AN EVALUATION OF LABORATORY TESTING TECHNIQUES IN SOIL MECHANICS

ADEL S. SAADA*, GERARDO FRIES** and CHING-CHANG KER***

ABSTRACT

An extensive soil testing program was conducted on clay and sand materials using three different devices, namely the standard triaxial, the N.G.I. simple shear device and the thin long hollow cylinder. Both monotonic and cycling loadings were used and led to results that dramatize the influence of the boundary conditions present in each device. The use of the simple shear test to simulate the conditions that prevail during landslides or earthquakes is found to lead to erroneous results when compared to the thin hollow cylinder. For both static and dynamic tests the triaxial tests is definitely an improvement over the simple shear one. The thin hollow cylinder is shown to be the most desirable configuration to be used in the soils laboratory for studies related to strength and stability under both static and earthquake situations.

Key words: damping, finite element method, laboratory test, repeated load, shear modulus, simple shear, torsion, triaxial test (IGC: D 6/D 7)

INTRODUCTION

The influence of the boundary conditions on the results obtained in laboratory soil tests has been the subject of many dissertations. The object of laboratory testing is to study the behavior of a given soil under conditions similar to those encountered in the field and to obtain those parameters which describe this behavior in a set of constitutive equations. In a laboratory test the specimen is intended and generally assumed to represent a single point in a soil medium. The validity of this assumption depends on

the uniformity of stress and strain distributions within the soil samples. This uniformity will depend on the configuration of the specimen and the control and measurement of stress and strain on its surface.

In the present study, after a discussion of the stress and strain distributions in the simple shear device, the standard triaxial and the thin long hollow cylinder, the results of actual tests on clay and sand materials are given. Both static and dynamic tests are conducted with equivalent conditions in the various apparatuses.

In their State of the Art on Laboratory

* Professor and Chairman, Department of Civil Engineering, Case Institute of Technology, Case Western Reserve University, Cleveland, Ohio 44106, USA.

** Engineer, Woodward-Clyde Consultants, Houston, Texas, USA.

*** Graduate Student, Department of Civil Engineering, Case Institute of Technology, Case Western Reserve University, Cleveland, Ohio 44106, USA.

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Strength Testing of Soils, Saada and Townsend(1981) discussed in great detail a large number of devices under static conditions; but they did not give or compare results obtained on the same soils simply because such data was not available. Here this comparison is made for normally consolidated as well as overconsolidated materials and for stress controlled as well as strain controlled tests.

STATE OF STRESS IN THE VARIOUS DEVICES

The Simple Shear Device

Two types are in use: The Roscoe type with a square cross section and rigid boundaries and the N.G.I. type with a circular section and a reinforced membrane. The N.G.I. type, minus the reinforcement has recently been placed inside a triaxial cell and the sample pressurized hydrostatically. The stress distribution when the specimen is subjected to shearing stresses has been studied at length theoretically and using finite elements. A closed form solution was found for the Roscoe type (Prevost and Hoeg, 1976; Roscoe, 1953) with and without slippage at the boundaries. A photoelastic study was conducted for both types (Wright et al, 1978): Fig. 1 shows the shearing stress distribution in the N.G.I. type.

The interest of researchers has primarily been directed at the nonuniform state of stress resulting from the application of shearing forces to the specimen. However, it was found that the lack of uniformity in the axial (σ_z) radial (σ_r) and circum-

Fig. 1. Shear stress distribution in the N.G.I. device

ferential (σ_θ) normal stresses was just as, if not more, serious when the specimen is subjected to axial loads alone in a wire reinforced membrane or to axial loads in a pressurized cell. The top and bottom platens of the simple shear device are rigid and rough and often have ribs to avoid slippage. Under such conditions there is often very little relation between the normal stresses acting on the lateral surface of the sample in a pressurized cell and σ_r and σ_θ within the specimen. The physical dimensions as well as the boundary conditions prevent any sort of uniformity to prevail. Fig. 2 shows the results of a linear elastic finite elements analysis conducted on a specimen of standard size subjected to an axial displacement of 0.0238 in. (0.6045 mm) and a lateral cell pressure of 30 psi (207 kPa). Young's modulus is chosen to be 2844 psi

