TYPES OF LABORATORY APPARATUS FOR SHEAR TESTING OF SOILS

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INTRODUCTION

In order to put subsequent discussions into proper perspective, it is convenient to list the various kinds of apparatus that have been used to measure the shearing strength and associated stress-strain properties of soils. More detailed attention will then be directed at the few types of tests that have achieved general usage by consulting and testing firms.

DOUBLE RING SHEAR

Probably the first type of laboratory apparatus used to measure the shearing strength of clays was one we will call the "double ring shear" apparatus. In its most common form it consists of a set of three metal rings (Fig. 1) containing clay and mounted in an apparatus such that the outer two rings can be supported and the middle ring can be sheared out from between the outer rings thus leading to a soil failure on two surfaces. One of the first apparatuses of this general type was used by Alexandre Collin (1846) who used samples 4cm x 4cm x 35cm long without any rings, but with the outer l5 cm ends of the clay prism supported and the center 5 cm sheared off by simply placing a plate on the top and applying dead 1oads.

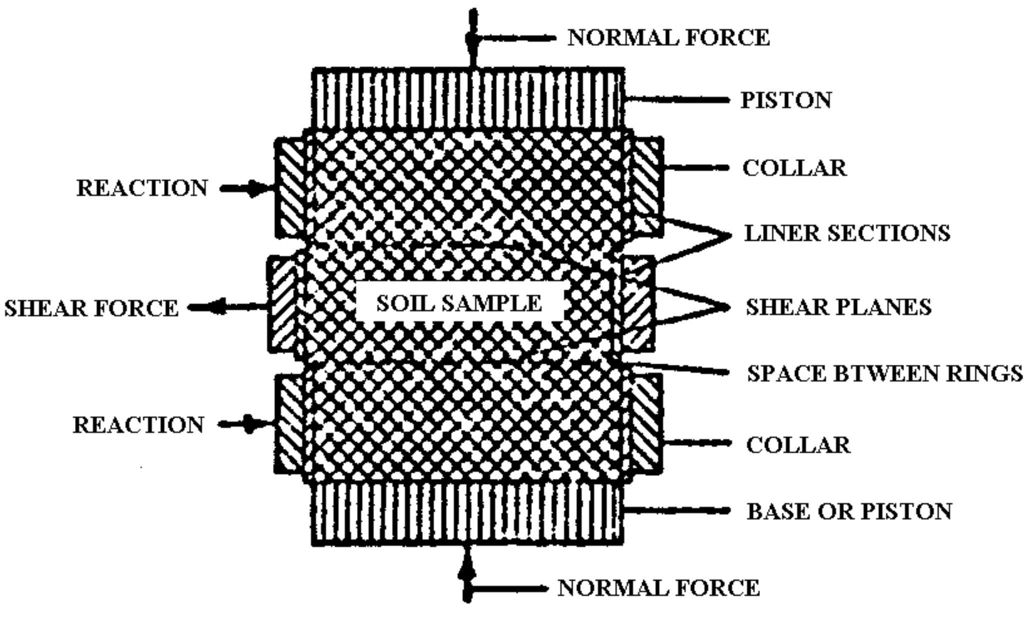

Fig. 1 Section through a Double Ring Shear Device (Hvorslev and Kaufman, 1952)

The ring shear apparatus has been used in the United States by Housel (1939) at the University of Michigan and the Michigan Highway Department, and also by the firm of Dames and Moore. In Housel's apparatus, the soil sample is 1.375 inches in diameter and is encased in three rings with the end rings 3.0 inches wide and the middle one 1.0 inch wide. No axial force is applied to the soil sample and the shearing load is developed by simply hanging a yoke loading it with lead shot.

Dames and Moore's rings have an inside diameter of 2.42 inches and are each 1 inch high. Their apparatus allows the application of a normal force N and the application of the shearing force F using a hydraulic system.

