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SIZE EFFECT IN SIMPLE SHEAR TESTING

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TABLE OF CONTENTS

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ABSTRACT

Simple shear testing is considered to be one of the most appropriate ways of reproducing in the laboratory the stresses that would be experienced by an element of soil subjected to earthquake loading. The main drawback concerns the sample size, in that for a small sized sample, the test results are affected by the non-uniformity of the stress in the sample. To investigate the sample size effect on the primary dynamic soil properties, namely the shear modulus and damping, a large scale simple shear apparatus was constructed. A total of 144 tests were performed to study the size effect and to choose an ideal size for testing dry sand. The suggested size gave results of shear modulus and damping independent of the sample boundaries. Formulas and charts for correction factors were also developed to be used to correct the results from simple shear tests on samples having sizes other than the ideal size proposed herein.

1. INTRODUCTION

Geotechnical engineering problems associated with soil dynamics are many (wind or wave action, traffic activity and vibrations, blasting, pile driving, machine vibrations, earthquakes, etc.) and occupy a wide range of amplitude excitations that vary from very small amplitudes of motion as in the case of some vibratory machine fondations up to large amplitudes accompanying strong motion earthquakes and nuclear explosions. A solution to such problems requires a better understanding and knowledge of the dynamic soil properties and characteristics.

Much research has been accomplished in the past few years on the study of dynamic soil properties using various laboratory and field measurement techniques. The object of many of these studies has been to evaluate the cyclic stress-strain properties and liquefaction potential of soil deposits under earthquake loading conditions. Dynamic soil properties are currently being evaluated using resonant column, cyclic triaxial compression, cyclic simple shear, torsional simple shear, and shaking table tests. The advantages and disadvantages of each of these devices and those for in-situ tests have been summarized by Woods (40).

Cyclic triaxial tests are the most widely used laboratory method for evaluating dynamic characteristics of cohesionless soils and the cyclic simple shear test is used modestly today (1984) for evaluating dynamic soil properties. As discussed by many investigators (13,22,25,31,33) the cyclic simple shear test comes the closest to approximating the field conditions during dynamic loadings at a reasonable cost in terms of equipment and sample preparation. The use of shaking tables for uni- and multi-directional loading (9,29), is also an excellent way to simulate field conditions but the cost involved becomes quite high.

One specific aspect of cyclic simple shear testing has remained a matter of concern. That aspect has been the stress concentrations and the non-uniformity of stress distribution in the soil sample. Since the size of the common simple shear apparatus available at the present time is quite small, it may provide unreliable results for the dynamic properties of soils. While the soil element in the field is far from the influence of any boundary that causes non-uniform stress distribution in the element, such a state cannot be represented by the small-scale simple shear apparatus where no part of the sample is far enough from the boundaries. As Seed (31) points out, to overcome boundary influence, the test specimens must be of sufficient size to eliminate these effects.

The overall objective of this study is to investigate the influence of sample size on the dynamic properties of dry sand tested under cyclic simple shear conditions. When sample size is mentioned, it includes both diameter and height. Another objective is to establish the sample size that will provide soil propoerties that are independent of sample configuration. A final objective is to develop correction factors accounting for the size effect in order to overcome the shortcomings of using the existing small-scale simple shear devices.

To accomplish these objectives, it was necessary first to build a versatile simple shear apparatus on which the tested samples could vary in size from the conventional 2.5 and 3.0 inch diameter to 12.0 inches and with the simultaneous capability of changing the sample height form 1/4 to 4.0 inches.

This report describes such a device and its verification, accuracy and reliability. The results of the experimental program are also summarized. An ideal sample size is suggested for the cyclic simple shear tests in order to eliminate the influence of the boundaries on the test results. Finally correction factors are developed to be used with any simple shear sizes other than the suggested ideal size.

1.1 Review of Cyclic simple Shear Devices

The use of the simple shear device goes back approximately fifty years. Kjellman (18) described the Royal Swedish Geotechnical Institute (SGI) direct-shear apparatus built in 1936. In this apparatus a cylindrical sample of 6 cm in diameter and 2 cm in height was placed between two grooved plates. The specimen was confined laterally by a rubber membrane and outside the membrane by a series of aluminum rings.

Roscoe (30) introduced the cambridge type simple shear apparatus that accepts a square sample of 6 cm on each side and 2 cm in thickness. The device has two fixed sides and two hinged end walls that rotate simultaneously to deform the soil uniformly. However, one of the major problems in testing is how to prepare a square uniform sand specimen. The Roscoe type device has been used by many investigators (13,25,33) in their studies on liquefaction potential.

