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AN EVALUATION OF LABORATORY TESTING TECHNIQUES IN SOIL DYNAMICS

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16. Abstract (Limit: 200 words)

An extensive soil testing program was conducted on clay and sand materials using three different devices: 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 emphasizing 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 long hollow cylinder. For both static and dynamic tests, the triaxial test is definitely an improvement over the simple shear one. The thin long 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.

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AN EVALUATION OF LABORATORY TESTING
TECHNIQUES IN SOIL DYNAMICS

by

Adel S. Saada

This report is the condensation of two Master's degree dissertations by Messrs. G. Fries and C. Ker working under the direction of the principal investigator. The proposed investigation has been fully completed and significant results obtained. The report, with some editorial adjustments will soon be submitted for publication in an international journal.

The following pages contain:

1 - An abstract of the report giving a very short summary of the research conducted.

2 - A list of personnel involved in this research.

3 - The actual report to be published soon.

One of the master's thesis by Mr. Fries is enclosed as well as two papers already published which have resulted from this work. The thesis by Mr. Ker is being written and when completed in a couple of months will be sent to the National Science Foundation. The two thesis contain all the details and test results.

Within the framework of this grant the Principal Investigator attended:

1 - The Symposium on Laboratory Shear Strength of Soil held in Chicago in June, 1980, where he presented the state of the art on soil testing (enclosed).

2 - The International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics held in St. Louis in April, 1981, where he presented two papers, one supported by a previous NSF grant and one supported by this grant (enclosed).

3 - The Tenth International Conference on Soil Mechanics and Foundation Engineering held in Stockholm in June, 1981, where he presented a paper summarizing a study supported by a previous NSF grant.

We trust the National Science Foundation finds this report satisfactory.

Respectfully submitted,

Adel S. Saada

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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 long hollow cylinder. For both static and dynamic tests the triaxial test is definitely an improvement over the simple shear one. The thin hollow cylinder is shown to be most desirable configuration to be used in the soils laboratory for studies related to strength and stability under both static and earthquake situations.

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AN EVALUATION OF LABORATORY TESTING TECHNIQUES
IN SOIL MECHANICS

by

Adel S. Saada*, Gerardo Fries** and Ching-Chang Ker ***

A Paper
To be submitted for evaluation and possible publication in
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INTRODUCTION

The influence of the boundary conditions on the numerical values of 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 were conducted and attempts were made to obtain equivalent conditions in the various apparatuses.

In their State of the Art on Laboratory Strength Testing of Soils Saada and Townsend (20) 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

A - 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 (20). A closed form solution was found for the Roscoe type (13,16) with and without slippage at the boundaries. A photoelastic study was conducted for both types (25): Fig. 1 from Ref. 25 shows the shearing stress distribution in the Roscoe type and Fig. 2 that 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 (7) that the lack of uniformity in the axial (σ_z) radial (σ_r) and circumferential (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 often have ribs (or similar arrangements) 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. 3 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. (0.6045mm) and a lateral cell pressure of 30 psi (207 Kpa). Young's modulus is chosen to be 2844 psi (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. 3 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. 3 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. The results of a complete finite element analysis for various height to diameter ratios and a wide range of Poisson's ratios are given in the appendix. This analysis applies to both the simple shear and the triaxial tests.

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. (2), 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 (3) 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 (8).

Finally, Bjerrum and Landva (3) 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 occured 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.

B - 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. Ref. 20 reviews most of the studies conducted on this subject. Of particular interest are the papers by Balla (1) who summarizes previous work and brings new insight to the problem, Moore (11) who examined the effects of six Poisson ratios, a height to diameter ratio of one and two and lateral confinement, and Radhakrishnan (18) 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 in the appendix 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 (20).

End restraints can be minimized by using rubber sheeting and silicone grease to obtain frictionless contacts (17) . However, Norris (12) 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.

C - 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. The previous references give proportions for which the end effects are reduced to a minimum. If the length is ℓ and the inner and outer radius are r_i and r_o it is recommended that

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

Such proportions were checked by photoelasticity and by finite element analysis (4) as well as experimentally (9) 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 coworkers 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 parallellepedic: 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.

D - Some Comparisons Among the Results Obtained in Various Devices

Until very recently, few systematic studies were made to compare results obtained in the various devices. Investigators have tried to match the stress conditions on a horizontal plane in a simple shear apparatus to those on a 45º plane in the triaxial test. It is important to remember that all the components of the stress tensor affect the behavior of the sample and not just what happens on a particular plane. As mentioned previously, Bjerrum and Landva (3) and Ladd and Edgers (8) found very substantial differences between the shearing strengths measured in the simple shear device and the equivalent triaxial tests. Seed and Peacock (23) found that cyclic strength in simple shear were about 30 to 50 percent smaller than comparable cyclic triaxial strengths. Park and Silver (14) attempted to compare the shear moduli and damping ratios measured in cyclic triaxial tests with results obtained by Thiers and Seed (24) using cyclic simple shear. They found close agreement when the comparison was made under conditions of equal mean effective stress; however, it must be remembered that the mean effective stress is not known in the simple shear device. This brings into the picture the whole subject of normalization. While normalizing has obvious advantages it seems to be used primarily as a curve fitting technique. When normalizing with respect to some parameter does not work another is used until the desired coincidence is obtained. In view of the results shown in Fig. 3 and in the appendix, which value of the normal stress is one supposed to take?

Pyke (15) presented a comparison of shear moduli and damping ratios of sand similar to that made by Park and Silver. He tried to match the static and cyclic shear stresses on the horizontal plane in the simple shear test and the 45° plane in the triaxial test; realizing that there are differences in the overall states of stress in the two tests. For example the normal stress in the simple shear test is constant while its value on the 45° plane of the triaxial test varies by $\pm \frac{\sigma_d}{2}$ where σ_d is the difference in the principal stresses. Pyke points out the difference in the loops obtained in the two apparatuses: While that of the simple shear is symmetric, the one obtained in the triaxial test is not.

Finally Lee (10) found that, while not perfect the cyclic triaxial test offered a reasonable compromise for obtaining dynamic properties of saturated sand.

The only comparison involving the thin hollow cylinder subjected to torsional stresses has been made by Saada (22); it is a part of the study reported herein.

EQUIPMENT AND SPECIMEN PREPARATION

A - 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_o consolidation in the triaxial cell and the hollow cylinder cell was obtained by means of a servo-system (19) 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 (20). The cyclic nature of the loading is controlled by an electro-pneumatic signal generator that can induce various wave shapes. A sinusoisal shape was used in this investigation. The computer and its loading frame are shown in Fig. 4.

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 Fig. 5.

B - 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 an 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. (82.55mm) height for the triaxial test; 3.16 in. (80.26mm) diameter and 1 in. (25.4mm) height for the simple shear; 2.8 in. (71.12mm) outside diameter, 2 in. (50.8mm) inside diameter and about 6 in. (152.4mm) height for the hollow cylinder. Those specimens were then K_o 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 unformity $C_u = 1.52$

and a D_{10} = 0.125mm. Its minimum void ratio as given by Durham and Townsend (5) is 0.529 and its maximum void ratio is 0.816. Its granulometric distribution is shown in Fig. 6. The Latin Sand contains some fine shell fragments and shows a larger than usual volumetric compressibility under hydrostatic stresses. Its granulometric curve is shown in Fig. 7. Samples were prepared to a void ratio of 0.72 by vibration on a shaking table for the Reid Bedford sand and to a void ratio of 0.68 by tamping in moist condition for the Latin Sand. Saturation was obtained using vacuum followed by percolation of CO_2 and deaired water; and back pressure in case of triaxial and hollow cylinder specimens.

C - Conventions Used in the Evaluation of the Experimental Results

When comparing the tests results, the current conventions will be followed. This means that the average shearing stress and strain in the simple shear device will be compared to the maximum shearing stress and strain in a triaxial compression test:

$$\tau_{45} = \tau_{max} = \tfrac{1}{2}(\sigma_1 - \sigma_3) = \tfrac{1}{2}(\bar{\sigma}_1 - \bar{\sigma}_3) = \tfrac{1}{2}\sigma_d$$

where σ_d is the excess axial stress also called the deviator.

$$\gamma_{45} = \gamma_{max} = \frac{3}{2}\,\varepsilon_z$$

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 $\frac{E}{3}$ 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, $\frac{1}{2}\tau\gamma$ or $\frac{1}{2}G\gamma^2$. 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. Fig. 8 and its caption shows the various definition.

Normalization which is the process used to bring down results to the same common denominator will be discussed as the data is presented.

STUDY OF CLAY SOILS IN THE VARIOUS DEVICES

A - Testing Program for Clay Soils

All the tests conducted on clay soils were stress controlled. 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, strain and pore water pressures. Hand calculations were complemented by a computerized data acquisition system which reduced immensely the processing time.

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 begain; both in pounds per square inch. K_o 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_o consolidation was released, equilibrium allowed then the sample tested undrained from a hydrostatic state of stress.

Pure torsion tests in the hollow cylinder be they static or cyclic started with the axial stress which produced the K_o 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_o consolidation ofthe 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 adviseable since the flexibility of the norwegian membranes is quite large. It was decided, however, to make the measurements 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 water pressure in the other. For comparison purposes the same type of tests were conducted on hollow cylinders subjected to static and cyclic torsional stresses.

B - Results Obtained from Static Tests

Fig. 9 shows the results of static tests obtained with the 48-18 clay and normalized with respect to an effective normal stress $\bar{\sigma}_n$.

The shearing stress τ in the ordinate is the shearing stress on a 45º 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 horizontal plane. The shear strain γ corresponds to the stresses defined above. In Fig. 9 as well as in all the ones to 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. 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 58-15 and the 33-18 clays.

Fig. 10 shows the secant shear modulus $G(= \frac{\tau}{\gamma})$ 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 corresponding 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. 11 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. The measurements of the pore water pressures in the simple shear device were certainly not accurate because of the flexibility of the reinforced membrane, but it was decided to use the most popular device in this investigation.

Various normalization parameters were used on the K_o consolidation clays (6) but none of them brought any improvement to the data shown in Figs. 9 to 11. 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.

C - Results Obtained From Dynamic Tests

For each level of stress a minimum of 60 cycles was applied to the samples. The results given herein refer to the 10th cycle. The shear moduli and damping ratios were calculated as shown in Fig. 8. In the constant force cyclic hollow cylinder tests HC(CF) only the hysteresis loops connected to torsion were considered. Fig. 12 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 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 (21). This seems to be true in this investigation too. Figure 13 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_o consolidated clays is different in tension and compression (21).

D - 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_o consolidated clays. Various normalizing procedures did not bring the results to coincidence (6). Fig. 14 shows the value of the shear moduli versus strain for the tests conducted.

STUDY OF SAND SOILS IN THE VARIOUS DEVICES

A - 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 identical to the ones conducted on K_o consolidated clay; with K_o assumed equal to 0.5. 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_o 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 latteral 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.

B - Results Obtained From Static Tests on the Reid Bedford Sand

Fig. 15 shows the results of static tests obtained with the (0.5-30) sand normalized with respect to the effective normal stress $\bar{\sigma}_n$ as was done for the K_o 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) sands (27).

Fig. 16 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 take place during constant length (constant volume) and constant force (undrained) 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 correspong to "at least some increase" of pore water pressure in an undrained test, as happened for clays, the opposite took place in the hollow cylinder. Fig. 17 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. 20 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 latteral movement that can take place in the hollow cylinder and the "relative" rigidity of the N.G.I. reinforced membrane. Indeed Fig. 21 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.

C - Results Obtained From Dynamic Tests on Reid Bedord Sand

Fig. 20 shows the results obtained from 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. 21 and they vary from test to test. Similar results were obtained with the (0.5-10) and (0.5-20) sands.

D - Results Obtained From Tests on Latin Sand

Fig. 22 shows the shear moduli versus the number of cycles for shearing strains γ = 0.15% and 0.34% respectively. Here again, for the smaller number of cycles the modulii 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. 23. 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 conditions affect the stress distribution in a very pronounced 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 true 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 is 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 latteral stresses beyond a thin skin. <u>No calibration constant could be found to justify the continued use of this device in</u>

research or commercial laboratories to study either static or dynamic problems. As stated by Saada and Townsend (20) its proper place is in the hands of designers who have calibrated their thinking in terms of the results of those tests and have successfully applied those results in their practice.

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 noninformities 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 not 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 critisim 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 pressues and subjected to axial and torsional stresses is the most reliabile and most versatile tool available today to test soil. Phenomena of cyclic mobility and liquefaction can be studied with it far more accurately than 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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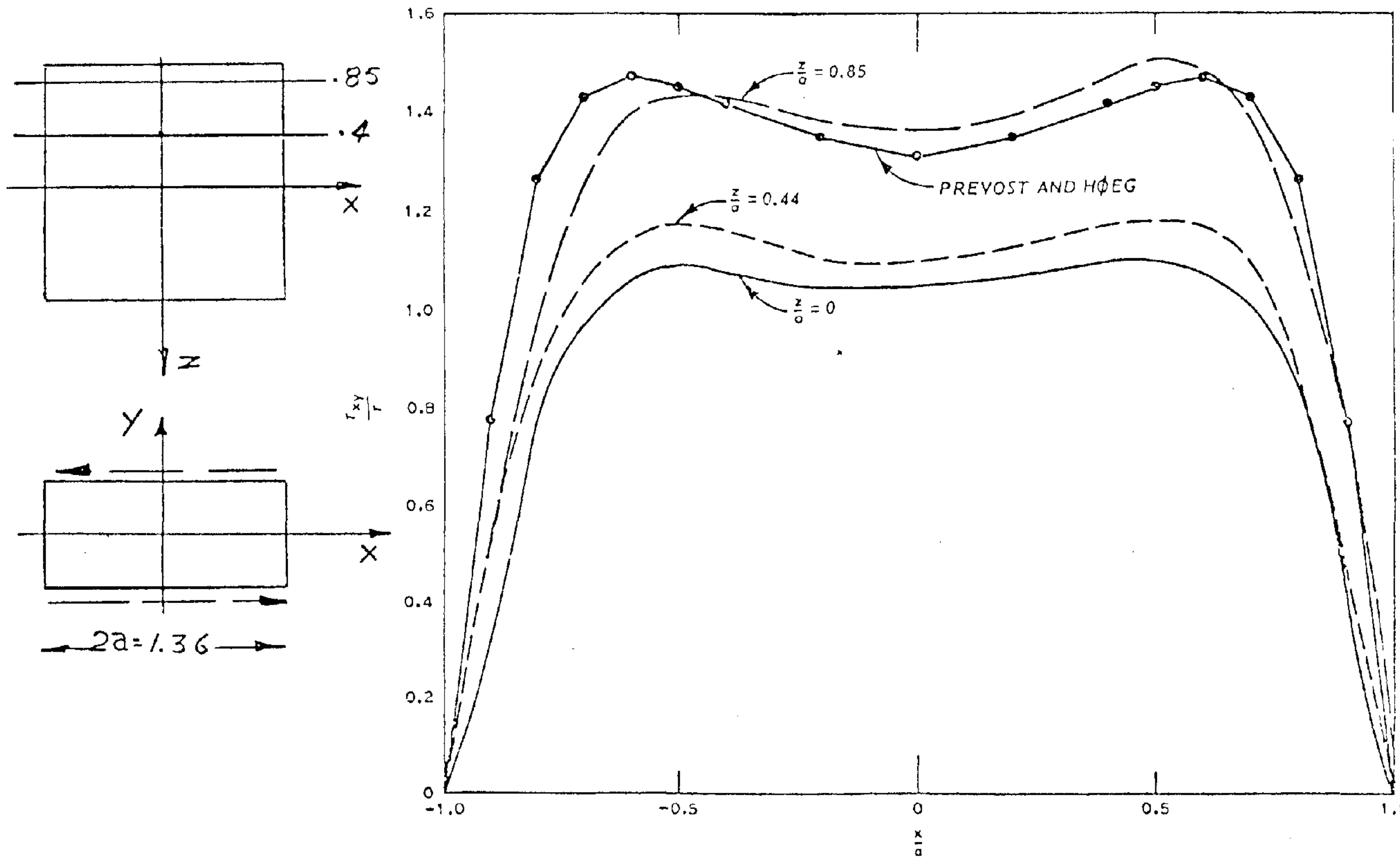


Figure 1. Shear Stress Distribution in the Roscoe Simple Shear Device.