The ring shear apparatus has the advantage of simplicity. The rings are usually mounted inside of a liner type sampler so the soil is inserted into the rings as the sample is taken and the rings provide a convenient means of support when the soil is shipped to the laboratory. The apparatus is generally considered suitable only for testing clays under undrained conditions. The presence of large particles, e.g., pieces of gravel or shells, in the shear zone causes the measured strength to be unrealistically large. Most engineers consider that this testing method leads to excessively non-uniform development of stresses in the shearing zone and thus to underestimates the strength of the clay. Further, since the soil sample is not trimmed, and the area ratio of the samplers is usually large, the strength is probably underestimated because of sampling disturbance as well. The apparatus is used successfully with insensitive clays and where previous experience in the area allows the results of the tests to be interpreted properly but the device seems generally less useful than other shearing devices and it use has steadily decreased in recent years.

DIRET SHEAR

In the "direct shear apparatus," the soil is contained in two rings (Fig. 2). The rings may be circular or, more commonly, square. The inside dimensions are typically 2" x 2" to 4" x 4" but sizes up to more than 12" have been used. A normal force N is applied through a mechanical loading system and failure is achieved by applying a force F to either the upper or lower halves of the shear box so that the soil is forced to fail on a single shear plane as indicated in Fig. 2.

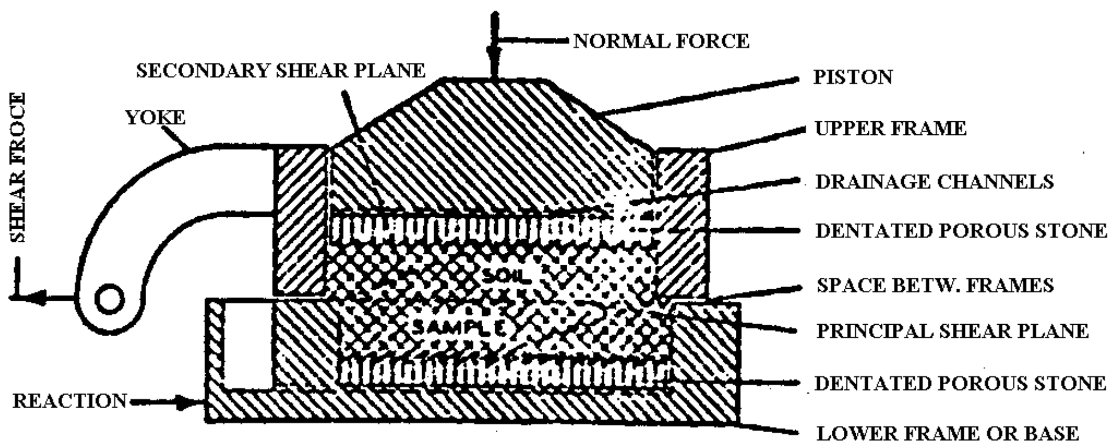

Fig. 2 Section through a Direct Shear Device
(Hvorslev and Kaufman, 1952)

The soil sample in the direct shear devices is normally trimmed from the original soil sample but it is possible to use a shear box with the same inside diameter as the soil sample so the soil can be extruded directly into the ring. The soil samples for direct shear tests are usually fairly thin (of the order of 0.5 inch thick) to facilitate rapid drainage and direct shear tests are almost always fully drained tests.

The direct shear apparatus has been in extensive worldwide use since about 1900 and will be discussed in more detail subsequently. The apparatus has the advantage of allowing the performance of fully drained tests in a reasonably short period of time. It is also often used when the engineer desires to predetermine the orientation of the failure surface and when the "residual strength" is to be determined. The defects in the apparatus involve the inability of the engineer to control the principal stresses and strains, problems with coarse particles in the shear zone, the fact that the sample doesn't necessarily fail on the weakest surface, which could be inclined to the horizontal, and certain problems involved with determining the state of stress inside the soil sample during shear. The problems will be discussed in more detail subsequently.

