stress–strain–strength–flow behaviour complex. They exhibit significant stress history effects, can have a high degree of anisotropy, and are strain rate sensitive. They are difficult to sample and test without causing excessive and irreversible sample disturbance. Given all these challenges, site characterization of clays is best done through a combination of in situ testing and laboratory testing of high quality undisturbed samples. Each approach has advantages and limitations, but provides complementary information when properly used. The key disadvantage to in situ testing is the reliance on empirical correlations for estimating soil parameters, whereas accurate laboratory measurements are largely dependent on the quality of samples available. The focus of this paper is on laboratory site characterization programs. The paper reviews laboratory methods for characterizing and measuring the static loading behaviour of soft saturated clays for determination of design parameters. This paper is a modified version of the paper by DEGROOT [7] and additional material is abstracted from LADD and DEGROOT [15].

Critical design parameters for soft clays include the preconsolidation stress (σ'_p), undrained shear strength (s_u), compressibility parameters $(\Delta e/\Delta \sigma'_v)$ and the consolidation/flow parameters coefficient of consolidation (c_v) and hydraulic conductivity (k_v). The preconsolidation stress or yield stress is the demarcation of small strain versus large strain deformation. For the majority of constructed facilities that involve soft clays, σ'_p and s_u are the most critical design parameters and thus particular attention is given in the paper to measurement of these parameters.

2. HISTORICAL PERSPECTIVE

In the early years of the profession, our basic understanding of soft clay behaviour was predicated on the concept that any in situ or laboratory test can provide a measure of undrained shear strength as long as no change in water content occurs during shear. Subsequent research has shown that soft clay behaviour is not so simple and that many other important factors, such as anisotropy, strain rate effects, stress history, and the disturbance to soil samples prior to laboratory testing, need consideration for development of design parameters. Research has greatly extended our knowledge of clay behaviour and it is important to note that many of these findings have been clearly shown to be important to the sound and economic practice of geotechnical engineering.

The state-of-the-art in geotechnical engineering laboratory testing has evolved significantly over the past decades. Modern geotechnical engineering laboratories are equipped with data acquisition systems coupled with electronic transducers that can reliably take readings at high frequencies and with high resolution. Data acquisition systems and accompanying PCs are now available at a modest price. Computer controlled load frames and flow pumps for displacement, force, or stress control are also available for commercial applications. Unfortunately, many laboratories have not upgraded their testing capabilities to take advantage of these advances. Furthermore, our ability to test soils using electronics has surpassed the level of implementation of many proper laboratory test procedures in geotechnical engineering practice.

This historical perspective serves as a background for the major goals of this paper: 1. To review reliable and practical laboratory equipment for characterization and measurement of soft clay behaviour. 2. To discuss the practical implications of results from research on clay behaviour. 3. To give recommendations for conducting laboratory test programs in practice.

3. EXPERIMENTAL CAPABILITIES

Laboratory test equipment and procedures for characterizing soft clays can nominally be divided into three categories: 1. Classification and basic index tests. 2. Express or strength index tests. 3. Advanced laboratory tests. Table 1 lists various common tests in each of these categories and their some advantages and disadvantages. The selection of the type and number of tests depends largely on the scope of the project. For simple and low risk projects (in terms of structure performance and human safety), it is not uncommon to rely almost exclusively on classification and index testing. This is also often the case for preliminary designs. However, reliable design parameters (e.g., strength, compressibility, etc.) from laboratory testing are best obtained through advanced tests conducted on good quality samples. Numerous advanced devices have been developed to measure the consolidation and stress–strain–strength behaviour of clays. Many papers have reviewed the capabilities of laboratory testing equipment including comprehensive reviews by LADD et al. [18], SAADA and TOWNSEND [23], JAMIOLKOWSKI et al. [12], and LADD [14]. This paper considers only devices and test methods that are acceptable for determining soft clay design parameters and that are realistically available to engineers. This limits the list to incremental load (IL) and constant rate of strain (CRS) consolidation, triaxial compression (TC) and extension (TE), and direct simple shear (DSS) equipment.