In 1961 the Norwegian Geotechnical Institute, (NGI), developed a simple shear apparatus that is basically an adaptation of the Swedish SGI device. The NGI simple shear apparatus also uses a cylindrical sample and non-rigid vertical bondaries. While the SGI apparatus uses stacked rings to confine the sample, the NGI-type uses a wire-reinforced rubber membrane for confinement. The current NGI device is an improved version of the original device initially described by Bjerrum and Landva (7). The NGI device uses a disc-shaped specimen up to 2 cm high and 8cm in diameter, and it has been used by many investigators (8,34,37).

In 1979, Franke, et al. (14) presented a new type of direct simple shear device. Their apparatus uses a round sample that is covered laterally by a rubber membrane and placed in a pressure cell in which vertical and horizontal normal stresses are applied, i.e., similar to the triaxial test equipment. The shear stresses are transmitted to the sample by a horizontally loaded top cap. The advantage of this apparatus is that the K_0 condition can be controlled. The device uses a sample size of 7.5 cm in diameter and a height varying between 1.0 and 2.0 cm.

1.2 Review of Simple Shear Test Resutls

Many investigators have looked into the stress conditions imposed on the soil specimen by these various devices to determine what effect these stress conditions have on the measured dynamic properties (6,11,23,24,26,27,28,34,35 and 41). In general, the results of these studies show that local stress conditions can greatly affect the measured dynamic properties in these tests. This is because a homogeneous state of stress that occurs under field conditions cannot be achieved in the laboratory due to the absence of the complementary shear stresses at the vertical bondaries of the sample. To reduce the effect of not having complementary shear stresses at the boundary of the sample, it is necessary to increase the diameter to height ratio. Very little experimental research has been accomplished on the effects of sample size on the results of simple shear tests.

In attempts to study the effect of sample size on the dynamic properties of clay tested in simple shear equipment Kovacs (19), and Kovacs, et al. (21) used large samples of reconstituted clay. The plan dimensions of these samples were 2" x 2", 4" x 4", 8" x 8" and 12" x 12". The sample height was varied from 1" to 8" depending on sample plan dimensions to achieve length to height ratios of 1 : 1 to 8 : 1. The samples were prepared as unconfined blocks of clay to be tested between two square plates. The results showed that the shear modulus normalized to the unconfined compressive strength decreased as the plan dimension and/or the length to height ratio increased.

Shen, et al. (34,35) performed a theoretical study of the NGI simple shear test using a finite element study. The results of their study showed the shear strain distribution was non-uniform and asymmetric. An error of 5 to 12 percent in shear modulus measurements was also reported for the variety of soils analyzed during their study. They also varied the sample height and found that a thinner sample yielded a more uniform shear strain distribution than the thicker sample.

Lucks, et al. (24) analyzed the stress conditions existing in the NGI simple shear specimen. Three-dimensional finite element analyses showed that local stress concentrations can be expected at the edges of a liner elastic, isotropic sample tested in the NGI simple shear apparatus. Approximately 70 percent of the sample was found to have a remarkably uniform stress condition. The average shear stress increment applied in the direction of translation was within 2 percent of the horizontal shear stress within the zone of uniformity. They concluded that the test can be used to measure the horizontal shear stress and that progressive yielding will be of minor importance unless the soil is significantly strain softening.

Vucetic and Lacasse (39) investigated the influences of height to diameter ratio and membrane stiffness on the behavior of clay in static NGI simple shear apparatus. Concerning the size effect, the height to diameter ratio was found to have no significant influence on the strength and deformation characteristics of the tested clay, when static loading was applied in the NGI simple shear device. However this is not the case for other types of materials and for cyclic or free vibration tests.

2. LARGE SCALE SIMPLE SHEAR DEVICE

2.1 Description

The equipment was originally constructed by Kovacs and Leo (20). Additions and modifications were introduced to expand the capabilities of the equipment and to be able to obtain more data during testing. The developed equipment is now capable of testing different diameter samples and of applying large horizontal loads. Thus, dense sand with high vertical pressures can be tested.

The simple shear apparatus consists mainly of the following parts: (Refer to Figure 1 for numbers in circles): Two 5 inch channel beams, 72 inch long and 25 inch apart ① along with channels ② to form the main frame. Two 3/8 inch gusset plates ③ . The plates have some freedom of movement in the longitudinal direction to facilitate proper adjustments. They hold the transverse block ④ which in turn supports the electro-hydraulic actuator ⑤ . A servo-valve ⑥ controls the amount of hydraulic fluid going to and from the actuator. The displacement of the actuator movement is controlled by a built-in LVDT (Linear Variable Differential Transformer) ⑦ . The horizontal load is controlled by a load cell ⑧ . A heavy duty crane ⑨ is to carry heavy samples as well as the confining pressure cell ⑩ . A steel angle braces the crane ⑪ . Two more 5 inch channels ⑫ are bolted above the long channels ② to support the lateral bearing plate ⑬ which in turn carries the circular bottom plate 14 of the confining cell. The plate ⑭ has two slots having very smooth (frictionless) stainless steel rods ⑮ forming sliding tracks for the horizontal movement of the sample. The soil sample ⑯ is prepared between two circular ribbed plates ⑰ and a rubber membrane ⑱ secured with O-rings. Outside of the rubber membrane a number