TORSIONAL SHEAR

One of the defects involved with either double ring shear or direct shear apparatuses is that the deformation is restricted. There are cases where engineers would like to know the shearing strength after very large deformations, e.g., after soil has slid some distance on a shear surface during a landslide. The torsional shear device is designed to allow measurements at such large shearing strains. The most common torsional shear device utilizes and a ring-shaped soil sample (location #1 in Fig. 3) which is supported laterally by inner and outer rings as indicated. The soil is subjected to a normal stress, σ, and then the

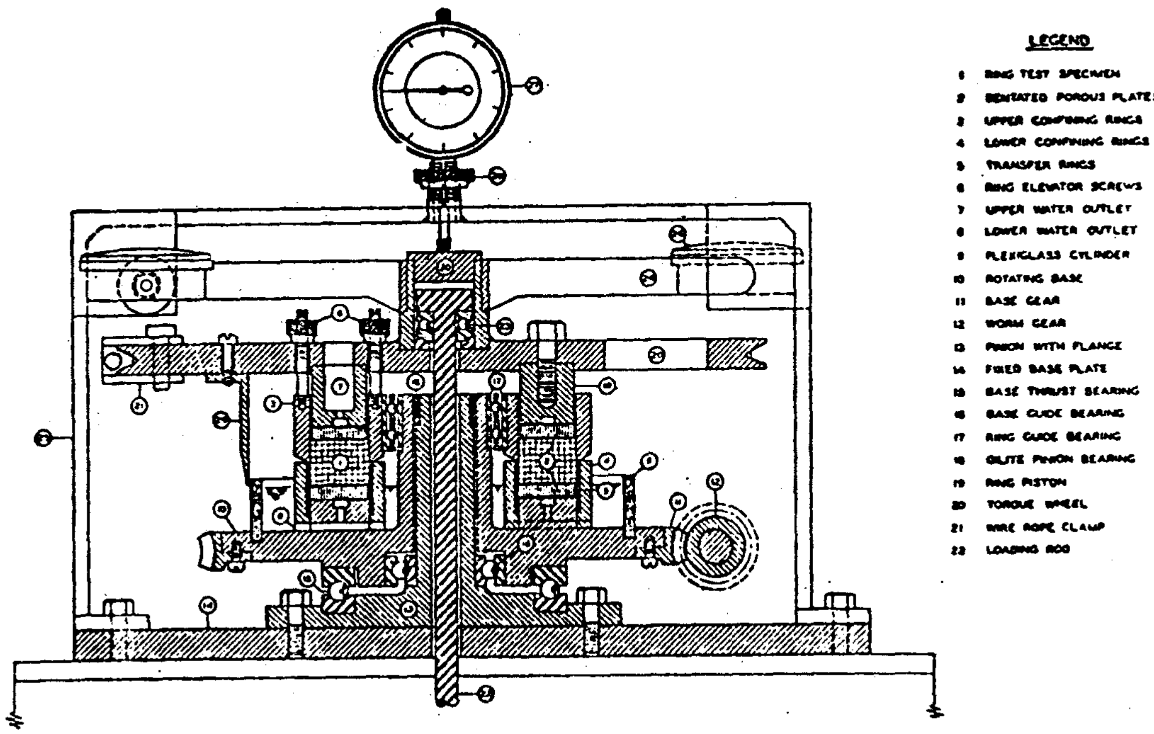

Fig.3 Section through a Torsional Shear Device
(Hvorslev and Kaufman, 1952)

upper half of the box is subjected to a torque which causes the upper surface of the sample to rotate relative to the lower surface and thus a shearing stress is generated.

This device has the advantage that theoretically unlimited shearing deformation can be applied without encountering any problems with area corrections, i.e., the area of the sample does not change as the soil shears. The major problems with a device of the type shown in Fig. 3 are associated with its complexity. The device is prohibitively expensive to build. Samples are so large that they must generally be hand carved. Trimming such samples into the apparatus is quite difficult. Strains in the sample vary linearly with radius so non-uniform strains develop unless inner and outer radii are nearly the same, leading to inconvenient sample shape. As a result of this problem, the device has no apparent practical use.

If the user is concerned only with residual strengths (measured at large strains) then an economical and simple device can be used with an outer diameter of about three inches, an inner diameter of about one inch, and a height of only about 0.5 inch. The design is similar to that in Fig. 3 but is much simpler. The test is performed by rotating the top surface until further rotation causes no further change in torque.