Table 1

Laboratory tests for characterization of clays

Test category	Test types	Advantages/disadvantages
Classification and basic index testing	• water content • density • Atterberg limits • grain size analysis • specific gravity	• simple and relatively quick to perform • equipment commonly available • necessary part of any site characterization program • cannot provide design parameters
Express/index strength testing	• pocket penetrometer • fall cone • torvane • laboratory vane • unconfined compression test	• simple and relatively quick to perform • equipment commonly available • often gives scatter results • successful use as design parameters requires soil/site specific empirical correlations
Advanced laboratory testing	• incremental load oedometer • constant rate of strain consolidation • triaxial • direct simple shear • direct shear box • hydraulic conductivity	• provides best control of soil state and conditions in the laboratory • provides direct measure of design parameters • PC automation potentially enhances productivity and reliability of test results • equipment more complex and expensive • higher operator skill level required • relies on good quality samples

3.1. CLASSIFICATION AND BASIC INDEX TESTING

Almost all geotechnical engineering laboratories are equipped to run classification and basic index tests, as they are relatively easy and quick to perform in accordance with internationally recognized standards (e.g., American Society of Testing and Materials (ASTM), British Standards (BS), etc.). While these tests are essential to any site characterization program, it is clearly recognized that they do not provide any direct information on design parameters. Many empirical correlations have been developed between basic index tests (e.g., Atterberg limits) and design parameters, however, these correlations typically have significant scatter and are often soil or site specific. Thus, these correlations cannot be used to provide reliable design parameters across a broad spectrum of soils and sites.

3.2. EXPRESS/STRENGTH INDEX TESTS

The inexpensive and simple-to-use express or strength index test devices such as the torvane, pocket penetrometer, fall cone, and unconsolidated undrained triaxial compression test (UUC) are popular in practice. However, these tests are greatly affected by sample disturbance, use fast shear rates, and different modes of shear. As a result, the data from these devices represent, at best, relative strength rather than values suitable for design, and s_u profiles developed using these devices often show significant scatter. Therefore, they are more suitably referred to as strength index tests and should only be relied upon to indicate the general consistency of soil layers. Reliable determination of undrained shear strength values for design must focus on use of equipment that can conduct consolidated-undrained (CU) tests. Options for conducting laboratory CU tests include TC, TE, and DSS equipment.

3.3. CONSOLIDATION EQUIPMENT

The 1-D consolidation test is the most effective laboratory method for determining the consolidation properties of clays. The test is typically performed using an oedometer cell with application of incremental loads. This equipment is widely available and the test is relatively easy to perform. However, the CRS test (WISSA et al. [27]) is a significant improvement over IL testing, as it allows for backpressure saturation and continuous measurement of deformation, vertical load, and pore pressure for direct calculation of the stress–strain curve and coefficients of permeability and consolidation. Furthermore, recently developed computer-controlled flow pumps and load frames allow for automation of most of the test.

3.4. ADVANCED STRENGTH TESTING EQUIPMENT

Great advances have been made in the past 20 years in computer automation of triaxial equipment. Once sophisticated and time-consuming tests, such as K_0 consolidated undrained shear (CK_0U), can now be reliably conducted through computer control of flow pumps and load frames with a significant reduction in potential for operator error and testing duration. Many basic features of top-level triaxial stress path cell equipment developed at research institutions (e.g., SHEAHAN and GERMAINE [25]) are commercially available to geotechnical laboratories. While capital investment in automated stress path equipment is not trivial, the benefits of improved data quality and test efficiency cannot be overstated. Use of modern instrumentation systems, and especially computer-controlled systems, do require operation in well-controlled constant temperature chambers or rooms. Unfortunately, some features of high quality triaxial equipment (e.g., BALDI et al. [2], LACASSE and BERRE [13], GERMAINE and LADD [10]), such as internal load cells and tie rods, smooth or lubricated end platens, and internal small strain measurements, are modestly used or almost nonexistent in practice.

The DSS device has the unique ability to test soil specimens where the major principal stress is free to rotate during simple shear strain conditions. DSS tests are relatively easy to run and use less soil than triaxial specimens. In the Geonor DSS device, a circular specimen is trimmed into a wire-reinforced membrane and consolidation yields a K_0 compression curve. The device, however, has non-uniform stress conditions and does not conveniently allow for backpressure saturation and direct measurement of pore pressure. In addition, the complete state of stress at failure is unknown, although it is common to assume that s_u is equal to the measured peak horizontal shear stress. However, in spite of these problems the device has been found to produce a reliable measure of the in situ mobilized undrained shear strength s_u(mob) for stability problems in non-varved sedimentary clays (LADD [14]). At the present, no other practical laboratory device can produce such results for design.