Fig. 2. Distribution of stresses due to axial displacement: a) normal stresses at the top; b) normal stresses at the center; c) shearing stresses at the top ($\sigma_3 = 30$ psi, 1 psi = 6.9 kPa)

(19 609 kPa). On this figure one notices that for an imposed vertical displacement the distribution of the three normal stresses is a function of Poisson's ratio ν and varies from the edge to the center. This is true on the upper and lower boundaries as well as the central section. The average value of σ_z also varies with ν . However, more important is the fact that σ_r and σ_θ are indeed quite different from the 30 psi (207 kPa) applied in the cell. Actually, depending on ν , those two components of the state of stress can be in the larger part of the sample closer to σ_z than they are to the laterally applied stress. As seen in Fig. 2 only a very thin layer close to the lateral faces "sees" the applied 30 psi (207 kPa).

Of equal interest are the radial shearing stresses τ_{rz} imposed by the end platens to the specimen because slippage is not allowed there. Fig. 2 shows the distribution for various values of ν . The magnitude of τ_{rz} due to axial normal force alone could be higher than the one due to the application of the shearing force supposed to place the specimen in a state of simple shear. Notice that depending on the value of ν the effect of the lateral stresses may overcome that of the vertical ones so that τ_{rz} changes in sign. This analysis applies to both the simple shear and the triaxial tests.

From these results it appears that a Poisson ratio close to 0.25 would be desirable; and if in addition one could manage to have a ratio $K_0 = \sigma_3 / \sigma_{av} = 0.5$ the stress distribution would be reasonable. A more complete finite element analysis was conducted by Saada et al. (1983) for a variety of lateral pressures and height to diameter ratios and showed that Poisson's ratio, the lateral stresses and the average vertical stress combine to give a specific stress distribution. Since it is a "displacement" that one applies to the specimen, the probability that one would have the ideal combination in the whole body of the sample is exceedingly small. Poisson's ratios varying between 0.1 and 0.5 are in constant use in the literature.

The discussion above refers to linear elastic

materials and does not introduce any interaction between the shearing and normal components of the stress and strain tensors. As pointed out by Bishop et al. (1971), when the end platens are rigid a nonuniform shearing stress distribution will result in nonuniform tendencies to expand or contract; thus, leading to nonuniform normal stresses. The end result is a totally intractable stress distribution with extremely high concentrations that lead to premature failure when data based on average values are compared to that obtained in other devices. Indeed Bjerrum and Landva (1966) concluded that the undrained shear strength of specimens consolidated in the N.G.I. apparatus was approximately equal to 2/3 of the average value measured in corresponding triaxial tests. Similar results were found by Ladd and Edgers (1972).

Finally, Bjerrum and Landva write that the constant volume test is equivalent to an undrained test and the change in applied vertical stress on the specimen is equivalent to the change in pore pressure which would have occurred in the specimen if the specimen had been prevented from draining for a condition of constant applied vertical stress. They also write that the validity of their assumption was demonstrated in one single truly undrained test in which the pore pressures were measured at the base of the specimen. The experiments conducted in this research in the N.G.I. device show that the drop in the vertical stress in the constant volume test was several times larger than the increase in pore pressure in the constant vertical stress test for the same consolidation pressure and the same shearing strain. The results will be shown in the coming sections.

The Triaxial Test

The nonuniformities of the stress distributions within the specimen are primarily due to the effects of the friction on the end plates. The problem of the influence of end restraint during uniaxial or unconfined compression of cylinders has been under investigation since the latter part of the nineteenth

century. Saada and Townsend (1981) reviewed most of the studies conducted on this subject. Of particular interest are the papers by Balla (1960) who summarizes previous work and brings new insight to the problem, Moore (1965) who examined the effects of six Poisson ratios, a height to diameter ratio of one and two and lateral confinement, and Radhakrishnan (1973) who used finite elements to study linear and nonlinear problems for height to diameter ratios of one and two.