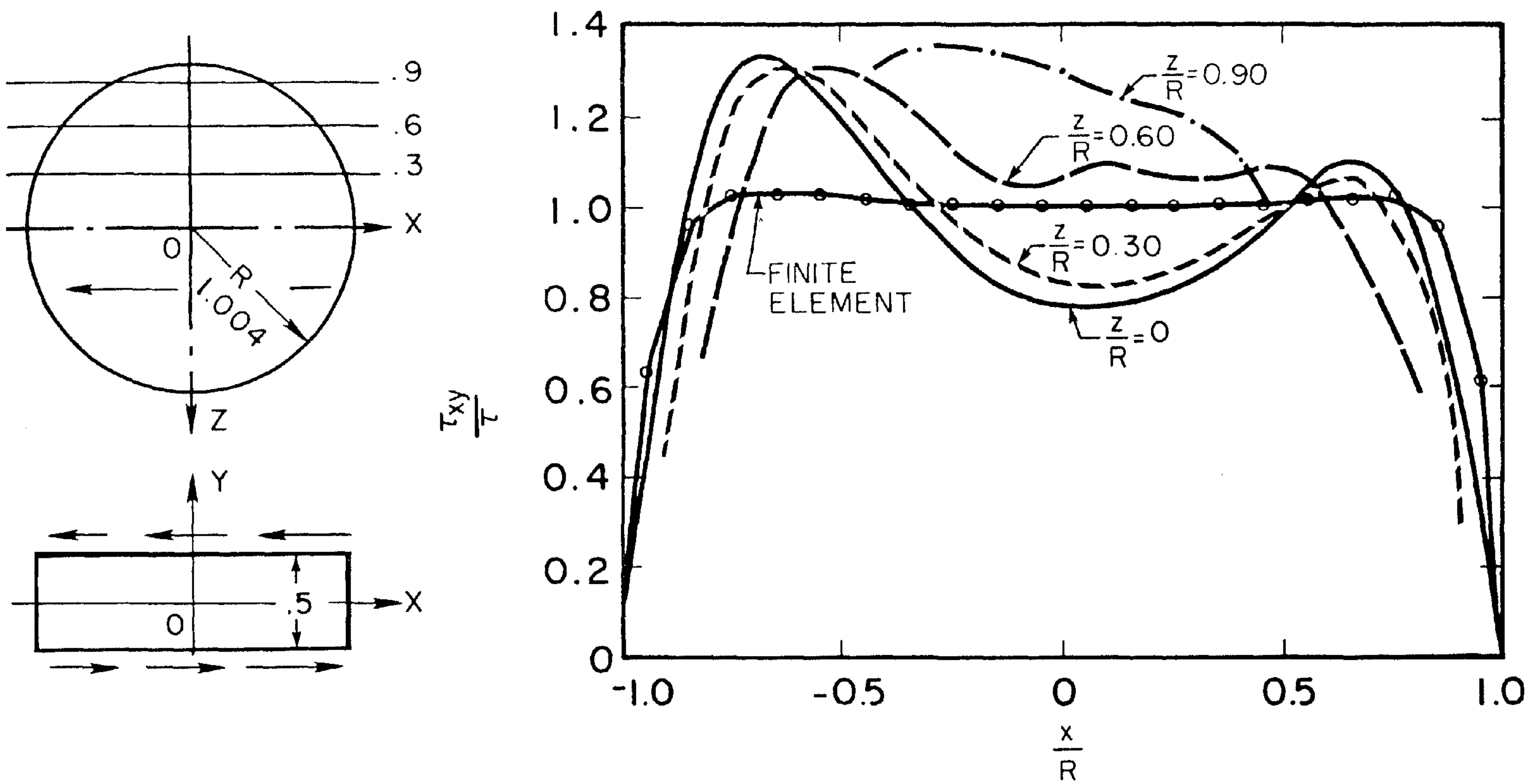


Figure 2. Shear Stress Distribution in the NGI Device.

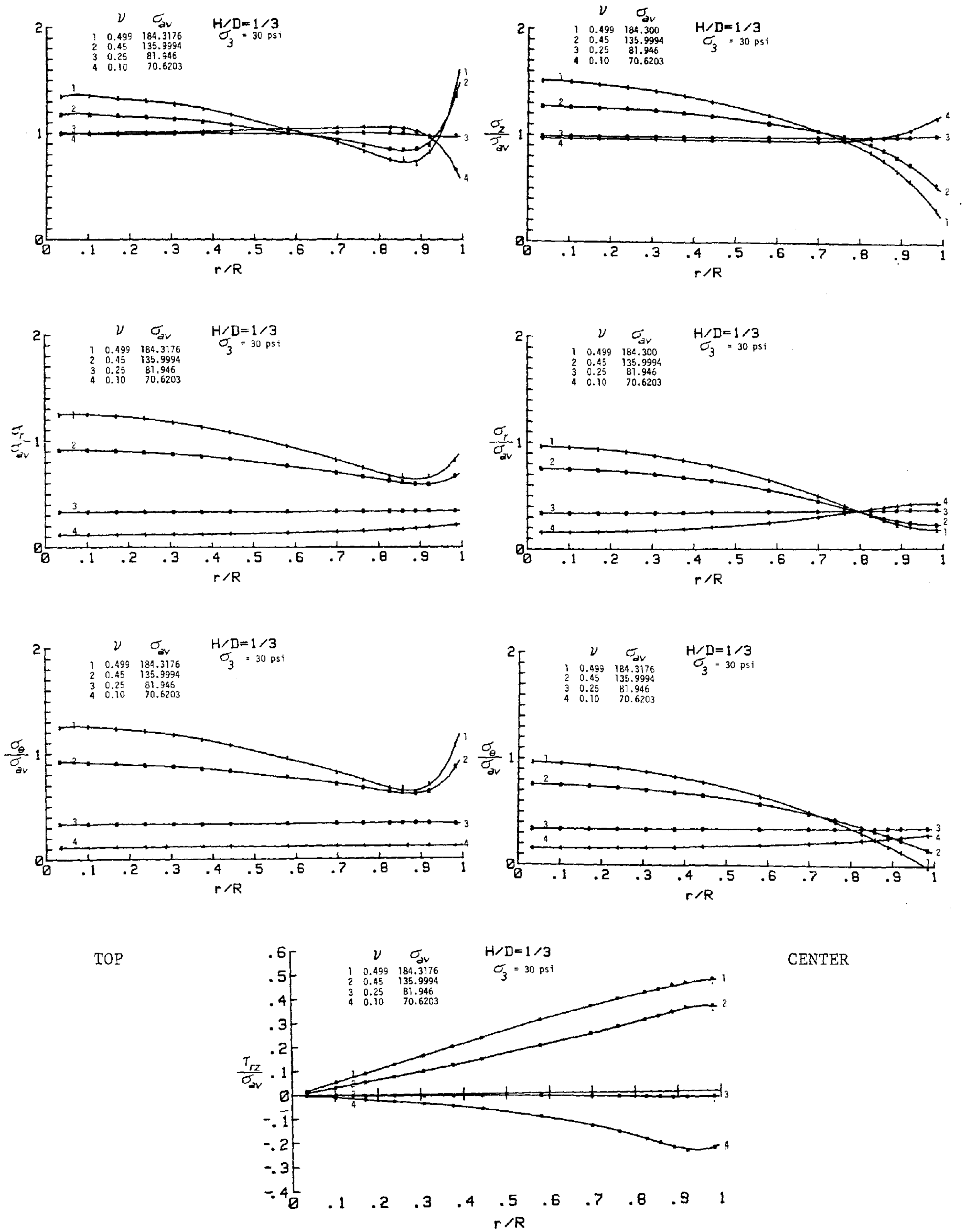
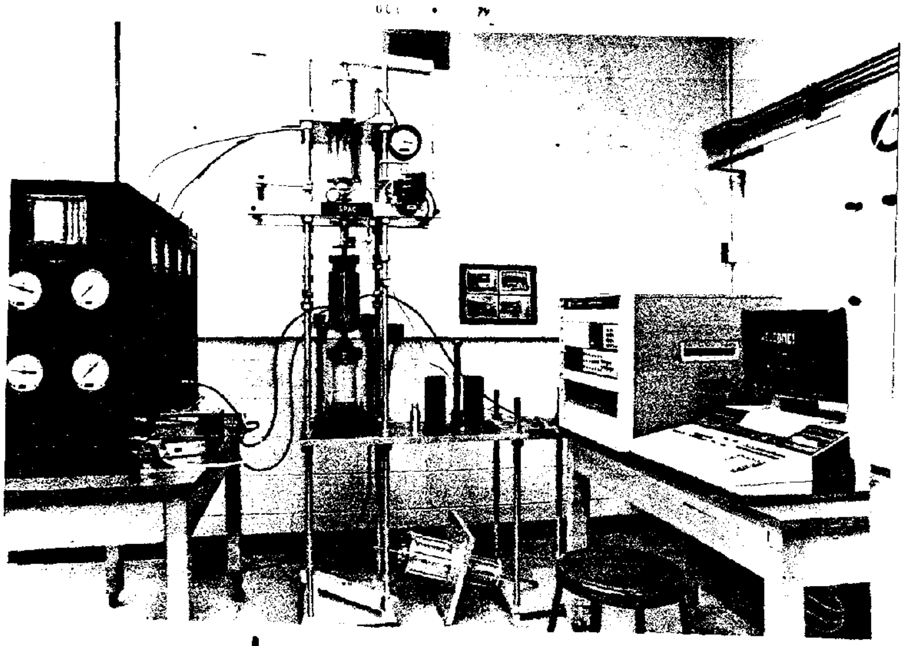


Figure 3. Results of Finite Elements Analysis for Different ν.



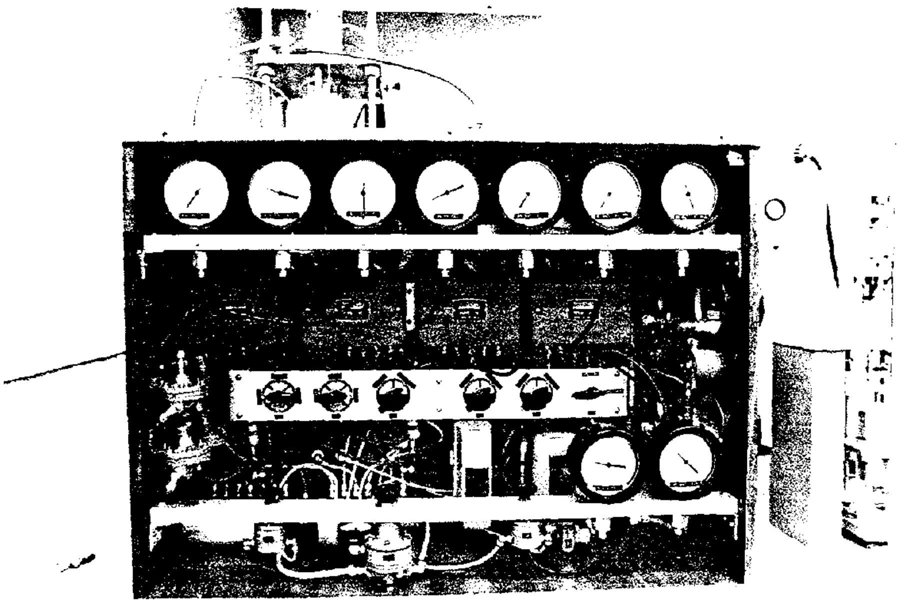


Figure 4. Controlled-Stress Pneumatic Analog Computer SPAC.

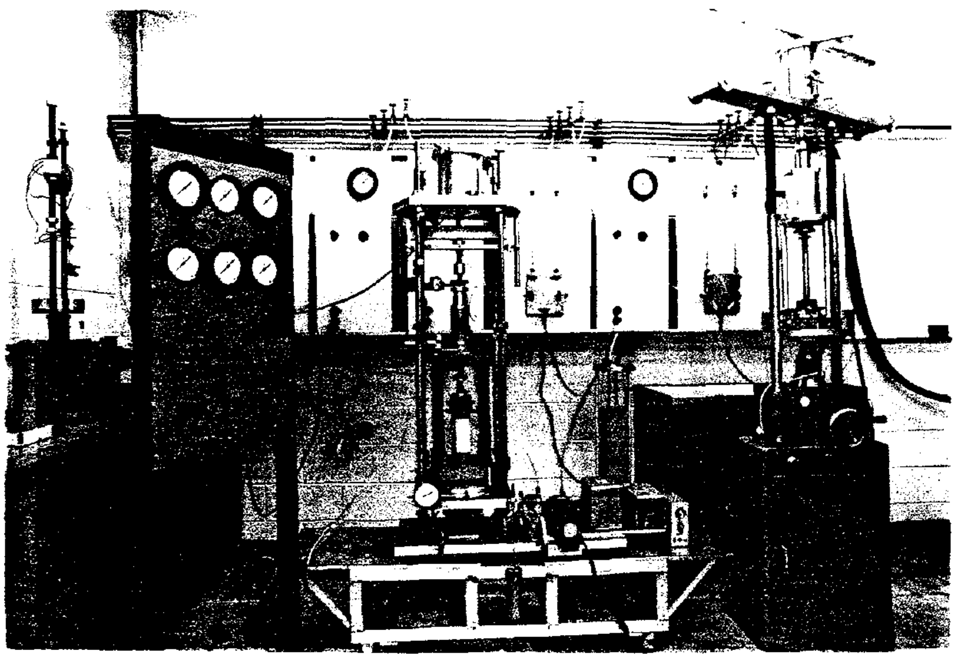


Figure 5. Controlled Deformations Pneumatic Analog Computer SPAC.