4. RECOMMENDED PROCEDURES FOR ADVANCED TESTS

Having all the right test equipment does not guarantee success in measuring the engineering properties of soft clays. In spite of advances in automation, there is still no substitute for skilled and knowledgeable personnel for field collection of samples, specimen trimming, and test progress monitoring. This section highlights test procedures targeted towards improving the quality of laboratory consolidation and strength data.

4.1. GENERAL PROCEDURES

The first, and arguably the most crucial, step in laboratory testing of clays is sample selection and specimen trimming. Radiographs of sample tubes provide important non-destructive visual detections of soil features (i.e., variations in soil type, macrofabric, inclusions, and voids) prior to trimming and testing specimens, which often cannot be determined from direct inspection and sample handling. ASTM D4452 describes the necessary equipment and techniques for conducting radiography of soil samples. 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 [13]). To prevent post-sampling disturbance, samples should not be extruded from tubes (except if done immediately after sampling) without first breaking any bonding at the soil-tube interface that develops during storage. The sample tube should be cut adjacent to the desired specimen location using a horizontal band saw or by hand and debonded according to procedures described by LADD and DEGROOT [15]. Sample sides should also be trimmed during specimen preparation to remove potentially disturbed material.

4.2. CONSOLIDATION TESTING

IL oedometer and CRS tests should ideally be conducted by first loading the specimen beyond σ'_p onto the virgin compression line, unloading and reloading (to better define the behaviour of OC clay), loading to the maximum desired stress, and finally unloading back to the seating load. An unload–reload cycle is unnecessary for high quality samples. For better definition of σ'_p and virgin compressibility, the load increment ratio can be reduced from the typical value of one (e.g., 1/2), though this may not be sufficient to properly define σ'_p for IL tests on more structured soils compared to continuous data from CRS tests. In addition, reduced load increment ratios result in deformation-time curves that are not well defined and cannot be interpreted using graphical construction methods (e.g., $\sqrt{t}$ or log$t$) for estimating c_v. In the case of CRS tests, continuous k and c_v data can be computed providing that an acceptable rate of deformation is selected.

Figure 1 plots data from IL and CRS tests conducted on Sherbrooke block samples of the sensitive Gloucester Leda Clay and Boston Blue Clay. These data show the IL test has poor definition of σ'_p (especially for conventional 24-hour load increments; figure 1b) and too low a compression ratio (CR = $\Delta\varepsilon/\Delta\log\sigma'_v$) just beyond σ'_p as compared to the CRS test. For the CRS tests in figure 1, the base excess pore pressure (Δu_b) was kept greater than 1%, but well below 10%, of the total vertical stress (σ_v).

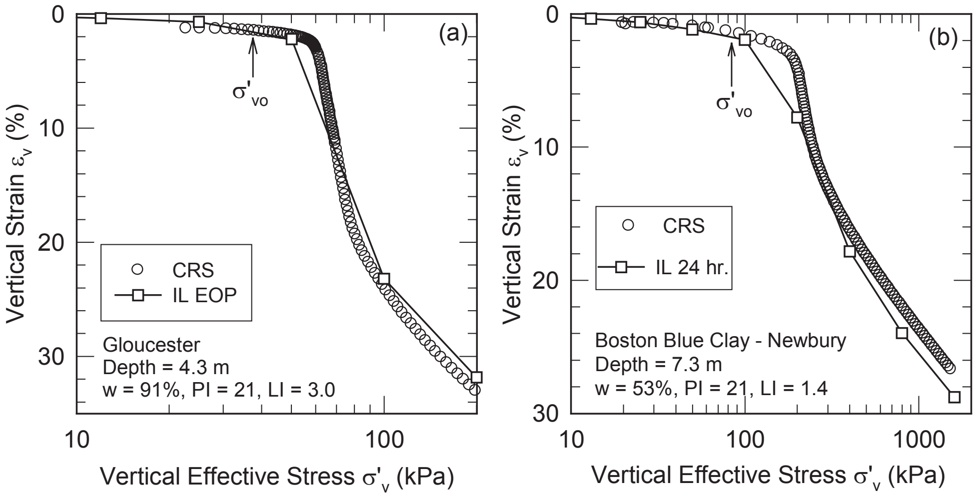


Fig. 1. Comparison of IL consolidation and CRS compression curves for Sherbrooke Block samples of: a) Gloucester Leda Clay (EOP = end of primary); b) Boston Blue Clay