A feature that is common to all the linear solutions mentioned above is the drop in the normal contact stress as one moves towards the center, and a high concentration on the edges. However, as shown by Saada et al. (1983), the situation becomes different as the height to diameter ratio decreases. The concentrations at the ends remain, followed by a drop, then a substantial increase in the stresses as one moves to the center of the sample. This is brought about among others by the zones of influence of the end platens interfering with each others. More complete information can be found in the references cited in the State of the Art of Laboratory Strength Testing of Soils by Saada and Townsend.

End restraints can be minimized by using rubber sheeting and silicone grease to obtain frictionless contacts. However, Norris (1981) showed that one could obtain different stress-strain curves for sands depending on the number of layers of greased rubber sheeting and the size of the grains.

The Thin Long Hollow Cylinder

When the inner and outer pressures on a hollow cylinder are equal the radial and circumferential normal stresses across the thickness are equal. Under a superimposed axial stress the nonuniformities in the distribution of the state of stress are due to the radial frictional forces that the end platens generate when the specimen is prevented from expanding or contracting. Those forces are self equilibrating and their influence vanishes as one moves away from the ends.

References 20 and 25 contain detailed analyses of the conditions within the hollow cylinder. In a hollow cylinder the thickness as well as the mean radius play an important part in the pressure distribution. If the length of the specimen is l and the inner and outer radius are r_i and r_o it is recommended that

$$l \geq 5.44\sqrt{r_o^2 - r_i^2} \quad \text{and} \quad n = \frac{r_i}{r_o} \geq 0.65$$

Such proportions were checked by photoelasticity by Wright et al. (1978), by finite element analysis by DeNatale et al. (1981), as well as experimentally by Lade (1981) and found quite satisfactory.

When the hollow cylinder is subjected to torsional stresses both shearing stresses and strains vary across the thickness. The larger the ratio n , the smaller the nonuniformity and the more justified is the assumption of a uniform distribution equal to the average. In addition, as the deformation increases one moves towards a uniformity of stress. A combination of axial and torsional stresses, added to a change in the hydrostatic stress (the same inside and outside the cylinder) allow one to rotate the principal stresses at will as well as generate practically any stress path desired. By keeping the ratios of axial to torsional stress constant any inclination of principal stress can be maintained during a given test; and changed from test to test. If this is coupled with a synchronized change in the cell pressure the inclination may remain constant and the mean stress varied at will. Saada and his co-workers have used hollow cylinders to study the properties of anisotropic clays and sands for years. Ref. 20 lists many of their studies and describes various stress paths made possible by this particular configuration.

Finally, it ought to be mentioned that when studying cross anisotropic materials the hollow cylinder device is rather unique. Because the system of stress used is axially symmetric cross anisotropy around the axis will be maintained even though its degree might change due to induced strains. This is not the case for prismatic samples, be they cubic or parallelepipedic: Indeed as soon as the

planes of the prism parallel to the axis of symmetry move a new kind of anisotropy is created, most probably of the orthotropic type. States of pure shear stress and simple shear strain can be studied using hollow cylinders without many of the boundary effects that plague other devices.

EQUIPMENT AND SPECIMEN PREPARATION

Testing Machines

The simple shear tests were conducted using the standard wire reinforced norwegian membrane. The top and bottom caps were modified to allow for saturation and measurement of pore water pressure. They were fitted with thin very short blades to avoid any possible slippage.

The triaxial tests were conducted in norwegian cells with rotating bushings. Enlarged and greased caps were used for clay samples and regular caps were used for sand samples. Positive attachment was provided between the piston and the cap to allow for tension during cyclic loading.

The hollow cylinder tests were conducted using a specially designed cell allowing for axial and torsional loads to be applied to the sample. A transducer can be placed both inside and outside the cell for accurate measurements. A special bushing and piston assembly allows for the proper balancing of the forces so that both extension and compression can be applied to the specimen.

K_0 consolidation in the triaxial cell and the hollow cylinder cell was obtained by means of servosystem described by Saada (1970) which applies to a sample a vertical displacement such that it keeps the same cross section during consolidation.

Both controlled stress static and dynamic tests on solid and hollow cylinders were conducted using a stress controlled SPAC. This pneumatic analog computer can be programmed to subject specimens to static and slow dynamic axial extension and compression alone, and pure torsion alone, or to all combined in a synchronized way. The cyclic nature of the loading is controlled by

Photo. 1. Controlled-Stress Pneumatic Analog Computer SPAC

an electropneumatic signal generator that can induce various wave shapes. A sinusoidal shape was used in this investigation. The computer and its loading frame are shown in Photo.1 and described in more detail in reference 20.