HOLLOW-CYLINDER APPARATUS

Soil samples can be subjected to complex states of stress, approximating those that might be encountered in the field, by using a hollow cylindrical sample as indicated in Fig. 4. The soil sample must be cut into the shape of a hollow cylinder and is then mounted in an apparatus with rigid rings above and below and flexible rubber membranes on the inside and outside. The apparatus is designed so the soil can be subjected to different fluid pressures on the inside and outside as well as to axial load and torque.

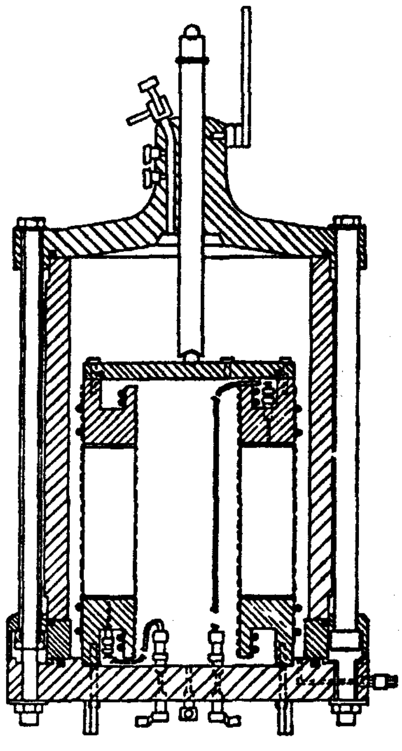

Fig.4 Section through a Hollow-Cylinder Shear Apparatus (Broms and Ratman, 1963)

Although the apparatus is apparently versatile, it suffers from the fatal disadvantage that trimming undisturbed soil samples into the required shape is difficult and expensive. Further, in actual usage it is found difficult to determine the actual area of the shearing zone once the sample has undergone deformation. Apparatus of this kind has been used for research (Kirkpatrick, 1957; Haythornthwaite, 1960; Broms and Ratnam, 1963; and Wu, Loh and Malvern, 1963) but has not been used for commercial testing and thus will not be considered further.

SIMPLE SHEAR

In the simple shear apparatus, a rectangular or cylindrical sample of clay is mounted in a special cell (Fig.5) and then subjected to an axial stress and to shear as indicated in Fig.6, in such a manner that the entire sample distorts without the formation of a single shearing surface. In the original apparatus developed at Cambridge University (Roscoe, 1953) the leading and trailing vertical surfaces of the soil were constrained by metal plates which were hinged in such a way that they forced the sample to deform in the desired manner.

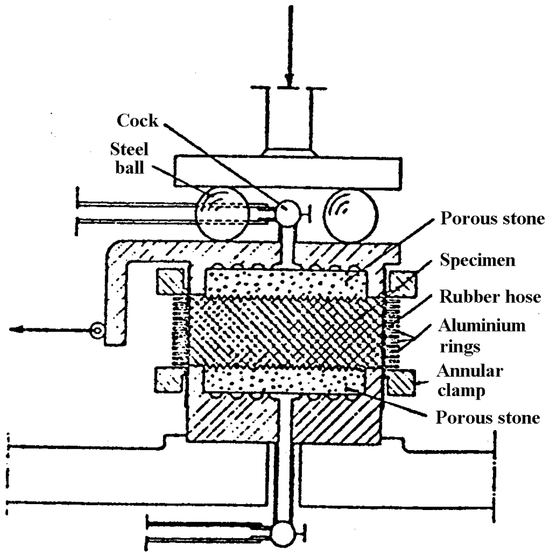

Fig.5 Section through a Simple Shear Apparatus (Kjellman, 1963)

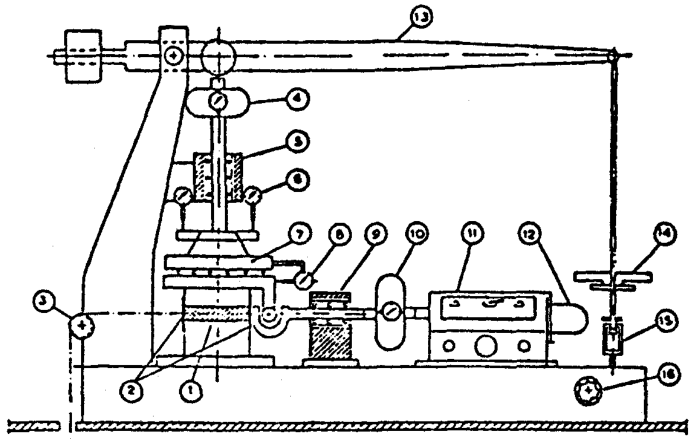

Fig.6 Norwegian Simple Shear Equipment (Bjerrum and Landva, 1966)