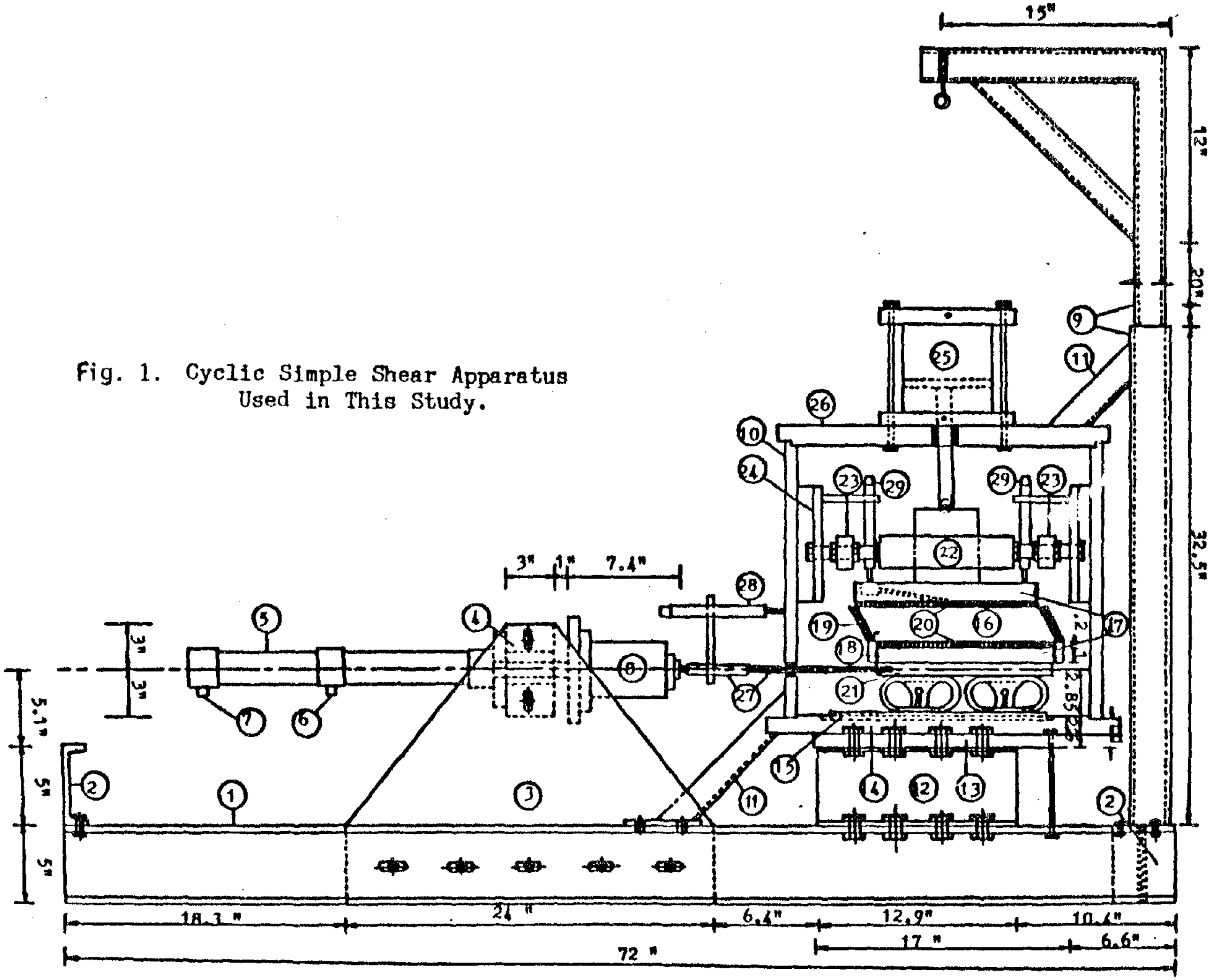


Fig. 1. Cyclic Simple Shear Apparatus Used in This Study.

of aluminum stacked rings ⑲ are used to control the sample height and to introduce lateral confining pressure. They were made of 60/61 aluminum alloy and fabricated in three sizes; of 3, 6 and 12 inch inner diameters of a high quality finishing to reduce friction to a minimum. Each of the upper and lower plates has a porous stone ⑳ at the center to permit drainage if necessary. The lower ribbed plate is mounted on another mobile square plate ㉑ which has extra smooth rollers to move horizontally upon the two tracks ⑮ . The upper ribbed plate is connected to a 4 inch diameter solid cylindrical block that goes through a rectangular loading plate ㉒ which keeps the upper plate restricted from any horizontal movement by means of locking nuts ㉓ fixed into two reaction plates ㉔ attached to the confining pressure chamber. The vertical pressure is applied by means of a double action air piston ㉕ . The piston moves down or up through a hole in the rectangular cover plate ㉖ . The sample is cycled by aligning and connecting the bottom mobile plate with the actuator through a rigid coupling ㉗ that is connected to the load cell ⑧ . The horizontal stroke is measured by either the built-in LVDT ⑦ or by an external LVDT ㉘ . Two vertical LVDT's ㉙ are used to detect if any vertical displacement has occurred.