Dense soils have a peak stress beyond which the stress strain curve falls off to the so called residual value. To go beyond this peak, strain controlled machines are needed. While a standard Whykam Farrance loading machine was used for axial loading, two special frames and a strain controlled SPAC were designed and built for use with the hollow cylinder. In the first, a torsional displacement is applied to the specimen and the resulting torsional stress measured with a transducer. The output of this transducer is amplified or reduced, transformed to a pneumatic signal and fed to an axial actuator to give a proportional axial stress. One can thus twist a sample beyond the peak and have principal stresses which maintain the desired constant inclination on the axis of symmetry; the torsional mechanical resistance of the sample being the controlling one. In the second, an axial deformation is applied to the specimen and the resulting axial stress measured with a transducer. The output of this transducer is amplified or reduced, transformed to a pneumatic signal and fed to a torque actuator to give a proportional shearing stress. Here one can go axially beyond the peak and the axial mechanical resistance is the controlling one. The two frames and their SPAC are shown in

Photo. 2. Controlled-Deformation Pneumatic Analog Computer SPAC

Photo. 2.

Materials and Specimens Preparation

Both clay and sand materials were used in this comparative study. The clay was Edgar Plastic Kaolin which has been extensively used in research on cohesive soil. Its liquid limit is 56.3 percent and plastic limit is 37.5 percent. The specific gravity of the solid particles is 2.62. Slurries at 125 percent water content were one dimensionally consolidated in an 8 in. (203.2 mm) consolidometer. From the resulting blocks samples for the simple shear, the triaxial test and the hollow cylinder were cut and stored. Before each test the specimens were trimmed to: 1.4 in. (35.6 mm) diameter and 3.25 in. (82.55 mm) height for the triaxial test; 3.16 in. (80.26 mm) diameter and 1 in. (25.4 mm) height for the simple shear; 2.8 in. (71.12 mm) outside diameter, 2 in. (50.8 mm) inside diameter and about 6 in. (152.4 mm) height for the hollow cylinder. Those specimens were then K_0 consolidated in their respective devices. A back pressure of 18 psi (124.1 kPa) was used for triaxial and hollow cylinder specimens.

Two sands were tested. One is a well known sand called Reid Bedford sand and the other a south American sand which will be called Latin sand. The Reid Bedford sand is a typically uniform fine sand with a specific gravity of 2.65 a coefficient of uniformity $C_u=1.64$ and a $D_{10}=0.155$. Its minimum void

where ϵ_z is the axial strain and no volume change takes place. The shear modulus G is the secant modulus equal to τ/γ and also equal to $E/3$ where E is Young's modulus. In the hollow cylinder the shearing stresses and strains due to torsion are the ones in question.

In dynamic testing, the specific damping ratios and the secant moduli obtained from the various devices will be compared. The specific damping ratio λ is defined as the specific damping capacity divided by 4π ; the specific damping capacity being defined as the energy loss per unit volume (represented by the area of the hysteresis loop) divided by the maximum potential energy, $1/2 \tau\gamma$ or $1/2 G\gamma^2$. The shear modulus is given by the ratio of τ from peak to peak and γ from peak to peak. This definition is necessary because in the triaxial test the loop is not symmetric and centered at the origin.

Normalization which is the process used to bring results to the same common denominator is made with respect to a normal effective stress. This effective stress is defined in the following section as the data is presented. The wide variety of boundary conditions present in this investigation result in different stress distributions and different pore water pressures making such a normalization necessary.

STUDY OF CLAY SOILS IN THE VARIOUS DEVICES

Testing Program for Clay Soils

All the test conducted on clay soils were stress controlled and of the consolidated undrained type with pore water pressure measurements. The following tests were conducted in the standard triaxial cell (ST):

- Static compression

- Cyclic axial

The following tests were conducted in the hollow cylinder device (HC):

- Static compression

- Cyclic axial

- Static torsion with constant length

- Cyclic torsion with constant length

- Static torsion with constant axial force

- Cyclic torsion with constant axial force

The following tests were conducted in the NGI simple shear device (SS):

- Static shear with constant length

- Cyclic shear with constant length

- Static shear with constant axial force

- Cyclic shear with constant axial force

The constant length tests in the simple shear device are also known as constant volume tests. The changes in the axial stress are measured with a very stiff diaphragm type transducer whose displacement is negligible.