In the Norwegian device (Bjerrum and Landvan, 1966) a 3.2-inch diameter by 0.6-inch high sample of soil is enclosed in a rubber membrane which contains a thin spirally wound steel wire. During consolidation under an axial load the wire reinforcement prevents lateral expansion.

The simple shear apparatus, of the Norwegian type, is finding increased use in geotechnical engineering. The soil sample may be either the original sample or a trimmed down version. The apparatus is tolerably simple and the test may be either of the fully drained or undrained types. However, since the apparatus has not been used to any significant extent in commercial testing in the United States, it will not be considered further in this discussion.

TRIAXIAL SHEAR

The triaxial shear apparatus has become established as the main means of determining the shear strength of soils when it is considered necessary to have a confining pressure. The soil sample is a solid cylinder with a height to diameter ratio of 2 which is subjected to confining pressure through a rubber membrane and loaded axially through a rigid top cap (Fig. 7). The

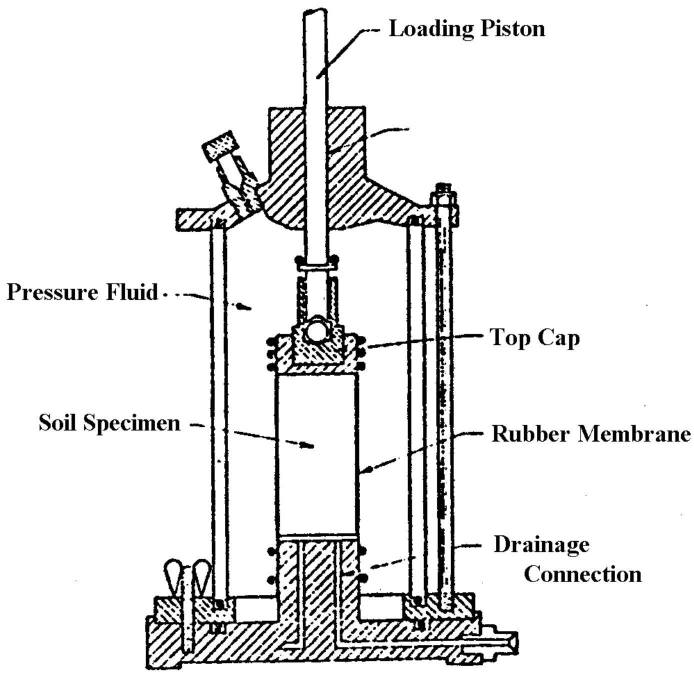

Fig.7 Triaxial Shear Apparatus

apparatus can be made reasonably inexpensive. Samples of a wide range of sizes can be tested in a single apparatus by simply altering the diameter of the base pedestal and the top cap so that either trimmed or untrimmed samples can be used without the necessity of building completely different apparatus for each sample size. The main advantage of the triaxial apparatus over other types of apparatus are: (1) the engineer has independent control over the vertical and lateral stress, (2) drainage conditions may be controlled, (3) samples of convenient size and shape are used, (4) the apparatus is simpler than that of other sophisticated types of apparatus, and (5) the location of the shearing surface is not predetermined so the sample tends to fail on the weakest surface thus leading to a comparatively more reliable measure of strength. Disadvantages include; (1) the higher cost than for unconfined tests or ring shear tests, (2) testing times for fully drained tests are longer than in a direct shear device, (3) large strains cannot be achieved, (4) the apparatus is restricted to a biaxial state of stress.

Because of its wide use in geotechnical engineering, the triaxial shear apparatus will be discussed in more detail subsequently and thus need not be considered further at this time.