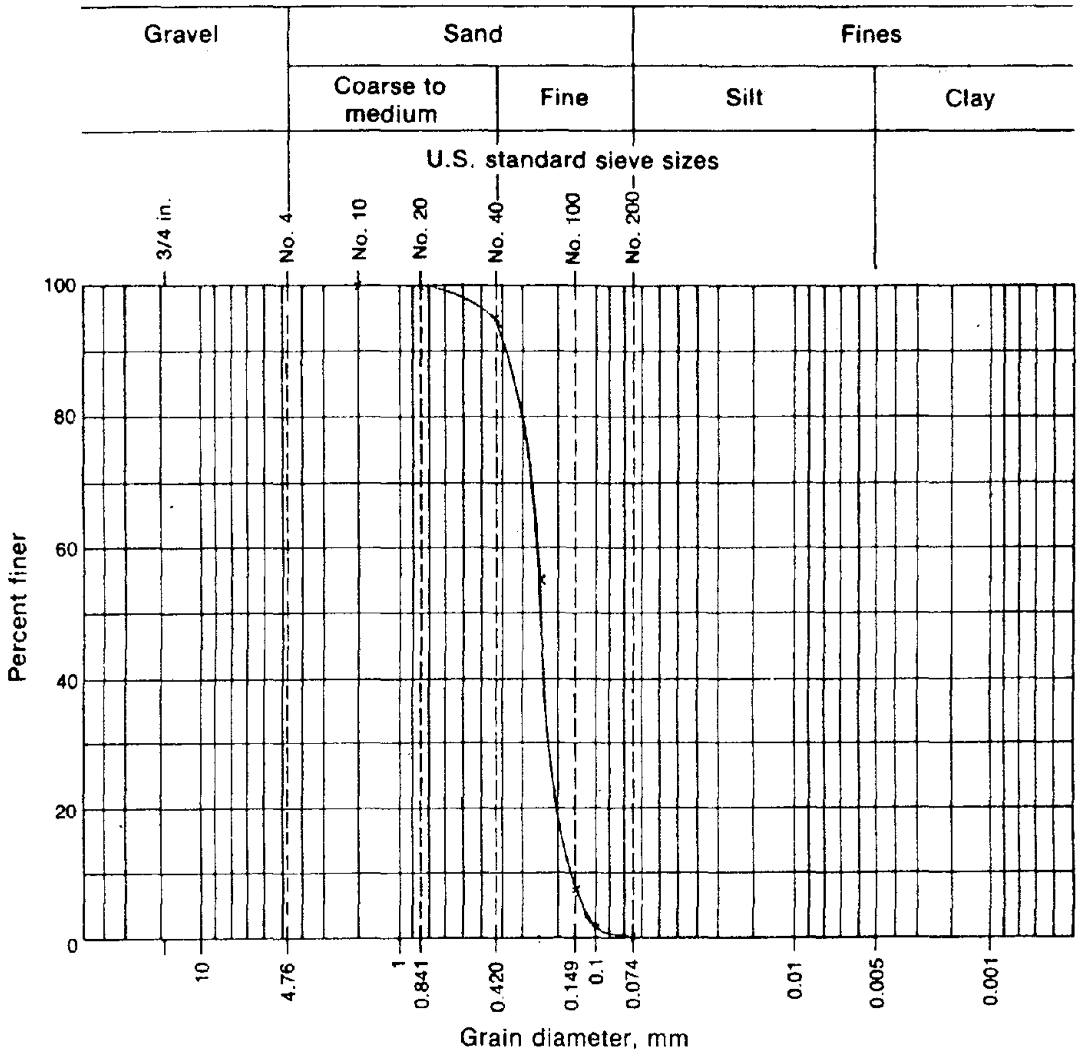


Figure 6. Granulometric Distribution of Reid Bedford Sand.

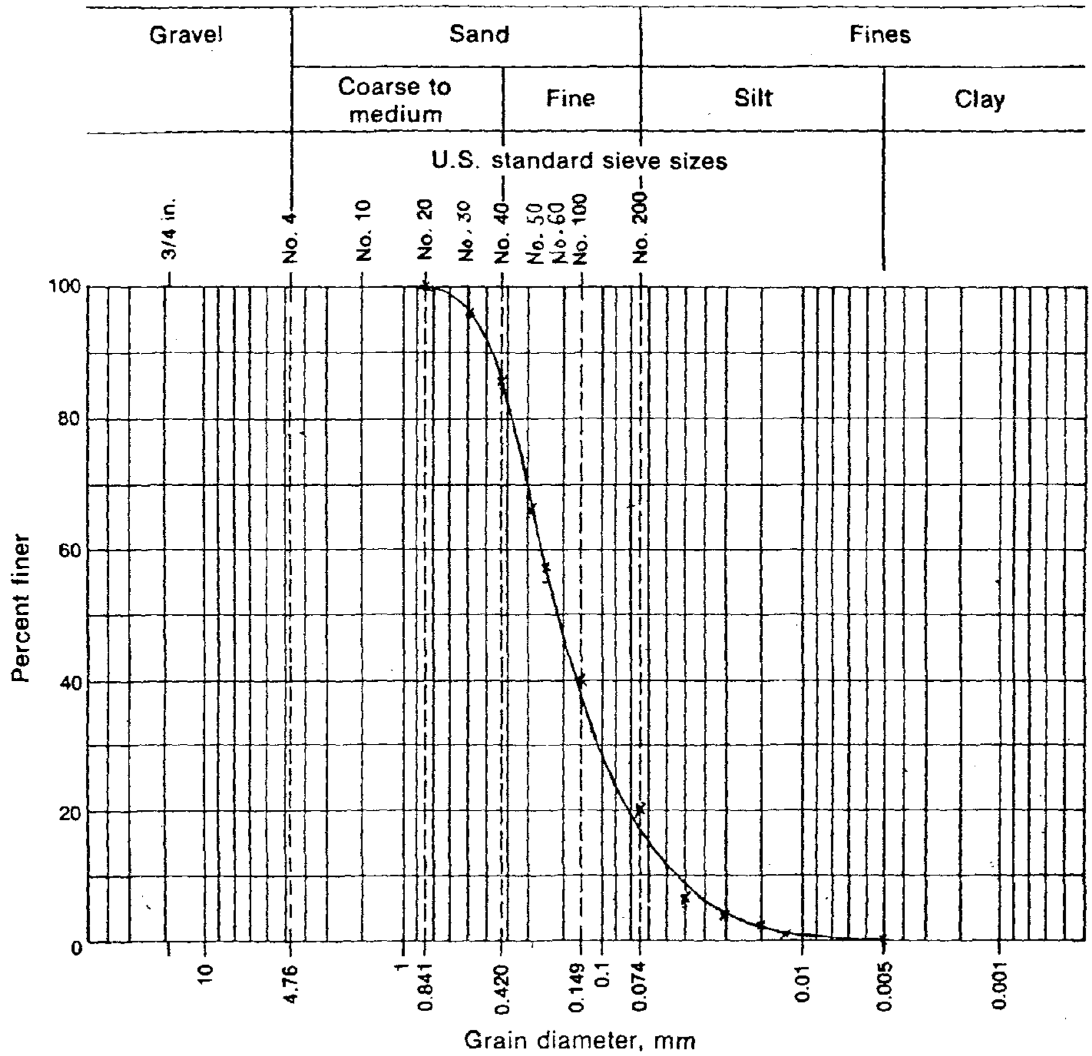
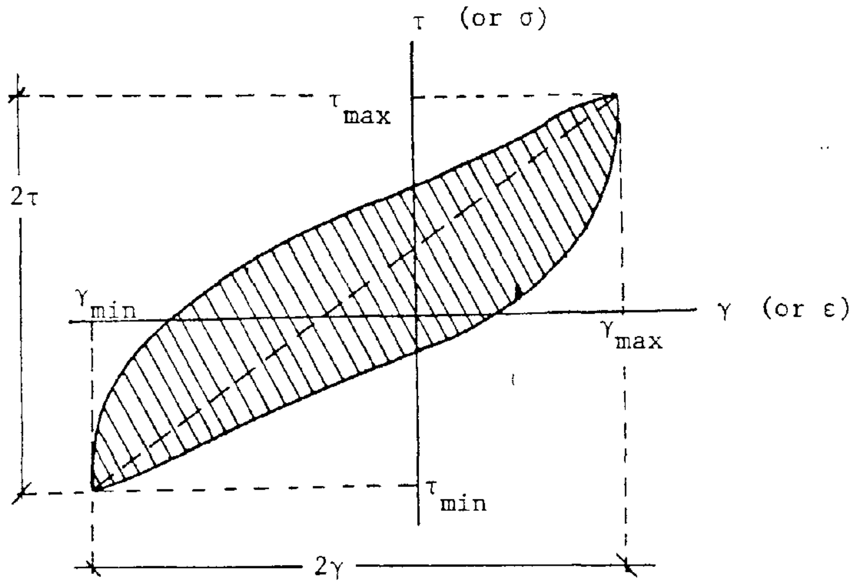


Figure 7. Granulometric Distribution of Latin Sand



$$\tau = \frac{\tau_{max} - \tau_{min}}{2}$$

$$G = \frac{\tau_{max} - \tau_{min}}{\gamma_{max} - \gamma_{min}} = \frac{\tau}{\gamma}$$

$$\gamma = \frac{\gamma_{max} - \gamma_{min}}{2}$$

$$\lambda = \frac{\Delta W}{(4\pi)(\frac{1}{2}\ \tau\gamma)} = \frac{\Delta W}{(4\pi)(\frac{1}{2}\ G\gamma^2)} = \text{Specific Damping Ratio}$$

Where ΔW = Total Energy Lost per Unit Volume, and represented by the Area of the Hysteresis Loop.

Figure 8. Hysteresis Loop and Definitions of Specific Damping Ratio (λ) and Secant Modulus (G).

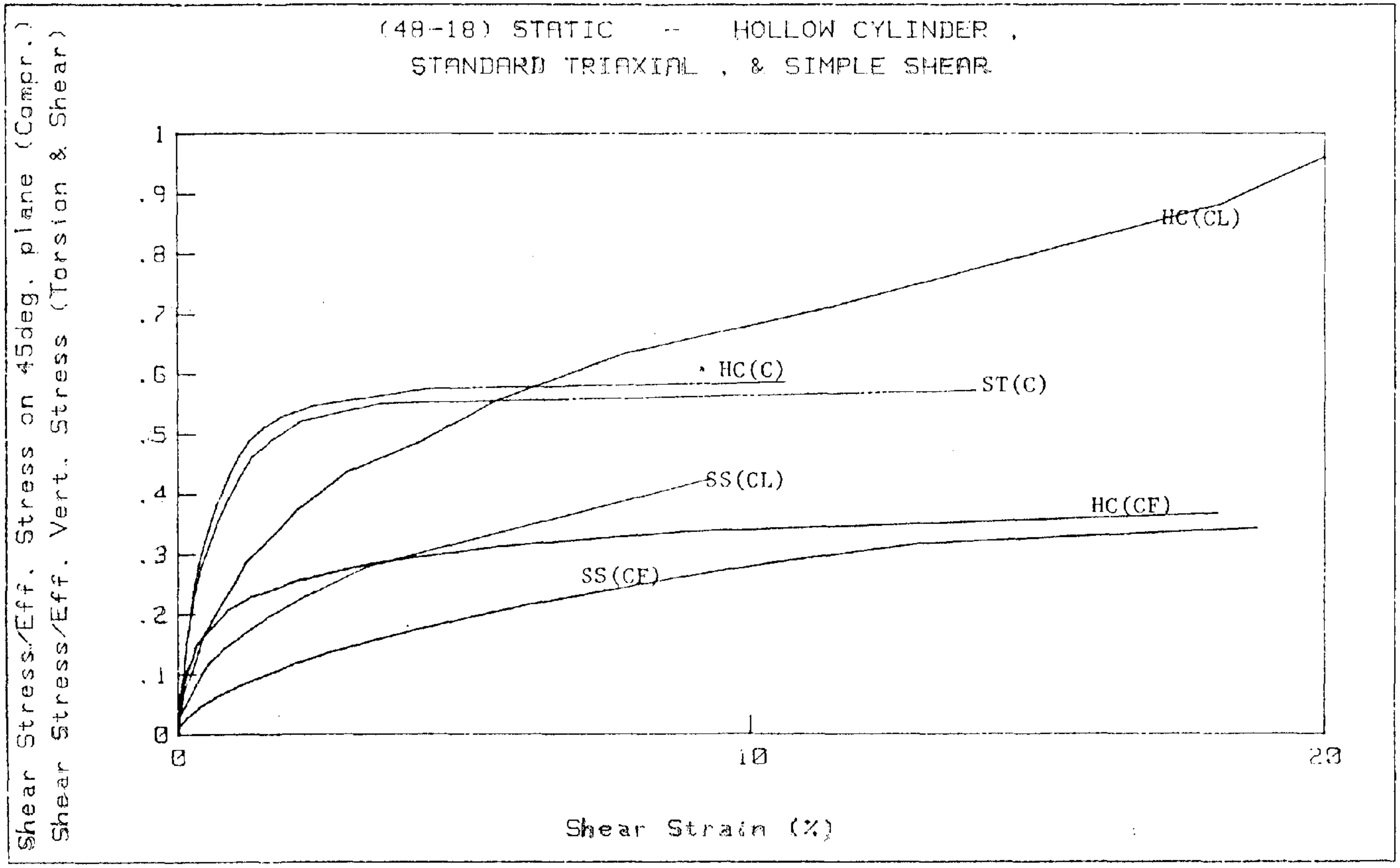


Figure 9. Normalized Shear Stress vs. Shear Strain
Curves from Ko-consolidated Clay, (48-18) series