A typical CRS test for most soft clays with back pressure saturation takes only 3 days. However, one problematic aspect of CRS testing is selecting an acceptable loading rate. Tests run too slowly experience appreciable secondary compression and tests run too fast generate high excess base pore pressures that lead to significant variations in specimen void ratio and σ'_v. Mesri and Feng [21] suggest selecting a strain rate that limits normalized base excess pore pressures ($\Delta u_b/\sigma_v$) to less than 15 to 20%, and give recommendations for selecting strain rates that yield essentially the same compression curve as the end of primary (EOP) curve from IL tests. But if c_v data are required, some base excess pore pressure is necessary and the recommended rate should be increased by a factor of 10. For typical soft clays, a rate of about 0.7% strain per hour should produce $\Delta u_b/\sigma_v$ less than 15%, although the resulting σ'_p will be about 10% greater than the IL EOP σ'_p (Mesri et al. [22]). Sandbeakken et al. [24] report that rates of 0.5 to 1%/hr are adequate for most clays and yield $\Delta u_b/\sigma_v$ between 2 and 7%.

4.3. TRIAXIAL TESTING

Baldi et al. [2], Germaine and Ladd [1], and Lacasse and Berre [13] give thorough recommendations on use of triaxial equipment and test procedures. The key steps in the process are specimen set-up, saturation, consolidation, and undrained shear. Backpressure saturation is essential for accurate measurement of volume

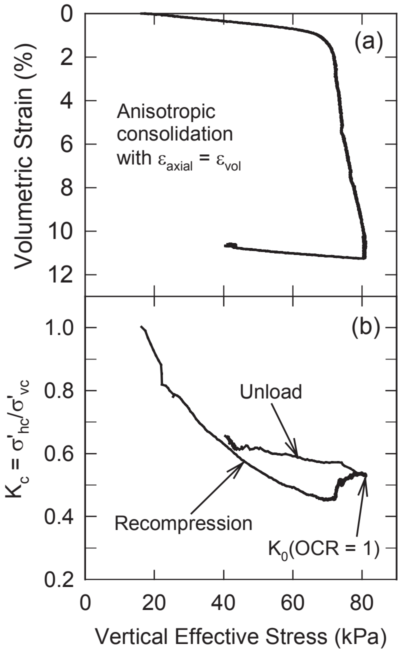


Fig. 2. Consolidation phase of a SHANSEP OCR = 2 test conducted using an automated triaxial stress path cell for Gloucester Leda Clay: a) compression curve, b) K_c values

change during consolidation and pore pressure changes during undrained shear, and should occur at the measured or estimated sampling effective stress to minimize specimen volume change and prevent swelling. A final back pressure of 200 to 300 kPa is typically sufficient for most soft clays, although Skempton's B value should always be checked to ensure saturation has occurred. Consolidation should follow an anisotropic effective stress path to the final required effective state of stress, which is typically a K_0 condition. Reconsolidation to the in situ stress state does require an estimate of in situ K_0, but this more realistic stress state yields a more reliable measure of the undrained shear strength as compared to using isotropic consolidation. Figure 2 plots an example of a K_0 consolidation curve obtained using automated triaxial stress path cell equipment for the sensitive Gloucester Leda Clay, Canada. The specimen was K_0 consolidated to a normally consolidated state and unloaded to a laboratory OCR = 2 prior to undrained shear (i.e., a SHANSEP test), where automation controlled the specimen to be deformed at a constant rate of vertical strain while varying the cell pressure to keep $\varepsilon_{axial} = \varepsilon_{vol}$ (i.e., 1-D strain condition). The rate of strain for undrained shear should be selected to account for strain rate sensitivity of clays and typical field loading rates. Germaine and Ladd [10] recommend a strain rate of 0.5 to 1.0% per hour for CU triaxial tests on soft clays.