UNCONFINED COMPRESSION APPARATUS

The unconfined compression apparatus is simply a special case of the triaxial shear apparatus in which the confining pressure is zero and the state of stress is restricted to axial compression. Samples of any convenient size and shape may be used and the testing apparatus is simple and inexpensive. As a result, the unconfined compression apparatus is used more extensively than probably any other kind of shear testing apparatus except for such devices as the Torvane or pocket penetrometer. The unconfined compression test will be given consideration subsequently.

PLANE STRAIN

Certain types of problems in practice approximate plane strain conditions rather than the axially symmetrical conditions involved in triaxial shear or unconfined compression testing. Plane strain is defined to be a state of loading such that deformation is one direction is zero. That condition could develop in problems of stability of slopes, retaining walls, braced excavations, and bearing capacity of long footings where the strain in the long direction is approximately zero.

In the laboratory, a plane strain apparatus utilizes a soil sample in the shape of a solid rectangular prism which is usually subjected to a compressive force on its upper surface, allowed to deform out on the face, but is constrained to have no deformation at the ends. Bishop's device (Bishop, 1961; Cornforth, 1964) uses a sample that is 4 inches high, 2 inches thick, and 16 inches long (Fig. 8). The apparatus has provisions for controlling drainage just

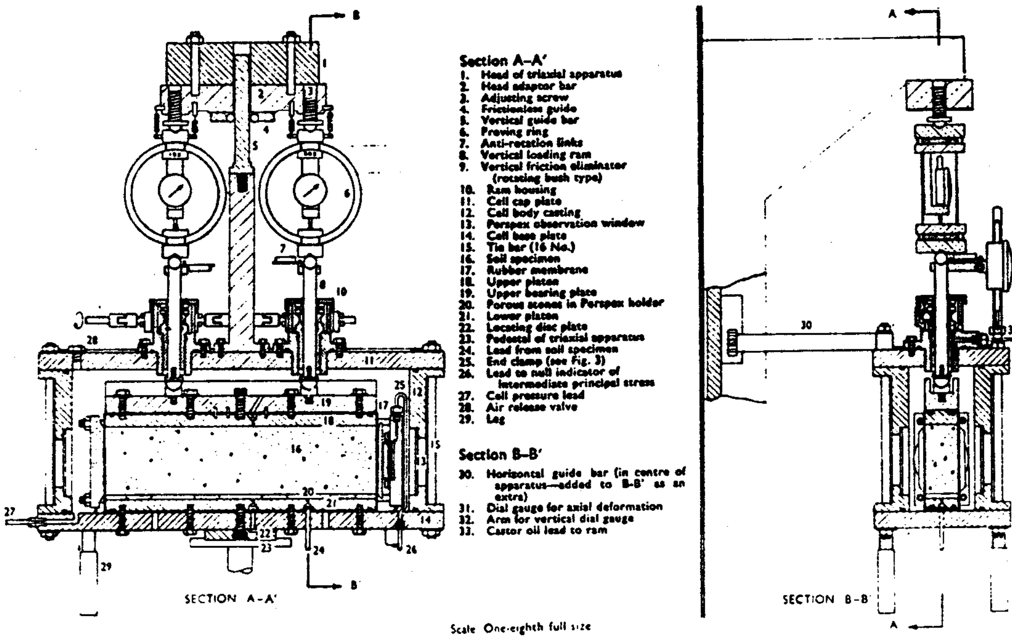

Fig.8 Section through Bishop's Plane Strain Device (Cornforth, 1964)

as in the triaxial shear apparatus. Although the state of deformation may approximate certain field conditions better than in the triaxial device, the Bishop plane strain apparatus is expensive to build and uses a soil sample that would have to be hand carved, and is thus not a type of device that could be used for commercial work.

A modified plane strain device was constructed at Berkeley (Duncan and Seed, 1966) in which a triaxial cell was used and a soil sample about 1.5 inches thick, 3 inches high, and several inches long was used. The soil sample could be obtained using commercial sampling techniques. Nevertheless, this type of test is rarely used for commercial purposes and thus will not be considered further.