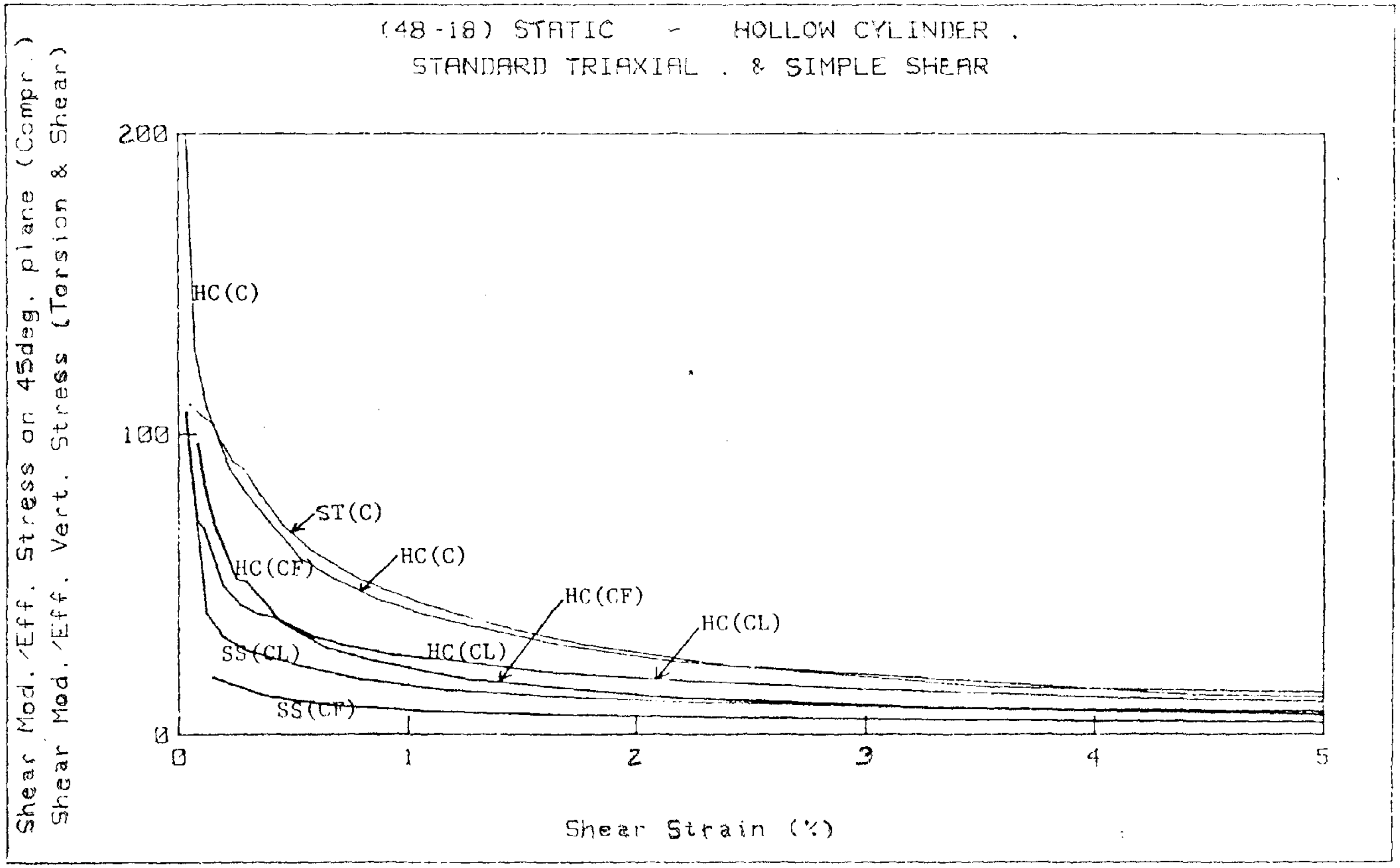
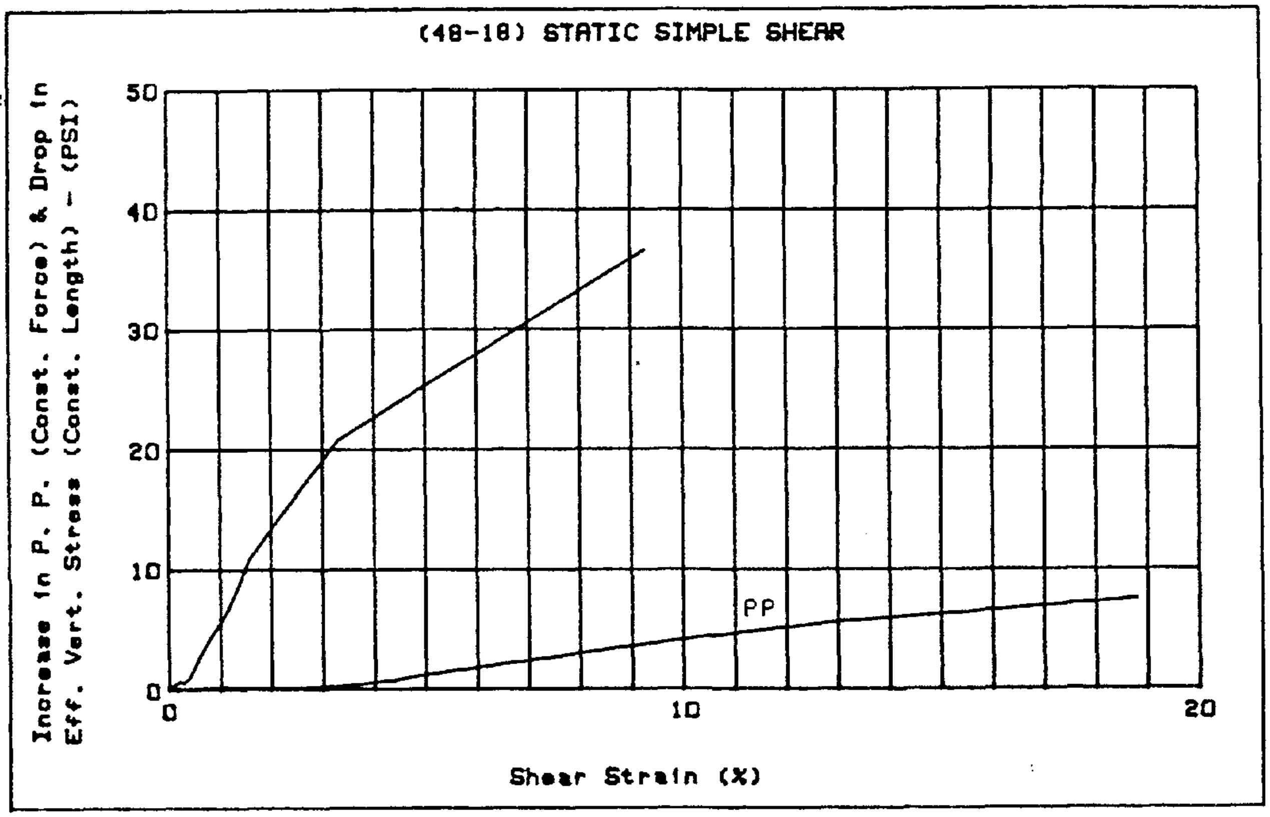


Figure 10. Normalized Shear Modulus vs. Shear Strain
from Ko-consolidated Clay, (48-18) series



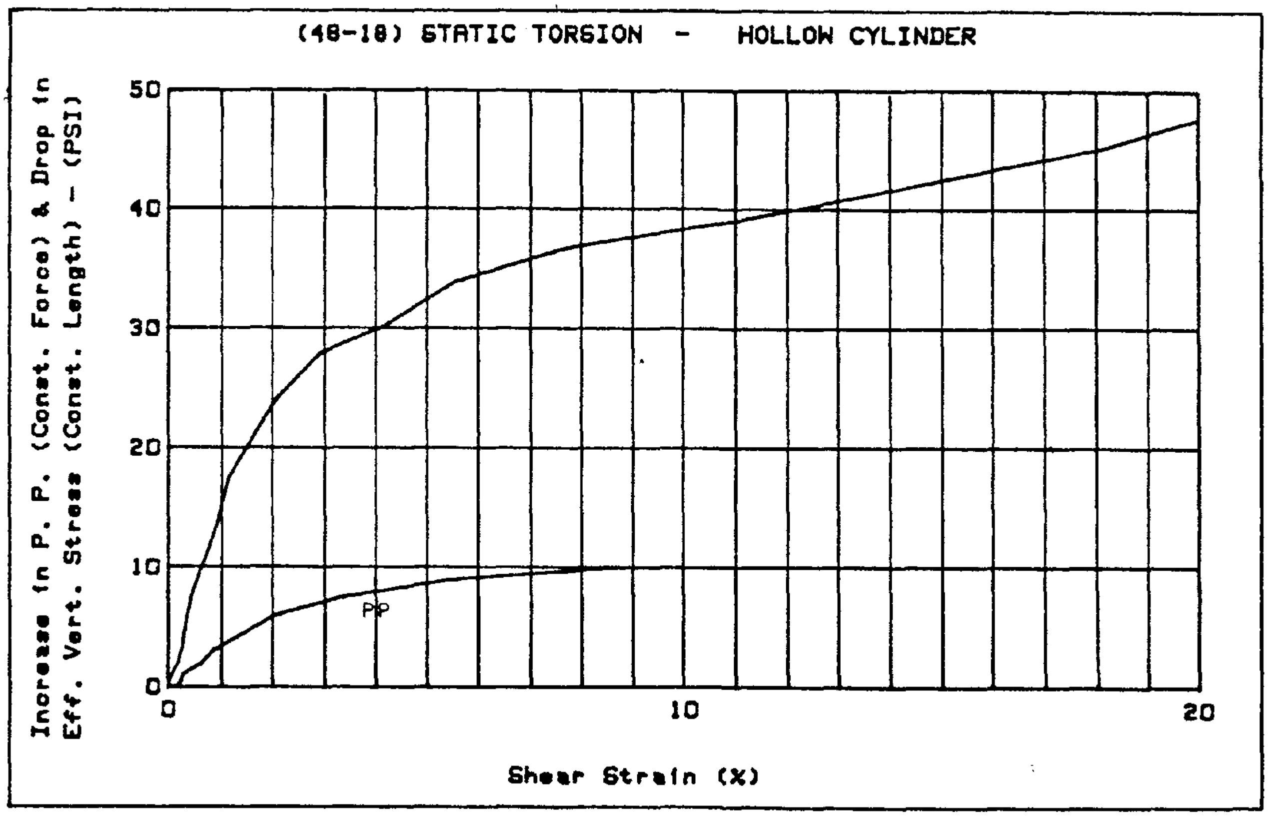


Figure 11. Comparison of the Increase in Pore Pressure to the Drop in Effective Vertical Stress in Simple Shear and Hollow Cylinder Tests. (1 psi = 6.9 Kpa)

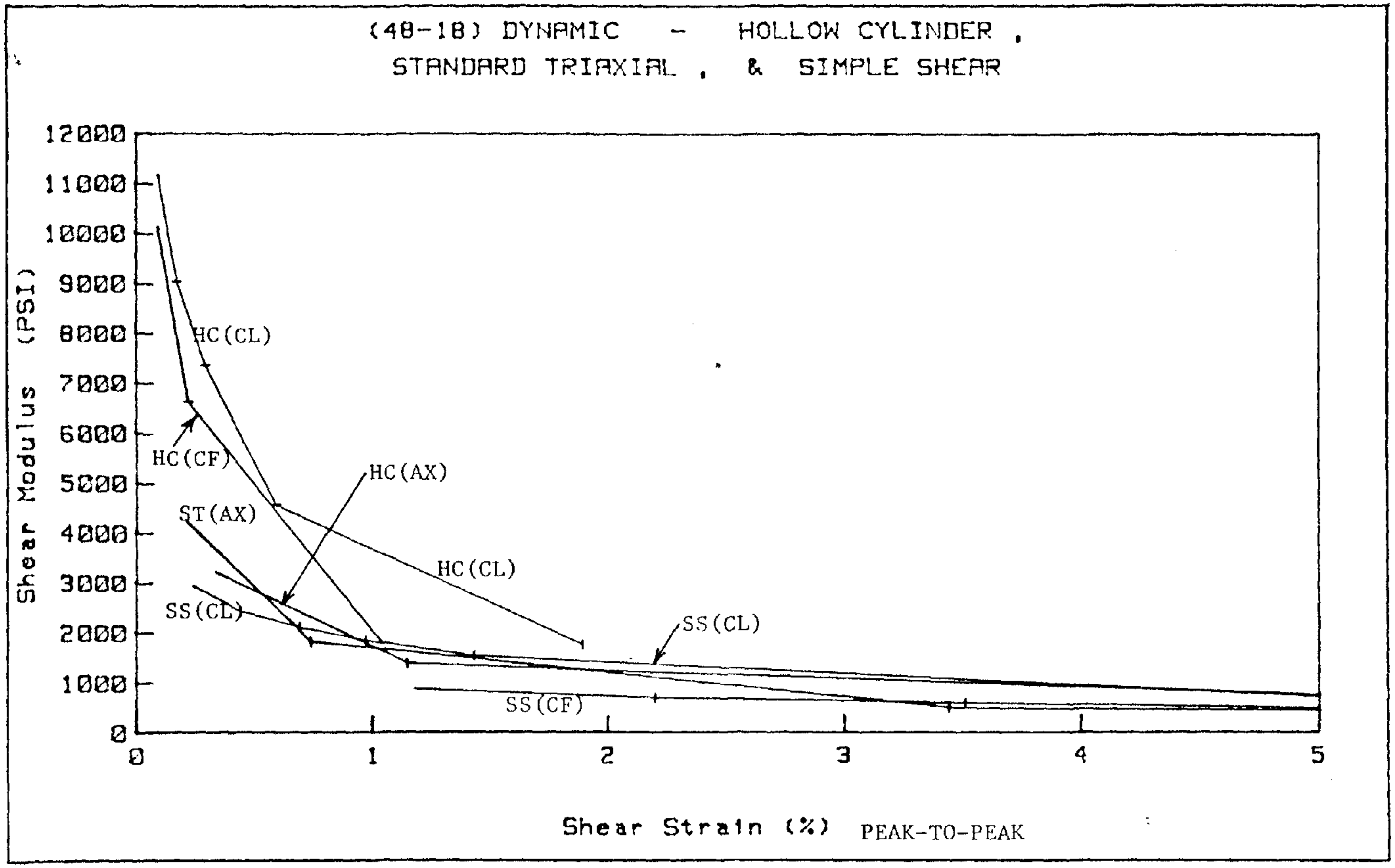


Figure 12. Shear Modulus Corresponding to 10th Cycle vs. Shear Strain Ko-consolidated Clay, (48-18) series. (1 psi = 6.9 Kpa)

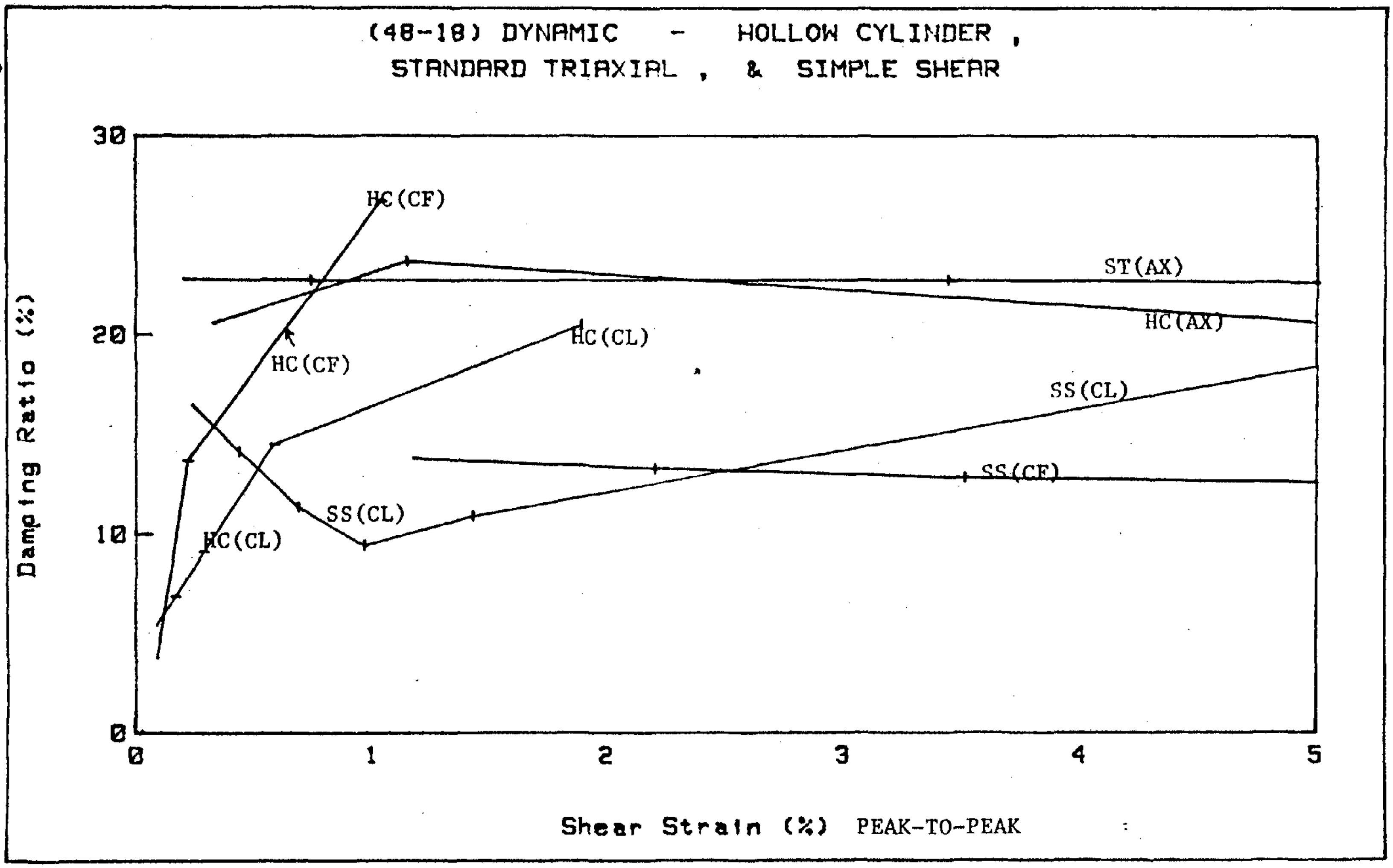


Figure 13. Specific Damping Ratio (10th Cycle) vs. Shear Strain
Ko-consolidated Clay, (48-18) series.