4.4. DIRECT SIMPLE SHEAR

Bjerrum and Landva [5], Ladd and Edgers [16], and DeGroot et al. [8] provide comprehensive reviews of DSS test equipment, data interpretation, and typical results for a variety of clays. In the Geonor device, undrained shear is usually conducted at approximately 5%/hour and by running a constant volume test that can either be performed manually or by computer automation. Recompression tests that reconsolidate the specimen to σ'_{v0} typically require the use of stones with embedded pins to prevent slippage. These stones are more difficult to seat and do create an unknown degree of disturbance. Another issue for recompression tests is the lack of sufficient horizontal stress developed during recompression to σ'_{v0} such that the resulting laboratory K_0 is typically lower than exists in situ (DYVIK et al. [9]). This can produce measured results that are markedly different from the correct behaviour corresponding to the in situ OCR. Therefore specimens must first be loaded up to a stress level beyond σ'_{v0} and unloaded back to σ'_{v0} to develop additional horizontal stress, which can be a tricky procedure. As a guideline, NGI typically loads to approximately 80% of the best estimate of σ'_p and then unloads back to σ'_{v0} prior to undrained shear.

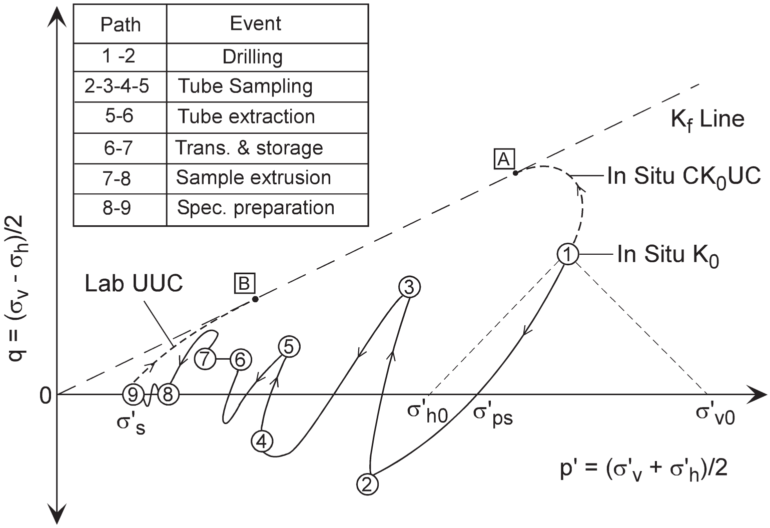
5. SOIL BEHAVIOUR ISSUES

The most important engineering property to determine for clay deposits is stress history as expressed by σ'_p and OCR, as stress history influences all significant aspects of clay behaviour. Sample disturbance is the most important issue affecting accurate measurement of stress history, as well as undrained shear strength. Other important soil behaviour issues include anisotropy and rate effects. While all of these effects are not yet fully understood, significant progress has been made in dealing with some of them in a manner practical for design. For example, use of a combination of shear modes in the laboratory (i.e., TC, DSS, and TE) allows for measurement of the strength anisotropy of clays. In addition, using reasonable laboratory shear rates allows for measurement of strengths that are consistent with anticipated field loading events. There remains, however, a significant lack of practical knowledge for how to assess sample disturbance and deal with its adverse effects, so accurate soil parameters can be obtained through laboratory testing.

5.1. SAMPLE DISTURBANCE

The most important effects of sample disturbance are significant reductions in the sample effective stress (σ'_s) and reductions in σ'_p estimated from one-dimensional compression. Figure 3 shows how the reality of sampling and testing can vary unpredictably from the ideal. This figure shows the anticipated stress paths for a normally consolidated clay as the stress state changes from the in situ stress state (point A) to the stress state at laboratory testing (point F) as a result of disturbance caused by sampling, storage and handling. While design is for in situ stress states, much of geotechnical engineering practice relies on strengths determined from samples starting from point F (e.g., UUC test), though it is clear that the stress state at point F is very different from the in situ state at point *A*. Figure 3 further shows the significant difference in potential stress paths for soil elements during undrained compression shear starting at points *A* and *F*. Based on this simple depiction of stress state evolution during sampling, it should come as no surprise that there is often a gross mismatch between field performance and design performance based on laboratory derived strengths.