A test in the standard triaxial or hollow cylinder has an "equivalent" test in the simple shear device. The equivalence is obtained by using the same effective consolidation stress, monitoring the water content and following similar testing patterns. Once the static strength is known, the cyclic loading is applied in percentages of the failure load, 20, 30, 40 percent until failure occurs. 60 cycles per level of stress were used for nearly all of the tests at about one cycle per minute. During all the tests constant recording was made of stresses, strains and pore water pressures. Hand calculations were complemented by a computerized data acquisition system. Three different consolidation pressures were used for the clay soil. They are referred to as 58-18, 48-18 and 38-18. The first number represents the cell pressure and the second the back pressure during consolidation and just before the undrained shear process began; both in pounds per square inch. K_0 consolidation was obtained through an additional axial load automatically generated by SPAC. Whenever axial loads were involved in the static or cyclic loading procedure the excess load producing K_0 consolidation was released, and equilibrium allowed, then the sample tested undrained from a hydrostatic state of stress. The value of K_0 for the clay investigated was 0.48.

Pure torsion tests in the hollow cylinder be they static or cyclic started with the axial stress which produced the K_0 consolidation. This stress was kept constant during

the constant axial force tests, while static or cyclic torsional stresses were applied to the sample. On the other hand this stress constantly dropped during the constant length tests, while static or cyclic torsional stresses were applied to the sample.

Simple shear tests were conducted in a manner similar to that used for the hollow cylinder tests. The vertical consolidation pressure was the same as the one indicated by SPAC during the K_0 consolidation of the equivalent hollow cylinder test. Then depending on whether the test was a constant force (CF) or a constant length one (CL) this stress would be kept constant, or the length fixed and the stress allowed to drop during shear. Pore water pressures were also measured during simple shear tests. This is not advisable since the flexibility of the norwegian membranes is quite large. It was decided, however, to make the measurement in the most popular devices.

Only static tests were conducted on one type of clay with overconsolidation ratios of 2, 4 and 8.

The reason for conducting constant length (also called constant volume) tests and constant force (also called undrained) tests in the simple shear device was to check the validity of Bjerrum's assumption regarding the equality of the drop in the vertical stress in one to the increase in the pore pressure in the other. For comparison purposes the same type of tests were conducted on hollow cylinders subjected to static and cyclic torsional stresses.

Results Obtained from Static Tests

Fig. 4(a) shows the results of static tests obtained with 48-18, clay, while Fig. 4(b) shows the same results normalized with respect to $\bar{\sigma}_n$. The shearing stress τ in the ordinate is the shearing stress on a 45° plane in triaxial compression test on solid or hollow cylinders; and the normal stress $\bar{\sigma}_n$ is the effective normal stress on that plane. For the simple shear test and hollow cylinder subjected to torsion, τ and $\bar{\sigma}_n$ are the shearing and normal effective stresses acting on the

Fig. 4 (a). Stress-strain curves for K_0 consolidated (48-18) clay

Fig. 4 (b). Normalized stress-strain curves for K_0 consolidated (48-18) clay

horizontal plane. The shear strain γ corresponds to the stresses defined above. In Fig. 4 as well as in all the ones that follow, (HC) refers to hollow cylinder, (SS) to simple shear, (ST) to standard triaxial, (C) to compression, (CL) to constant length and (CF) to constant force. In Fig. 4(b) one notices that for strains as high as five percent the triaxial compression tests give the steepest curves. The lowest strength was obtained from the simple shear test at constant force and the largest from the hollow cylinder at constant length. Identical results were obtained for the 58-18 and the 33-18 clays.