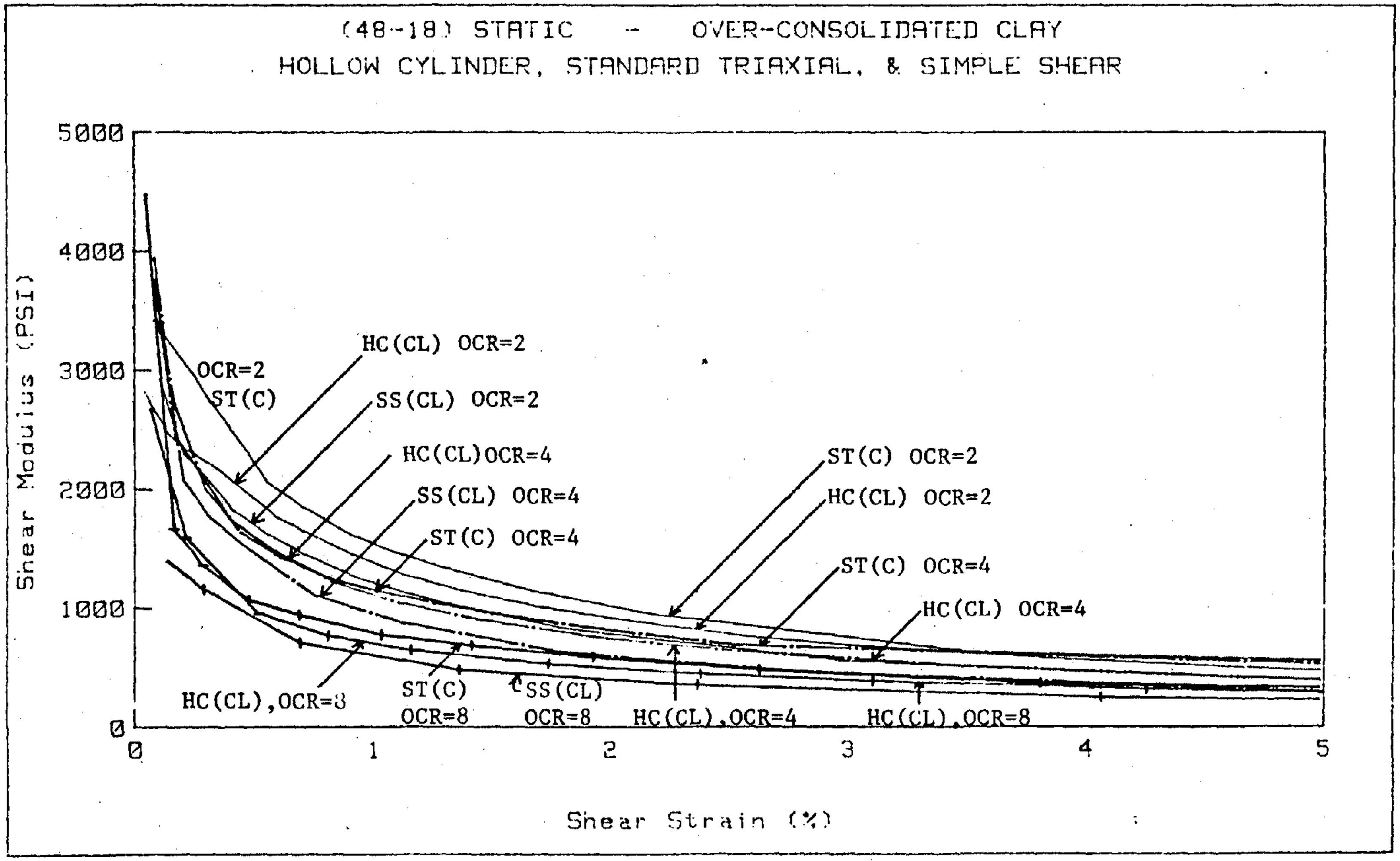


Figure 14. Shear Moduli vs. Shear Strain Over-consolidated Clay, OCR = 2.4 and 8. (1 psi = 6.9 Kpa)

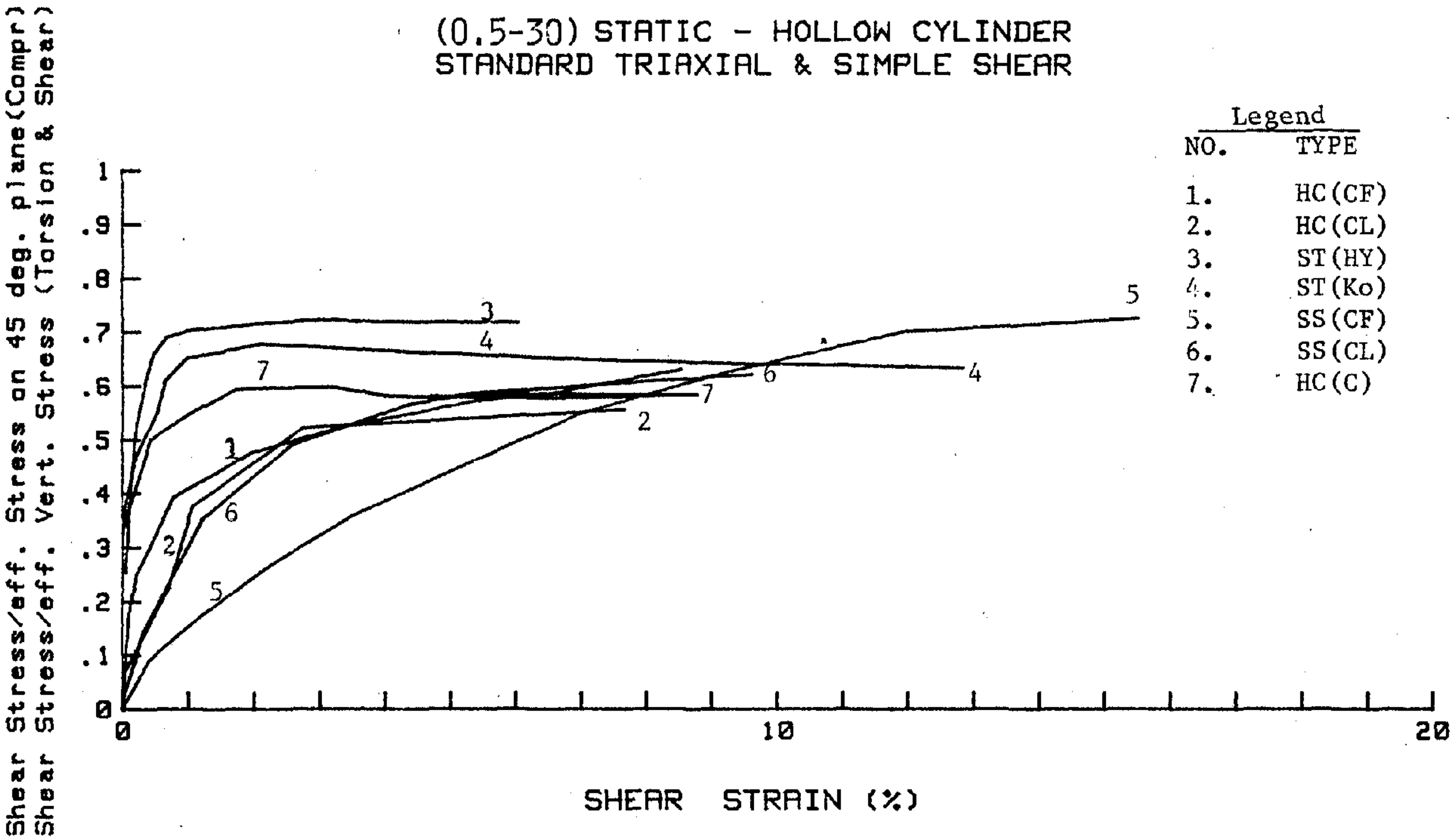


Figure 15. Normalized Stress-Strain Curves for Various Devices.

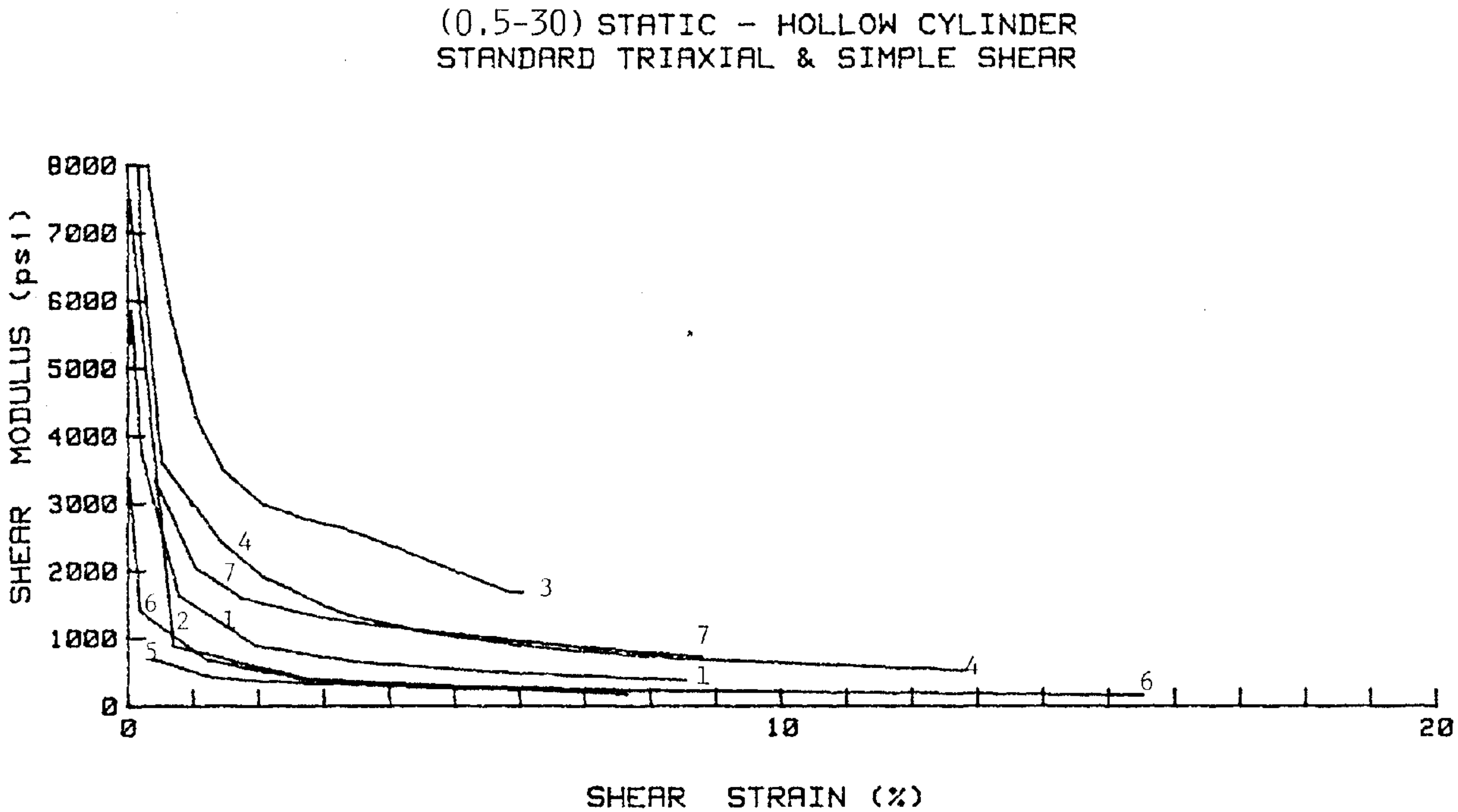


Figure 16. Shear Moudli for Various Devices. (1 psi = 6.9 Kpa)

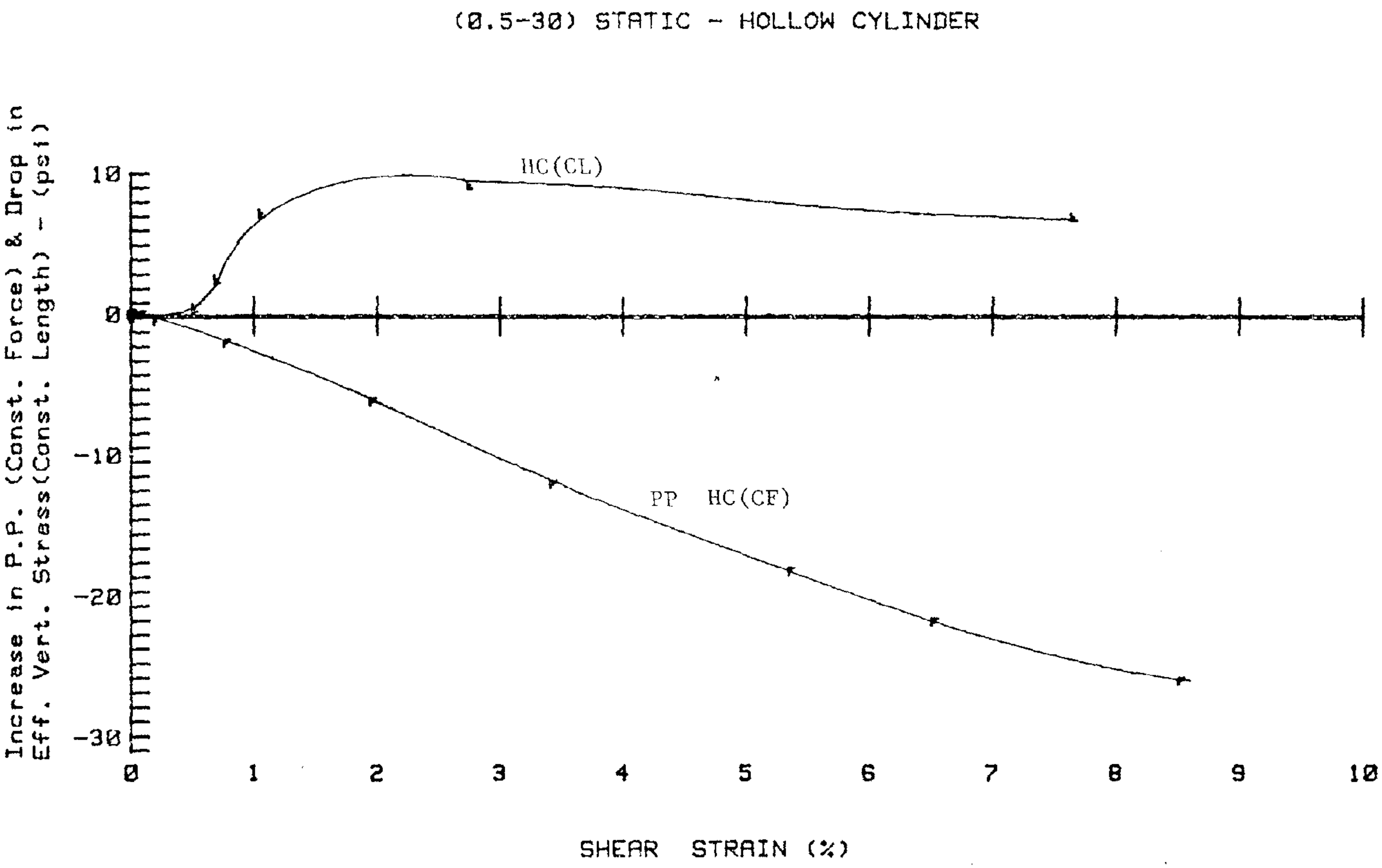


Figure 17. Comparison of the Increase in Pore Pressure to the Drop of Effective Vertical Stress in the Hollow Cylinder Tests.