Many researchers have theoretically and experimentally studied the influence of sampling techniques and sampler design on the quality of soft clay samples (e.g., Hvorslev [11], Baligh et al. [3], Clayton et al. [6]). Some aspects of sample disturbance such as stress relief are unavoidable, but improvements in field sampling procedures and laboratory handling of samples can help to minimize additional degrees of disturbance. Use of an appropriately weighted drilling mud is essential for maintaining borehole bottom stability prior to sample collection and for tube sampling, the use of large diameter, sharp edged, small area ratio tubes and a fixed piston sampler are best (e.g., Ladd and DeGroot [15]).



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. 3. Hypothetical stress path for an OCR = 1 clay element during tube sampling/specimen preparation and undrained shear (from Ladd and DeGroot [15])

It is essential to evaluate sample quality when evaluating consolidation and strength data, yet this is not commonly done in practice. The simplest and most effective method is the measure of $\varepsilon_{\mathrm{vol}}$ at σ'_{v0}. Andresen and Kolstad [1] first presented this method and Terzaghi et al. [26] adapted it with the term specimen quality designation (SQD). Under this method, sample quality ranges from A (best) to E (worst) as listed in table 2 and Terzaghi et al. [26] suggest that reliable estimates of engineering parameters such as σ'_p and s_u require samples with an SQD of A or B. Recently, LUNNE et al. [19] updated ANDRESEN and KOLSTAD [1] with the measure of $\Delta e/e_0$ for reconsolidation to σ'_{v0} as listed in table 2. Measurements of $\varepsilon_{\mathrm{vol}}$ or $\Delta e/e_0$ are objective and easy to obtain from laboratory specimens and should be reported for every consolidation and CU strength test conducted on clays.

Table 2

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

Specimen quality designation (SQD) (TERZAGHI et al. [26])		$\Delta e/e_0$ criteria (LUNNE et al. [19]		Rating*
Volumetric strain (%)	SQD	OCR = 1 – 2 $\Delta e/e_0$	OCR = 2 – 4 $\Delta e/e_0$	
< 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.

5.2. UNDRAINED SHEAR STRENGTH ANISOTROPY

Research has clearly shown the important effects of soil anisotropy on selection of design strengths for stability problems involving soft clays, especially those with low plasticity, where the difference in s_u between TC and TE is often an average of approximately 2 (figure 4). While isotropically consolidated (CIU) triaxial compression tests are routinely used because of the widespread availability of basic triaxial equipment and the relative simplicity of this test procedure, CIUC undrained shear strengths are often much too high when used alone for stability problems. GERMAINE and LADD [10] report that $s_u(\mathrm{CIUC}) = 0.33\,\sigma'_c$ on average based on data from 30 soils, independent of plasticity index. The CIUC approach ignores the well known effects of soil anisotropy on s_u for stability problems. It is appreciated that test programs involving TC, DSS, and TE modes of shear are comprehensive and likely only possible for final design of major projects. An alternative and cost effective approach is use of DSS data alone. On average, $s_u(\mathrm{DSS}) = 0.23\,\sigma'_{vc}$ for non-varved clays that plot above the *A*-line and shows very little trend with plasticity index (LADD [14], DEGROOT et al. [8]). This compares well with MESRI's [20] analysis of Bjerrum's field vane data, in which Bjerrum's field vane correction factor was applied to field vane data normalized by σ'_p and resulted in $s_u(\mathrm{mob}) = 0.22\,\sigma'_p$.

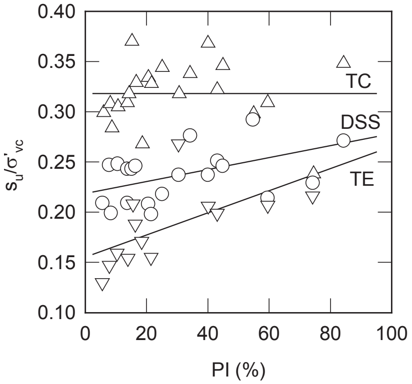


Fig. 4. Undrained strength anisotrpoy for normally consolidated clays and silts: TC – triaxial compression, DSS – direct simple shear, and TE – triaxial extension (from Ladd and DeGroot [15])