Fig. 5(a) shows the values of the secant modulus while Fig. 5(b) shows the same values normalized with respect to $\bar{\sigma}_n$. One notices that the results of the simple shear test, whether they are conducted with constant length (constant volume) or constant force (undrained) are still the lowest. The differences are very noticeable for small strains where the simple shear test gives results two to three times smaller than cor-

Fig. 5 (a). Shear modulus for K_0 consolidated (48-18) clay

Fig. 5 (b). Normalized shear modulus for K_0 consolidated (48-18) clay

responding hollow cylinder and standard triaxial tests. Here too the three consolidation pressures yielded similar results.

The changes in the effective vertical stresses and in the pore water pressure which take place during constant length (constant volume) and constant force (undrained) tests were recorded during simple shear and hollow cylinder tests. Fig. 6 shows that whether it is the simple shear test or the hollow cylinder test the pore pressure in the undrained test is very different from the drop in the axial effective stress in the constant volume test.

Various normalization parameters were used on the K_0 consolidated clays but none of them brought any improvement to the data shown in Figs. 4 to 6. A normalization of the shear modulus with respect to the undrained shear strength which is sometimes used in practice was also found to be totally unacceptable. Details can be found in the thesis by Fries (1981).

Results Obtained From Dynamic Tests

For each level of stress a minimum of 60

Fig. 6. Comparison of the increase in pore pressure and the decrease in effective vertical stress a) in the simple shear device b) in the hollow cylinder subjected to pure torsion

cycles was applied to the samples. The results given herein refer to the 10th cycle. In the constant force cyclic hollow cylinder tests HC(CF) only the hysteresis loops connected to torsion were considered. Fig. 7 shows the shear moduli obtained for the 48-18 clay plotted against the peak to peak value of the shearing strain 2γ . Similar results were obtained for the 55-18 and the 33-18

Fig. 7. Dynamic shear moduli for the 10th cycle for K_0 consolidated (48-18) clay (1 psi = 6.9 kPa)

Fig. 8. Damping ratio for the 10th cycle for K_0 consolidated (48-18) clay

clays. For small values of 2γ (<2 percent) the differences in the magnitudes of the moduli obtained in the various devices are quite noticeable. The hollow cylinder seems to yield the highest values and the simple shear the lowest ones.

It is well known that for small strains the damping ratio increases with strain. However, as the strain becomes larger this ratio remains more or less constant as shown by Saada and Shook (1981). This seems to be true in this investigation too. Fig. 8 shows the data obtained in this investigation at the tenth cycle. Again, each device gives a different answer for the same material.

Finally, it must be noticed that the hysteresis loops kept a reasonable symmetry with respect to the origin for the simple shear and torsional tests on hollow cylinder. On the other hand there was a constant shifting of the loops during axial cyclic tests since the behavior of K_0 consolidated clays is different in tension and compression.

Analysis of Results for Overconsolidated Clay

Tests on overconsolidated clays were conducted only on the 48-18 clay and for 3 overconsolidation ratios, namely 8, 4 and 2. Only static tests were conducted; static compression in the standard triaxial cell, pure torsion at constant length in the hollow cylinder device and simple shear at constant length (constant volume). The results are similar to those obtained for K_0 consolidated clays. Various normalizing procedures did not bring the results to coincidence. Fig. 9

Fig. 9. Shear moduli for overconsolidated clay (1 psi = 6.9 kPa)

shows the value of the shear moduli versus strain for the tests conducted.

STUDY OF SAND SOILS IN THE VARIOUS DEVICES

Testing Program on Sand Soils

Stress controlled tests were conducted on the Reid Bedford sand and strain controlled tests were conducted on the latin sand.

The simple shear tests and hollow cylinder tests involving torsion conducted on the Reid Bedford sand were very similar to the ones conducted on K_0 consolidated clay, with K_0 assumed equal to 0.5; the only difference is that the constant length tests were sheared drained and the volume change measured with an accurate standpipe. The specimens tested in the standard triaxial cell were consolidated under a hydrostatic stress equal to the mean stress acting on the corresponding simple shear or hollow cylinder test. If for example a specimen at a void ratio of 0.72 is subjected to a vertical consolidation stress of 10 psi (68.9 kPa) in the simple shear

device, the corresponding consolidation effective stress in the triaxial test would be 20/3 psi. One void ratio, 0.72 and three consolidation pressures were used for the Reid Bedford sand. All the tests will be identified in terms of K_0 and the vertical consolidation pressure. For example, (0.5-10) means that during consolidation the vertical effective stress was 10 psi (68.9 kPa) and the lateral was 5 (34.47 kPa); and (1-15) means that the consolidation was hydrostatic at an effective normal pressure of 15 psi (103.4 kPa). This latter case applies to the standard triaxial tests. In all, three vertical consolidation pressures of 10 (68.9), 20 (137.8) and 30 psi (206.8 kPa) were used.