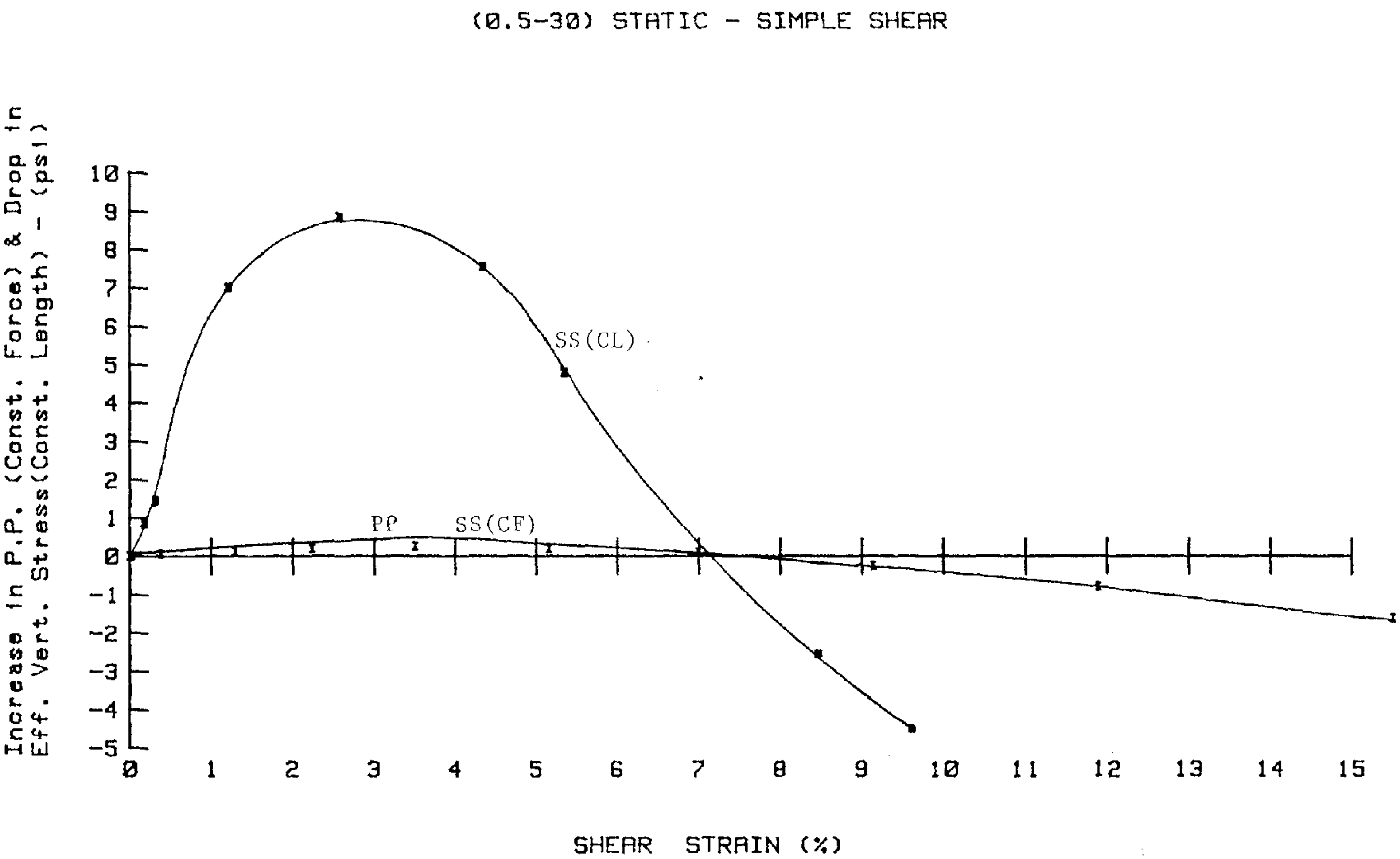


Figure 18. Comparison of the Increase in Pore Pressure to the Drop of Effective Vertical Stress in the Simple Shear Device.

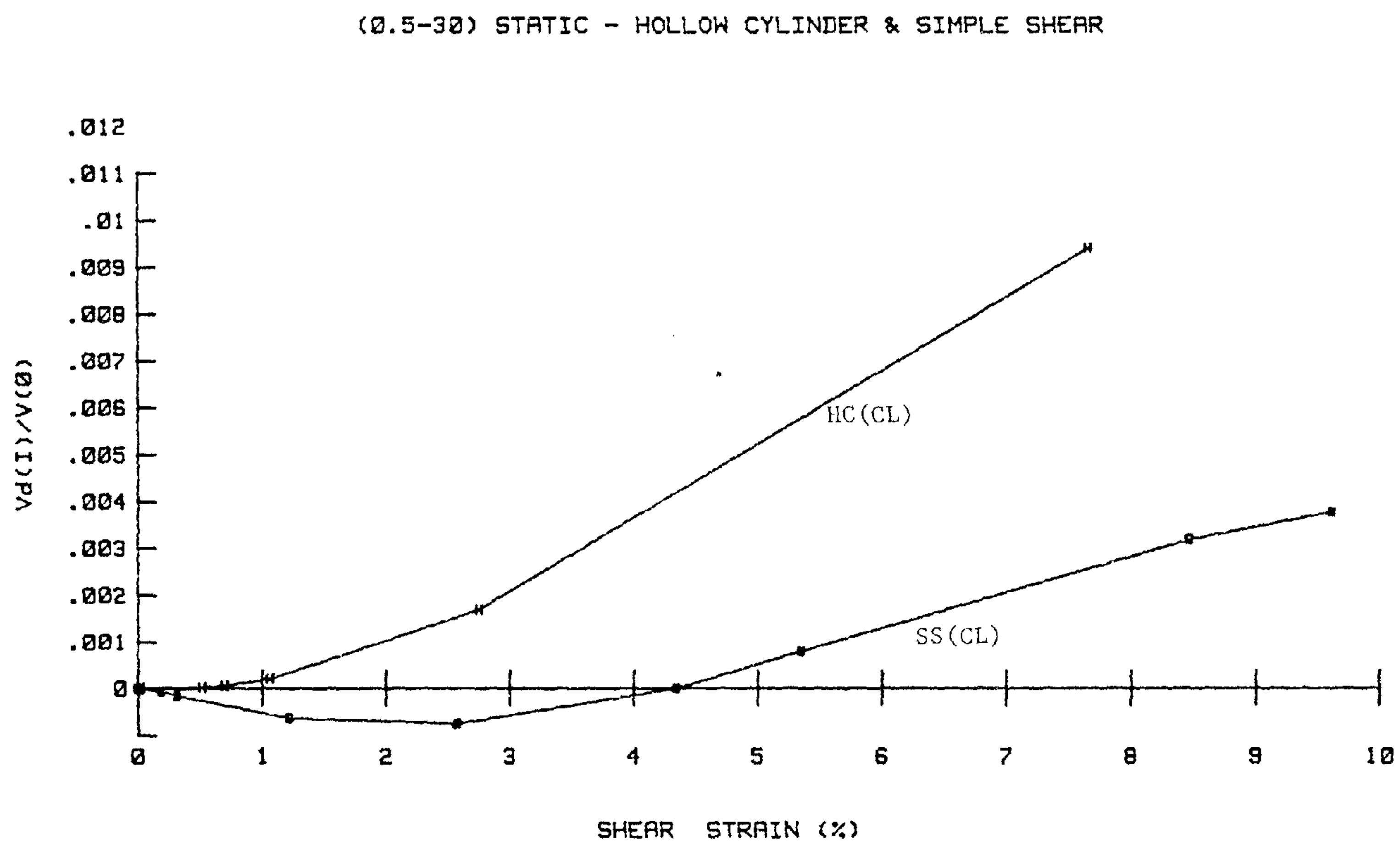


Figure 19. Volume Changes in the So Called "Constant Volume" Tests.

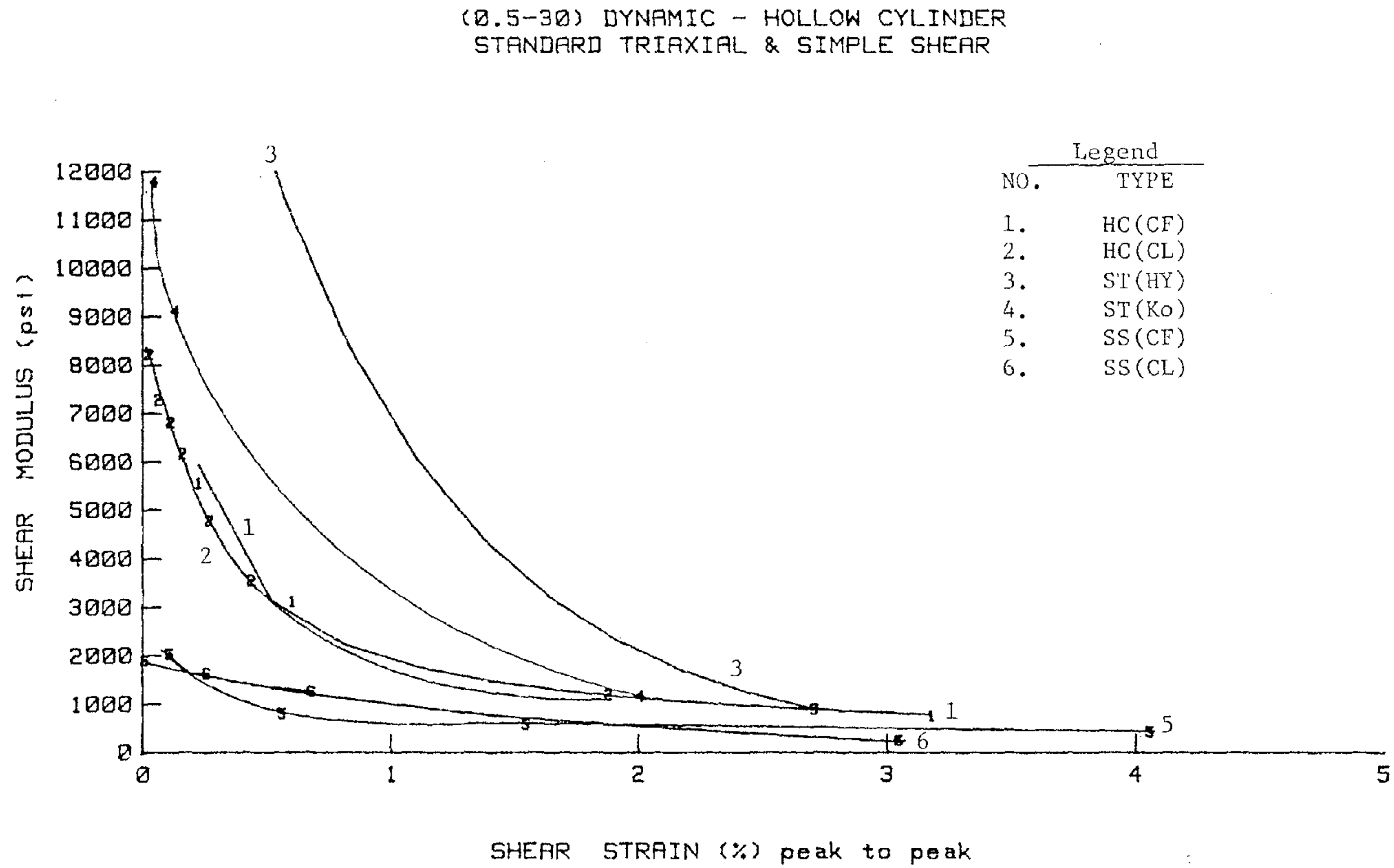


Figure 20. Dynamic Shear Moduli at the 10th Cycle for Various Devices. (1 psi = 6.9 Kpa)

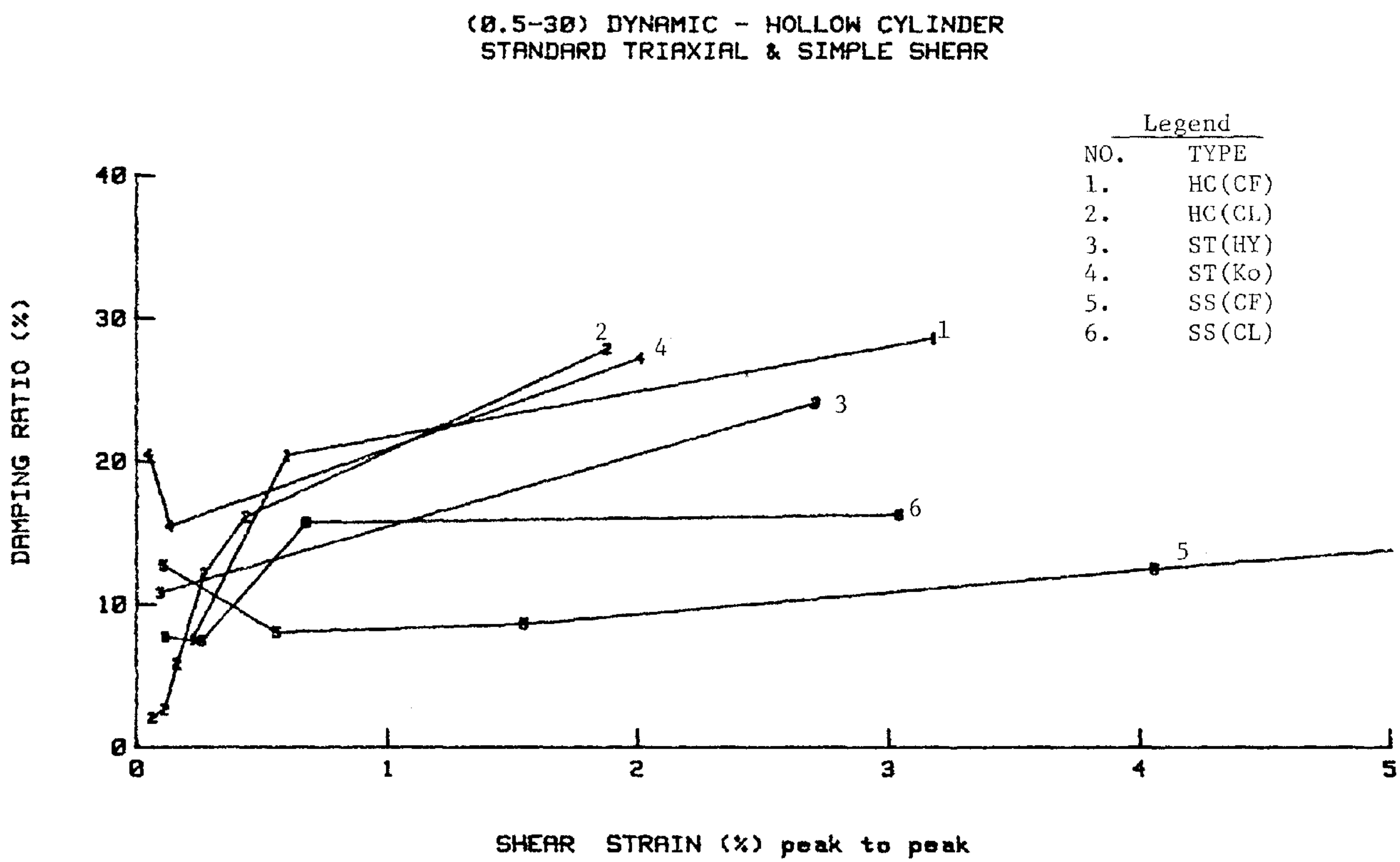
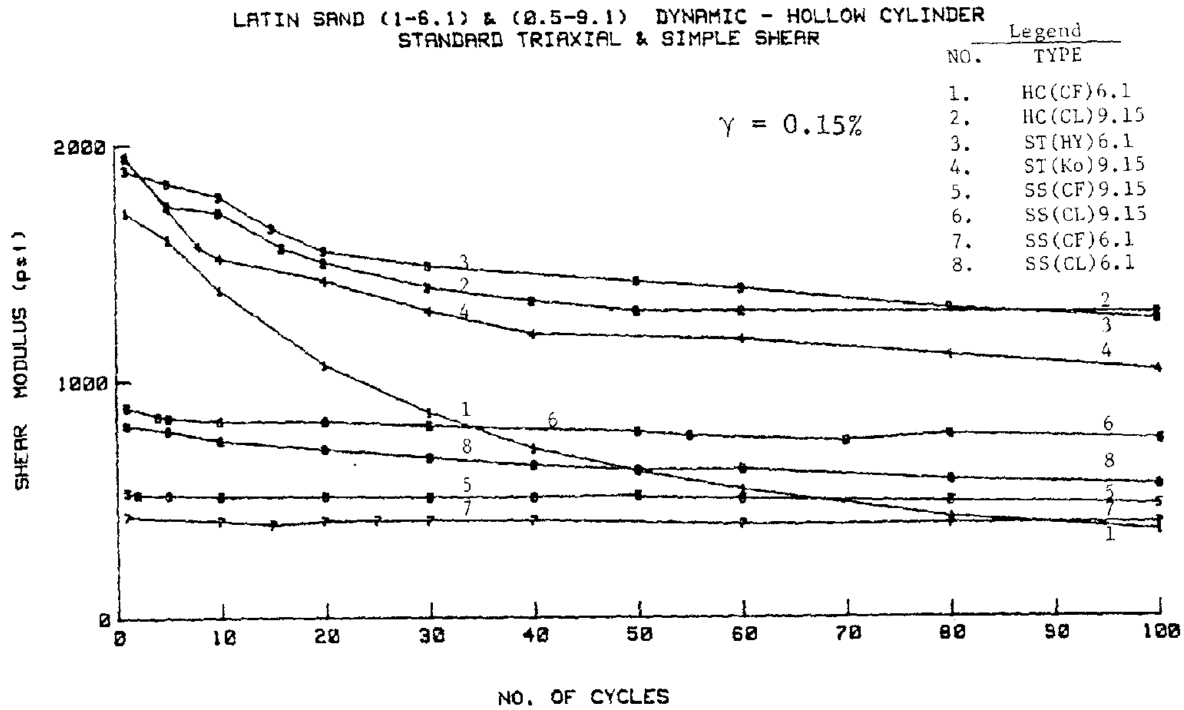


Figure 21. Damping Ratio for Various Devices.