5.3. RATE EFFECTS

Increases in measured s_u of the order of 10% per log cycle increase in strain rate are commonly reported, but may be even higher at very high rates and with increasing OCR (Ladd [14]). Rate effects are reasonably easy to control by using recommended laboratory shear rates as quoted in Section 4 on laboratory methods (i.e., 0.5 to 1%/hr for TC/TE and 5%/hr for DSS). These rates represent a balance between expected field behaviour and selection of practical laboratory shear rates. It is significant to note that in the popular UUC test, the typical strain rate is 60%/hr (ASTM D2850 or 2166), and it is even higher for other index type tests such as torvane and fall cone.

6. LABORATORY RECONSOLIDATION

The long, popular practice of conducting UU strength tests for s_u design parameters overlooks the important soil behaviour issues listed in the previous section. For example, use of UUC undrained shear strength data for stability problems violates all of these issues, i.e., (1) the effective stress prior to undrained shear is generally much less than in situ stresses because of sample disturbance; (2) with the incorrect preshear effective stresses, no consideration is given to stress history; (3) use of the compression mode of shear ignores anisotropy; and (4) the fast rate of shear ignores strain rate effects. Thus, one can only conclude that successful (defined here as acceptable performance, but not necessarily economical) use of UUC data in practice relies on a combination of compensating errors, development of empirical correlations that are soil and test method specific, or overly conservative design. Investing in more accurate and reliable means of measuring soft clay behaviour can be economically significant. For example, Terzaghi et al. [26] report that UUC tests without cell pressure on SQD = D quality tube samples can result in s_u values less than 50% of that measured for A quality samples. However, the error is not always on the safe side. The use of improved sampling techniques may offset a significant portion of the decrease in s_u due to sample disturbance that compensates, to some unknown degree, for errors in s_u(UUC) related to anisotropy and rate effects. GERMAINE and LADD [10] present UUC data for four well studied cases with high quality and well defined in situ reference strengths for which the s_u(UUC) strengths were considered unsafe. In sum, UUC testing is not a rational framework within which engineers can control the important soil behaviour issues that influence s_u.

The recompression (BJERRUM [4]) and SHANSEP (LADD and FOOTT [17]) laboratory testing methods were developed for clays to address the aforementioned soil behaviour issues with emphasis on minimization of the adverse effects of sample disturbance. Both approaches advocate the use of anisotropic consolidation with shearing in different modes of failure (i.e., TC, DSS, and TE) at appropriate strain rates to account for anisotropy and strain rate effects, however they differ significantly on how to deal with sample disturbance. Details on the both procedures and their pros and cons are given in LADD [14] and LADD and DEGROOT [15]. Advanced laboratory test programs should use recompression and/or SHANSEP testing for measurement of undrained shear strength for design.

7. CONCLUSIONS

Experimental research during the past few decades has led to significant advances in our understanding of soft clay mechanical behaviour. Important soil behaviour issues that have been identified include sample disturbance, stress history, anisotropy, and rate effects. Many of the advances in our knowledge of soil behaviour are important to design and can realistically be implemented in practice. Selection of design parameters for most projects should rely on a test program that uses advanced laboratory test equipment and procedures. Measurement of consolidation behaviour should rely more on constant rate of strain tests. Undrained shear strength behaviour should rely on use of consolidated undrained triaxial and direct simple shear tests. Consolidation for shear testing should ideally be anisotropic to the appropriate K_0 condition for the target final vertical effective consolidation stress. The use of triaxial compression/extension and direct simple shear stress systems and recommended rates of shear provide effective means for dealing with soil anisotropy and rate effects for design. It is essential to evaluate sample quality through a combination of radiography and physical measurements such as volume change of specimens during laboratory reconsolidation to the in situ vertical effective stress. The recompression and SHANSEP methods were developed as a means to handle all of the important soil behaviour issues noted above. When properly used, these methods provide a much more rational framework for determining design parameters than conventional unconsolidated undrained laboratory test programs.

ACKNOWLEDGEMENTS

Some of the data presented in the paper is based upon work supported in part by the National Science Foundation under grants CMS-0219480 and OISE-0530151.

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