In the strain controlled tests conducted on the Latin sand one void ratio 0.68 and one consolidation pressure 6.1 psi (42 kPa) were used. The hollow cylinders were all tested under a hydrostatic consolidation pressure of 6.1 psi (42 kPa). In the simple shear test two vertical consolidation pressures were used namely 6.1 (42) and 9.1 psi (62.74 kPa). In the standard triaxial test a hydrostatic pressure of 6.1 psi (42 kPa) was used. For dynamic tests the amplitudes of the shearing strains were 0.15 percent and 0.34 percent. Here too the constant length tests were sheared drained and the volume change measured.

Results Obtained From Static Tests on the Reid Bedford Sand

Fig. 10(a) shows the results of static tests obtained with the (0.5-30) sand, while Fig. 10(b) shows the same results normalized with respect to the effective normal stress $\bar{\sigma}_n$ as was done for the K_0 consolidated clay. On the same figure the curve obtained with the (1-20) sand is also shown. From those curves one can see that depending on the type of test one obtains different stress-strain curves; and that normalization with respect to a mean or a normal effective stress does not bring them into coincidence. The differences are quite pronounced for values of strain less than 5 percent. Similar results were obtained with the (0.5-10) and (0.5-20)

Fig. 10 (a). Stress-strain curves for (0.5-30) Reid Bedford sand

Fig. 10 (b). Normalized stress-strain curves for (0.5-30) Reid Bedford sand

sands. More details can be found in the thesis by Ker (1982).

Fig. 11 shows the secant shear modulus G for the (0.5-20) sand. The results vary from device to device with the simple shear test at constant force showing the smallest G at strains below 5 percent. Similar results were obtained for the (0.5-10) and (0.5-20) sands.

As in the case of clays, the change in the effective vertical stresses and in the pore water pressure which respectively take place during constant length (constant volume) and constant force (undrained) tests were recorded during simple shear and hollow cylinder tests. While one would expect that a drop in the vertical effective stress of a constant length test would correspond to "at

Fig. 11. Shear moduli for (0.5-30) Reid Bedford sand (1 psi=6.9 kPa)

Fig. 12. Comparison of changes in pore pressures and effective vertical stresses in hollow cylinder tests on (0.5-30) Reid Bedford sand

least some increase" of pore water pressure in an undrained test, as happened for clays, the opposite took place in the hollow cylinder. Fig.12 shows the drop in vertical effective stress of the constant length hollow cylinder test and the "decrease" in pore water pressure in the undrained test. Fig.13 shows the results recorded for the simple shear tests: There the trends are what they are expected to be but the magnitudes are totally different. Part of the above is, of course, due to the free lateral movement that can take place in the hollow cylinder and the "relative" rigidity of the N.G.I. reinforced membrane. Indeed Fig.14 shows the measured volumetric strains in the constant length hollow cylinder and the so called constant volume simple shear test.

Similar results were obtained with the (0.5-10) and (0.5-20) sands.

Results Obtained From Dynamic Tests on Reid Bedford Sand

Fig.15 shows the results obtained from

Fig. 13. Comparison of changes in pore pressures and effective vertical stresses in simple shear tests on (0.5-30) Reid Bedford sand

Fig. 14. Volume changes in the so-called constant volume tests on (0.5-30) Reid Bedford sand

Fig. 15. Dynamic shear moduli for the 10th cycle for tests on (0.5-30) Reid Bedford sand (1 psi=6.9 kPa)

dynamic tests on the (0.5-30) sand for the 10th cycle. Here too the results obtained with the (1-20) sand are shown; and again depending on the type of the test the moduli can vary very widely.