REAL TRIAXIAL SHEAR

The apparatus normally termed the "triaxial shear apparatus" is in fact a biaxial apparatus only two principal stresses can be controlled independently. In a true triaxial shear apparatus, all three principal stresses are subject to independent control. The details of the many true triaxial shear devices are beyond the scope of this discussion. A number of them are discussed in papers published in the proceedings of the Roscoe Memorial Symposium (Parry, 1971). The devices are all characterised by considerable complexity and expense and none have been used for commercial type testing.

SOURCES OF ERROR IN STRENGTH TESTIN8

Although the main topic of discussion will be the proper manner of performing shear tests, it seems important to precede this discussion with a brief summary of some of the sources of error that occur in shear testing. Some of these errors will be discussed further as part of our considerations of proper testing techniques.

Sampling and Testing Disturbance

Experience indicates that a major source of error in laboratory shear testing is involved with use of samples whose properties differ substantially from those of the soil in the field because of disturbance during the sampling operation, shipment to the laboratory, storage, and preparation of the test specimen.

Improper Drainage Condition

The properties of soils depend to a great extent on the conditions of drainage in the field during the life of the structure. Laboratory drainage conditions should generally be the same as those in the field for the conditions to be analyzed. Thus, analyses of the immediate response of soils to loading are generally based on the assumption that no drainage occurs and consequently undrained tests are used in the laboratory. Conversely, long term loading problems generally necessitate the use of fully drained tests in the laboratory. Since fully drained tests take considerable time and cost more money than undrained tests, it is common practice to use undrained tests to represent all drainage conditions in the field. In some cases this simplification leads to unconservative estimates of field strength and thus potentially to failures.

Use of Non-Representative Samples

Although it seems obvious that the laboratory samples must be representative of the soil in the field, it is often difficult to obtain and test truly representative material. The most obvious and simple case is probably in stiff fissured clays where the samples tend to break apart on the fissures when the soil is extruded from the sampling tube. The normal tendency is to look for a piece of intact clay to test whereas it is apparent that the field strength is determined by the orientation of the fissures and the strength along the fissures.

Improper Stress Conditions

The strength of soils are substantially affected by the general state of stress used in measuring the strength. It is convenient to express the strength in dimensionless terms by dividing the measured strength by the vertical consolidation pressure prior to beginning of shear. Ladd and Foote (1974) performed plane strain, triaxial, and simple shear tests and obtained the dimensionless strengths shown in Table 1. Similarly, Bjerrum and Kenney (1967) obtained the strengths shown in Table 2 for a Norwegian clay. For some soils at least the strength is affected to an important extent by the strain conditions imposed during testing.

Table 1 Undrained Shearing Strengths of Boston Blue Clay Obtained from Various Types of Laboratory Tests using Normally Consolidated Samples (Ladd and Foote, 1974)

Type of Test	c/p
Plane strain active (CK_0U-PSA)	0.34
Triaxial compression (CK_0U-TC)	0.33
Simple shear (CK_0U-DSS)	0.20
Plane strain passive (CK_0U-PSP)	0.19
Triaxial extension (CK_0U-TE)	0.16

Table 2 Undrained Shearing Strengths of Manglerud Quick Clay Obtained from Various Types of Tests (Bjerrum and Kenney, 1967)

Type of Test	Shear Direction	c/p
In-situ vane	vertical	0.12
	45^o	0.14
	horizontal	0.18
Large in-situ shear box	horizontal	0.24
	45^o - down	0.30
	45^o - up	0.08
Triaxial tests	compression	0.29
	extension	0.13
Simple shear	horizontal	0.18

Apparatus Defects

Apparatus defects of a myriad of types can occur and lead to substantial errors in measuring shearing strength. Some of these errors will be discussed for the direct shear and triaxial shear apparatuses and thus need not be considered at this time.

Conclusions

Clearly, the laboratory strength of a sample of clay may differ substantially from the strength of the same material in the field under real loading conditions. The possible errors are so large that in some cases use of typical factors of safety will not ensure safety of the structure. A reduction in magnitude of these errors requires an increased level of understanding on the part of the engineers, and also an increased level of sophistication in sampling and testing.