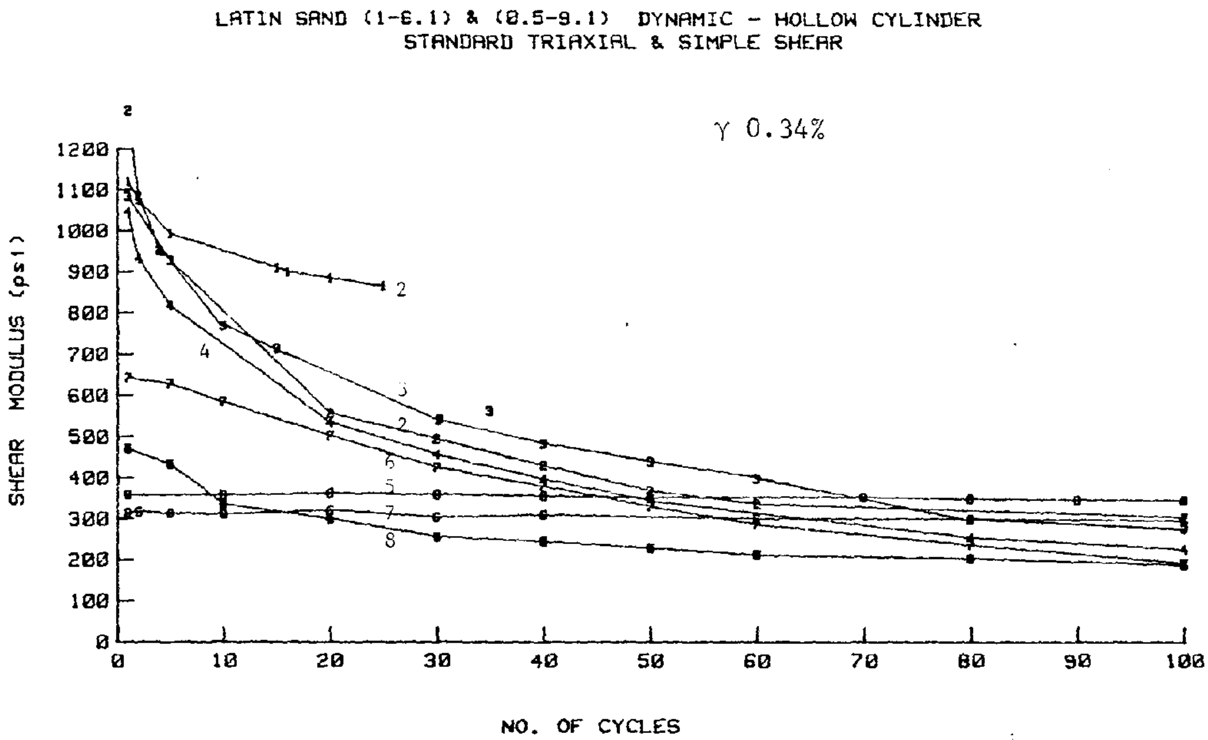
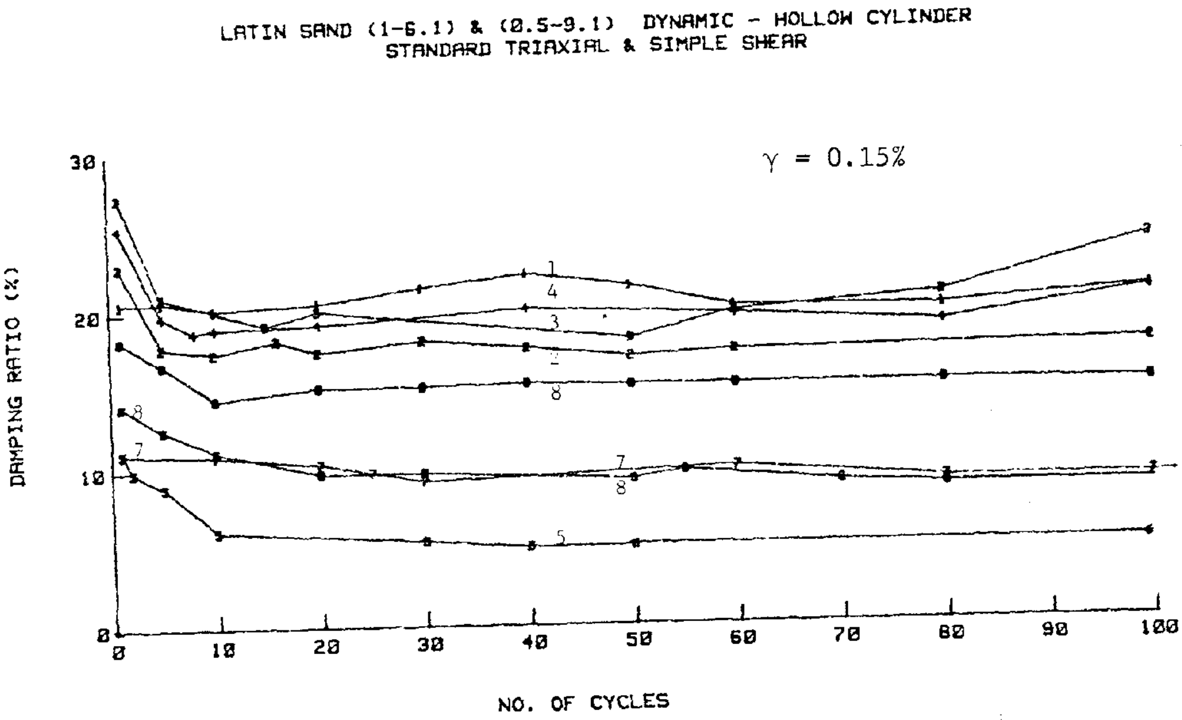


Figure 22. Variation of the Shear Moduli With the Number of Cycles for Controlled Strain Tests. (1 psi = 6.9 Kpa)



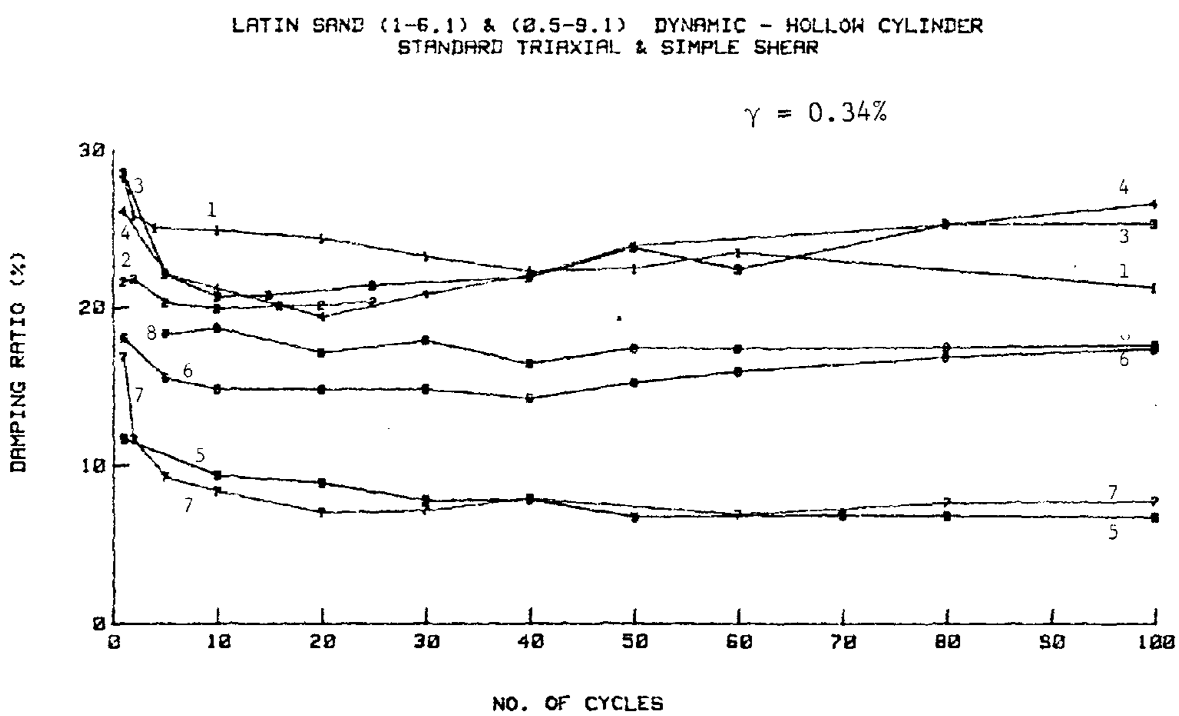


Figure 23. Variation of the Damping Ratios With the Number of Cycles for Controlled Strain Tests.

APPENDIX I

Elastic finite elements analysis of the stresses induced in a cylinder subjected to axial deformation and lateral pressures.

A linear elastic finite element analysis was made to investigate the magnitude of the stresses generated in short circular cylinders subjected to axial displacement with rigid end platens and lateral stress; no slippage being allowed between the specimens and the platens. The use of a fine grid helped bring out the stress concentrations at the edges (Fig. A1). Four Poisson ratios namely 0.499, 0.45, 0.25 and 0.1 were used, as well as lateral pressures of 0, 20, and 30 psi (10, 137.9, 206.8 Kpa). For a Poisson ratio of 0.45 and no lateral stress, the problem was solved for height to diameter ratios H/D of .167, 1/3, 1/2, 1 and 2. This last step was taken to compare the results of this study with published results (1, 11, 18) as well as to extend such results to smaller height to diameter ratios. The results have been normalized with respect to the average vertical stress σ_{av} which is the total axial force divided by the area. Young's modulus was chosen to be 2844 psi (19609 Kpa) and the average axial strain 2.38 percent. Under such conditions "if the ends are perfectly smooth and do not have any effect on the sample" the average stress should be 67.55 psi (465.73 Kpa). This indeed is not the case and this average stress varies with both H/D and Poisson's ratio, it is written on each of the figures so that the actual magnitudes of the elastic stresses can be computed.

Figure A2 shows the distribution of σ_z at the top and the middle section of an unconfined specimen for a Poisson ratio of 0.45 and five different H/D ratios. The curves related to H/D equal to 2 and 1 at the top of the sample are characterized by a ratio $\frac{\sigma_z}{\sigma_{av}}$ close to unity along 70 percent of the radius followed by high stress concentration along the edges. This is in line with previously published results. However, as H/D decreases the stresses increase substantially in the central part then vary as shown in the figure. Notice that the proximty of the curves may be misleading since each ordinate has to be multiplied by a different σ_{av} to obtain σ_z.

Figures A3 and A4 show the distributions of σ_z, σ_r, σ_θ and τ_{rz} for the same H/D = $\frac{1}{3}$ which relates to the NGI size of specimen, and values of σ_3 equal to 0 and 20 psi (137.9 Kpa). Each figure shows four different Poisson ratios. The common features of all these figures are that at a ratio H/D = $\frac{1}{3}$, the pressure distribution as well as the average vertical stress are highly dependent on Poisson's ratio and vary very substantially as one moves along the radius as well as across the thickness of the sample. The values of σ_r and σ_θ, for the higher values of Poisson's ratio, have very little resemblance to the laterally applied stress; in other words, except for a thin outer shell, the sample is very highly affected by the friction of the platens. The value of τ_{rz} is, of course, equal to zero on the middle section, but against the platens it reaches values that can be higher than the applied shearing stresses during a shear test; in addition, depending on the lateral stresses and Poisson's ratio it can take positive or negative values.

The analysis above shows that it is practically impossible to talk about some average representative value of the state of stress within the simple shear device. The combination of a shearing force and the normal displacement studied above results in a very strongly nonuniform distribution of stress and strain in the sample. Normalization of test results appears to be an exercise in forced curve fitting.