The damping ratios for the 10th cycle are shown in Fig.16 and they vary from test to test. Similar results were obtained with the (0.5-10) and (0.5-20) sands. Notice that in Fig.16 the points obtained have just been joined together by straight lines. No curve fitting was attempted.

Fig. 16. Damping ratio for the 10th cycle for tests on (0.5-30) Reid Bedford sand

Fig. 17. Variation of the shear moduli with the number of cycles for (1-6.1) and (0.5-9.1) Latin sand (1 psi=6.9 kPa); a) $\gamma=0.15$ percent, b) $\gamma=0.34$ percent

Results Obtained From Tests on Latin Sand

Fig. 17 shows the shear moduli versus the number of cycles for shearing strains $\gamma=0.15\%$ and 0.34% respectively. Here again, for the smaller number of cycles the moduli vary very widely depending on the cycle number and consequently on the degradation of the reacting stress: The triaxial and hollow cylinder tests give the higher magnitudes of shear moduli when compared to the simple shear tests.

The damping ratios as a function of the number of cycles are shown in Fig. 18. The simple shear constant force test is once more at the bottom of the set of curves.

CONCLUSIONS

The analysis of the states of stress in the most popular testing devices in soil mechanics has shown that the boundary condition affect the stress distribution in a very pronounced

Fig. 18. Variation of the damping ratio with the number of cycles for (1-6.1) and (0.5-9.1) Latin sand; a) $\gamma=0.15$ percent, b) $\gamma=0.34$ percent

way. The extensive testing program conducted on both clay and sand soils supports this analysis. The standard triaxial test is still the favorite when it comes to static or dynamic testing in axial extension or compression; but extrapolations made to simulate shearing conditions leave a lot to be desired.

The simple shear test originally conceived to simulate soil conditions during landslides and earthquakes underestimates the soil properties by very substantial amounts. The strength, the dynamic and static shear moduli, the damping ratios it yields are consistently a small fraction of their values as measured in the thin long hollow cylinder. This test underpredicts every parameter it is supposed to measure. The contention that the drop of the vertical stress in a so called constant volume test is equal to the increase in porewater pressure in an undrained test has absolutely nothing to support it either theoretically or, as shown in this study, experimentally. The volume in this constant

volume test is not constant at all and the reinforced membrane has substantial flexibility. Using a standard membrane and placing the device in a cell does not result in any improvement; since, as shown by the finite element analysis the sample in general does not see the applied lateral stresses beyond a thin skin. No calibration constant could be found to justify the continued use of this device in research or commercial laboratories to study either static or dynamic problems.

In the thin long hollow cylinder the natural cross anisotropy is maintained and shearing stresses can be applied to horizontal planes without resulting in the kind of stress concentrations and nonuniformities present in the simple shear device. It does require a special cell which, although not as simple as that of the standard triaxial test, is much simpler than the ones required for prismatic elements.

Making a hollow cylinder of sand is no more complicated than making a solid cylinder, once the cell is made. Any clay that can be cut with a piano wire can provide a hollow cylindrical specimen. It is obvious that many natural clays cannot be easily trimmed; but the same criticism holds when one is trying to prepare a standard triaxial specimen. The thinner the specimen the closer to uniform are the shearing stresses and strains.

In conclusion it is felt that the thin long hollow cylinder with the same inner and outer pressures and subjected to axial and torsional stresses is the most reliable and most versatile tool available today to test soil. Phenomena of cyclic mobility and liquefaction can be studied with it far more accurately than with any laboratory tool of its kind. It is recommended that it be adopted for standard laboratory investigations of earthquake related problems.

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NOTATION

- E = Young's modulus
- G = shear modulus
- K_0 = coefficient of earth pressure at rest
- l = length
- n = ratio
- r_i, r_o = inner and outer radii
- γ = shearing strain
- ϵ_z = axial strain
- ν = Poisson's ratio
- $\sigma_r, \sigma_\theta, \sigma_z$ = normal components of the stress tensor
- $\sigma_1, \sigma_2, \sigma_3$ = principal stresses
- τ = shearing stress
- $\tau_{r\theta}, \tau_{rz}, \tau_{\theta z}$ = shearing components of the stress tensor

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