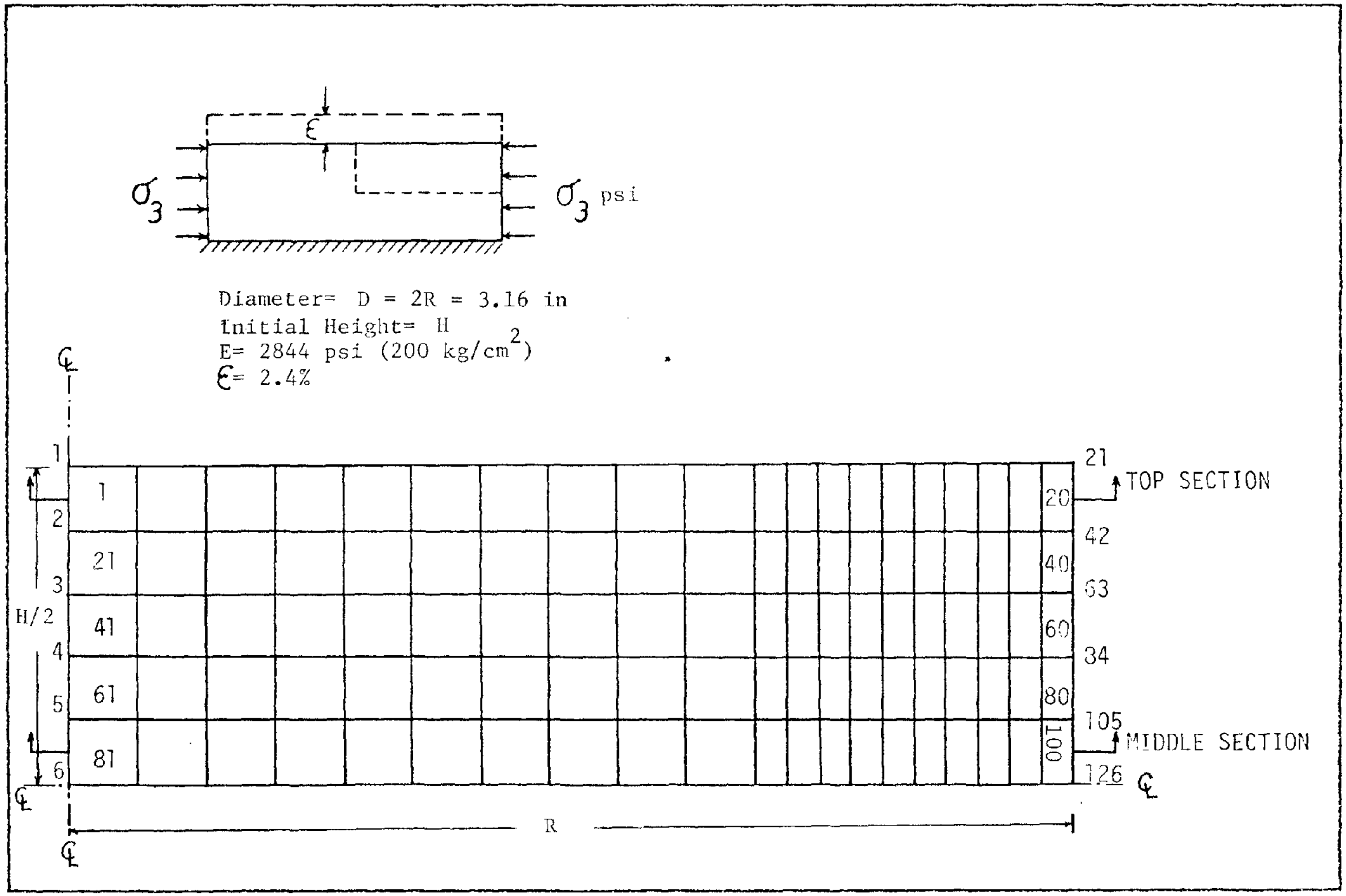
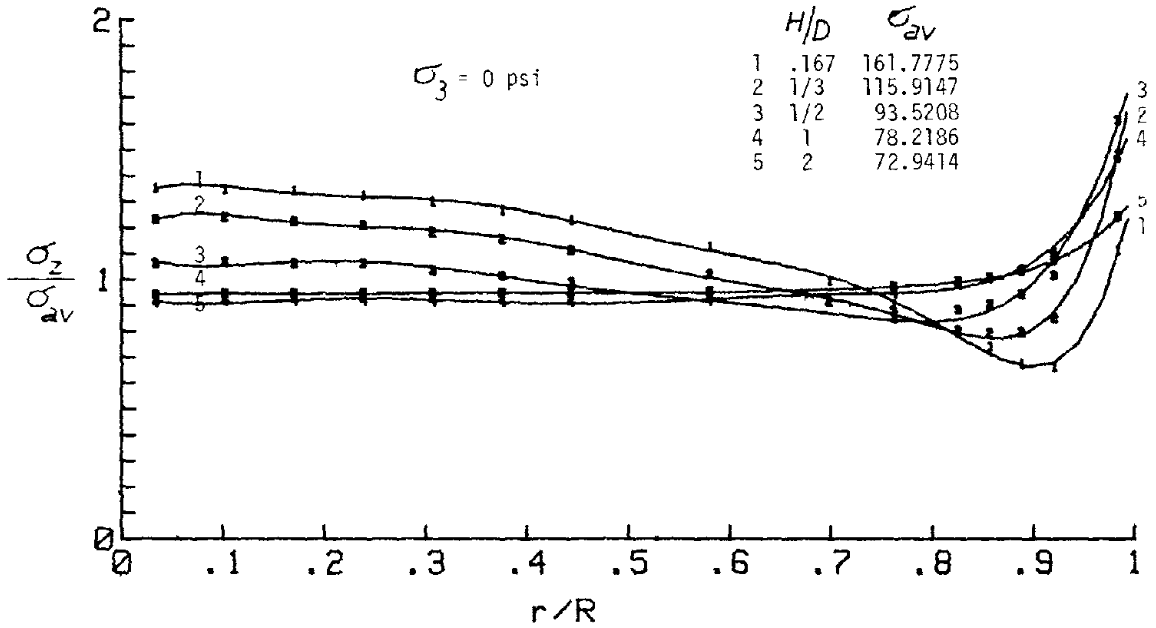


Figure A1. Finite Element Grid for Simple Shear Device

TOP



CENTER

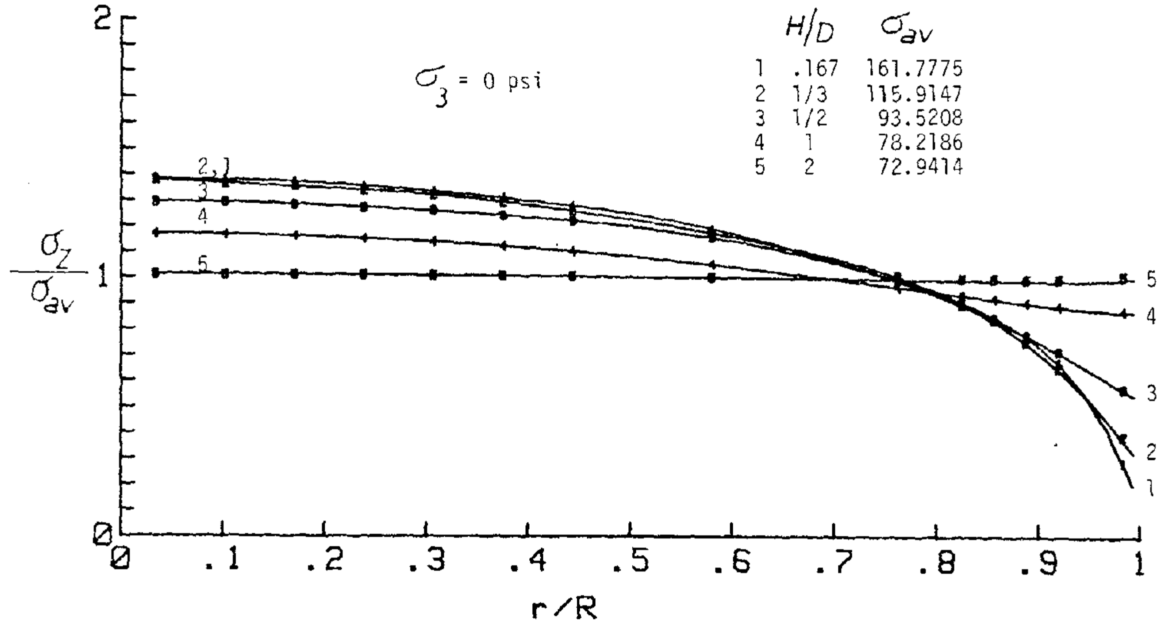
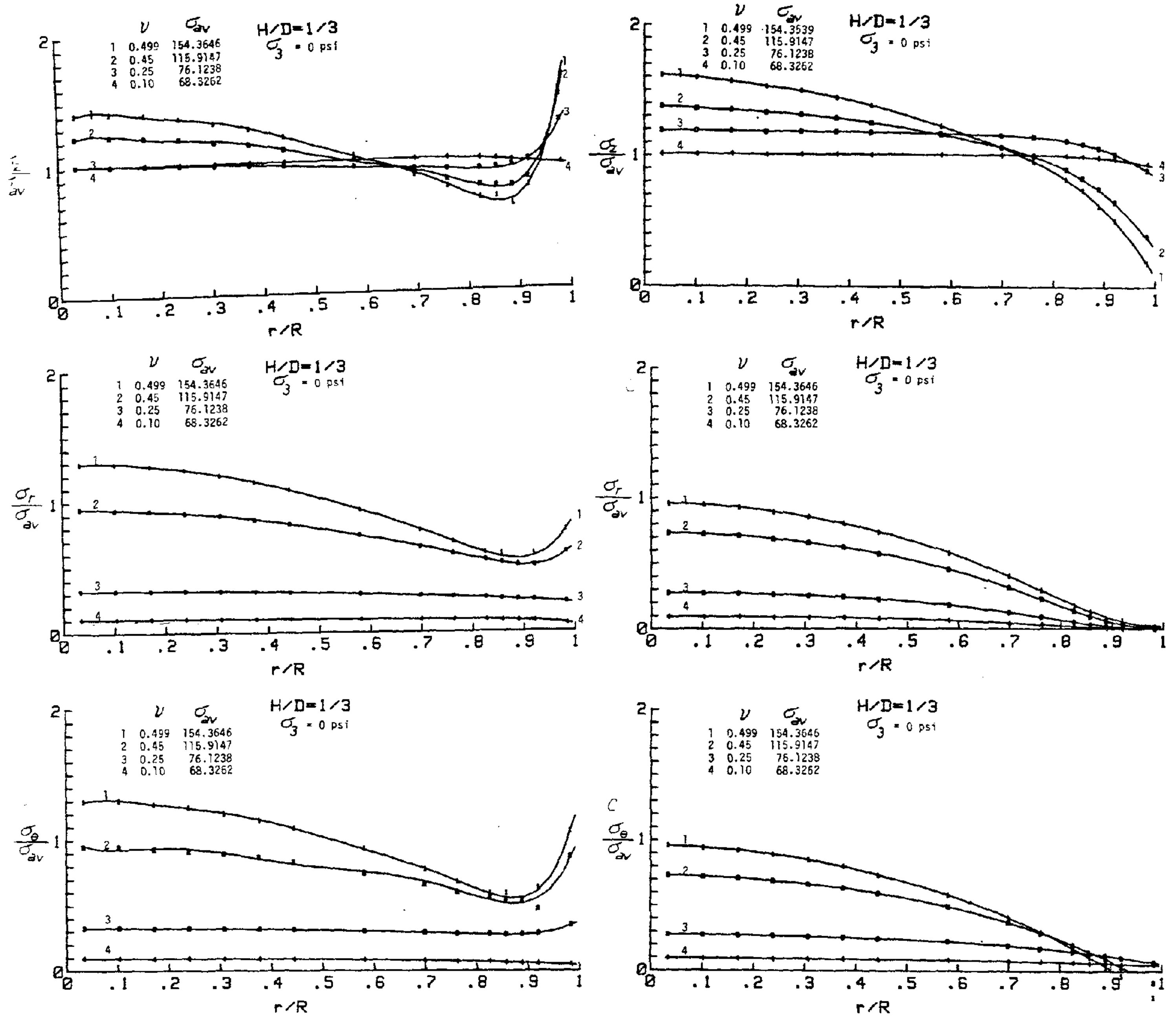


Figure A2. Distribution of Vertical Stresses In An Unconfined Condition.



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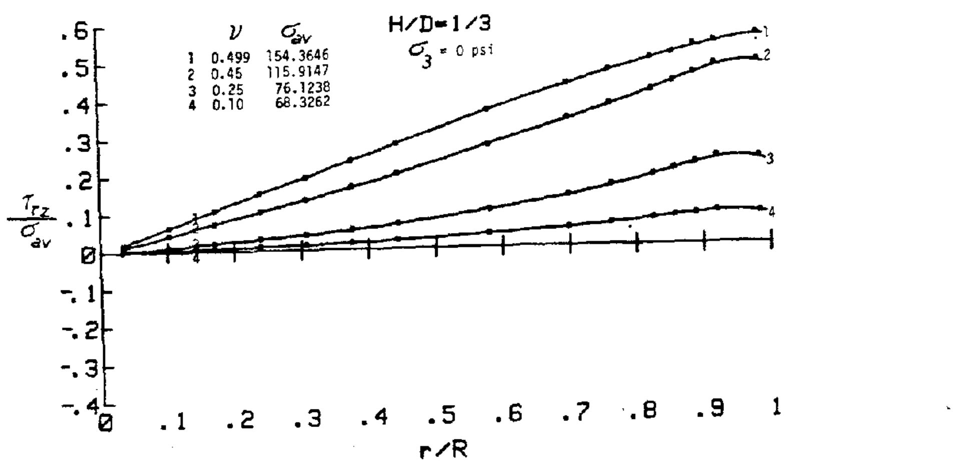

Figure A3. Results of Finite Element Analysis for Different ν.

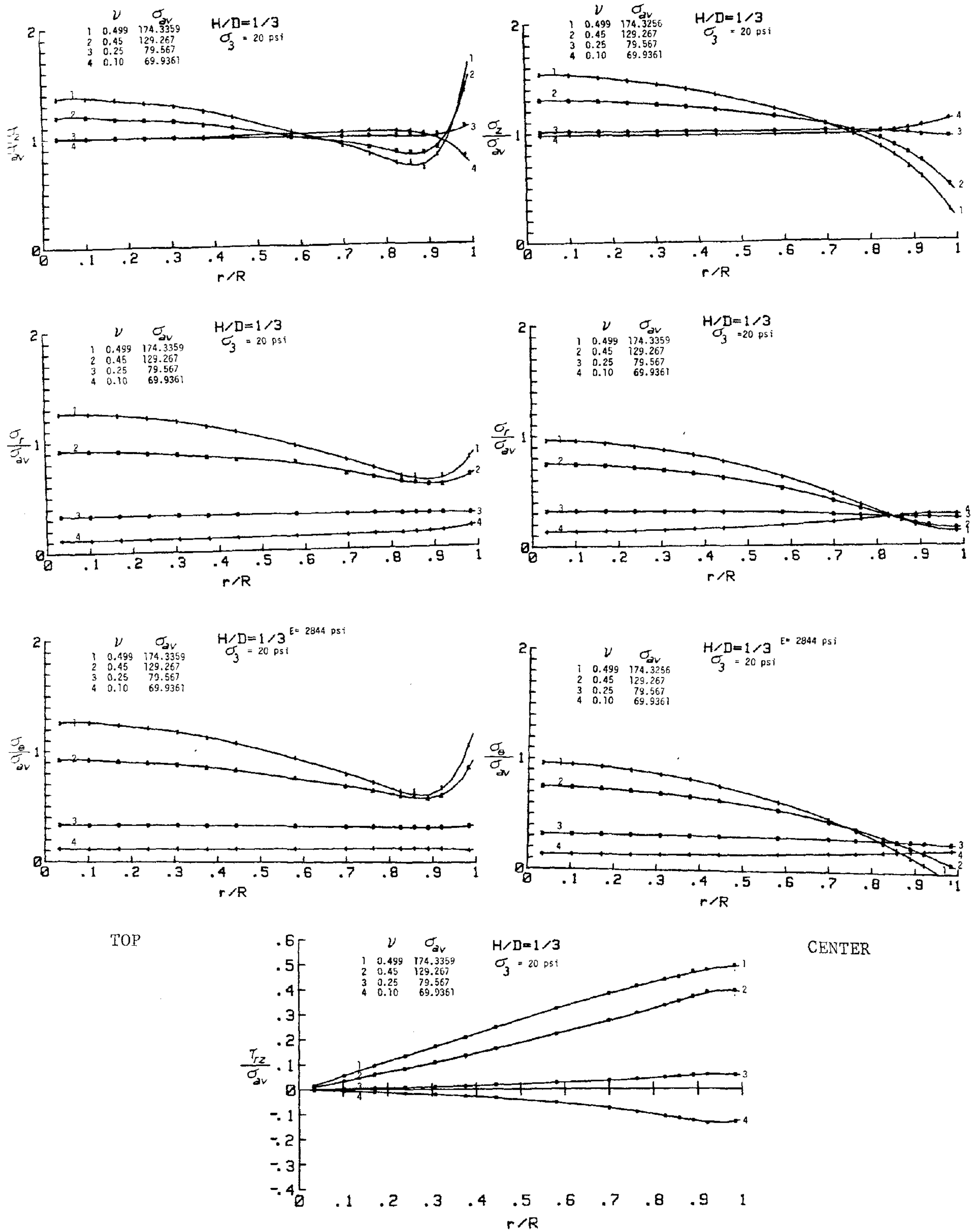

Figure A4. Results of Finite Element Analysis for Different ν.