All the connections were made of either high carbon steel or stainless steel and all the bolts were high carbon-heat treated cap screws. Most of the bolt holes were elongated for precise alignment, future adjustment and/or modifications. Figure 2 shows a photograph of the equipment.

2.2 Control System and Data Calculation

The simple shear assembly is operated by a closed-loop hydraulic system by controlling either the stress or the strain applied to the sample. In

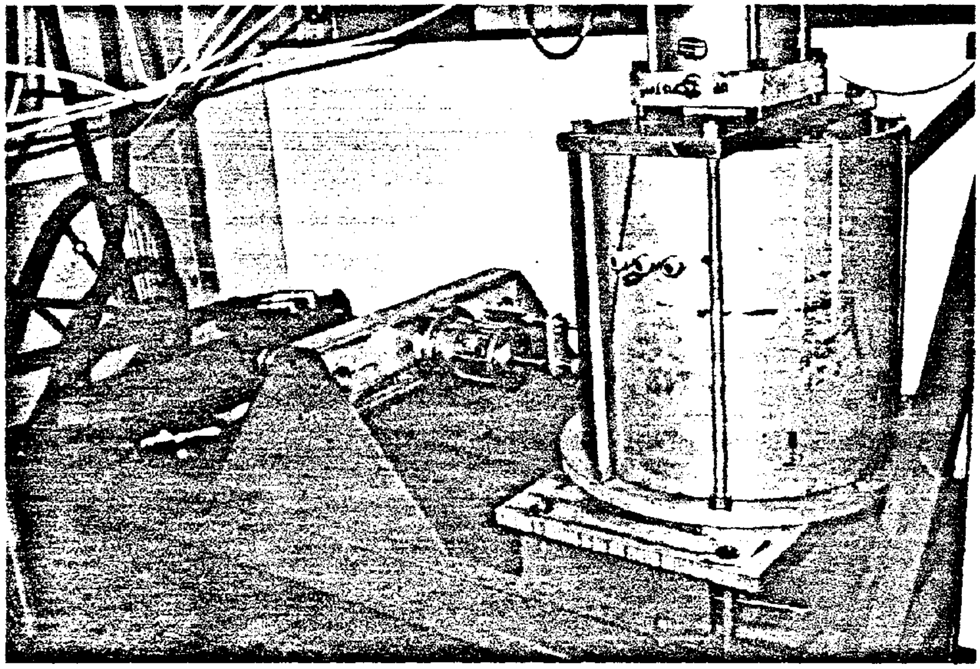


Fig. 2 A Photograph of the Cyclic Simple Shear Equipment Used in This Study.

addition to the main MTS control console, several pieces of electronic equipment were used during the testing program to control the tests as well as to display the resulting data. These include an X-Y recorder, brush recorder (8-channel strip chart), and signal amplifiers used to record all the data in different formats. The X-Y recorder was used to plot the hysteresis loops of the cyclic testing. The load was connected to the Y-channel (vertical) while the displacement was shown on the X-channel (horizontal). The scales of both the horizontal and vertical channels were adapted to the feedback voltage from each conditioner separately. Figure 3 is a diagram of the instrumentation arrangement of the simple shear test.

A computer program was written to analyze the data obtained from the cyclic simple shear test. The shear modulus was calculated from the hysteresis loop at any cycle as the slope of the chord connecting the two extreme points of the loop. The percent of critical hysterestic damping was also calculated from the area of the hysteresis loops.

2.3 Sand Tested and Sample Preparation

The sand used in this study was a special screened silica sand (Ottawa 20-30) produced by Bellrose Silica Company, Ottawa, Illinois. This is similar to the type of sand that were used by others (1,12,15,20,37,38). This uniform sand was chosen to avoid segregation during sample preparation using pluvial compaction through air. The coefficient of uniformity of the sand was found to be 1.22 while the effective size and mean size were 0.67 mm and 0.80 mm, respectively. The maximum and minimum void ratios obtained using the ASTM-D2049 standards were 0.67 and 0.47, respectively. However, these values may be different for different mold diameters or mold heights using the pluvial technique through air.

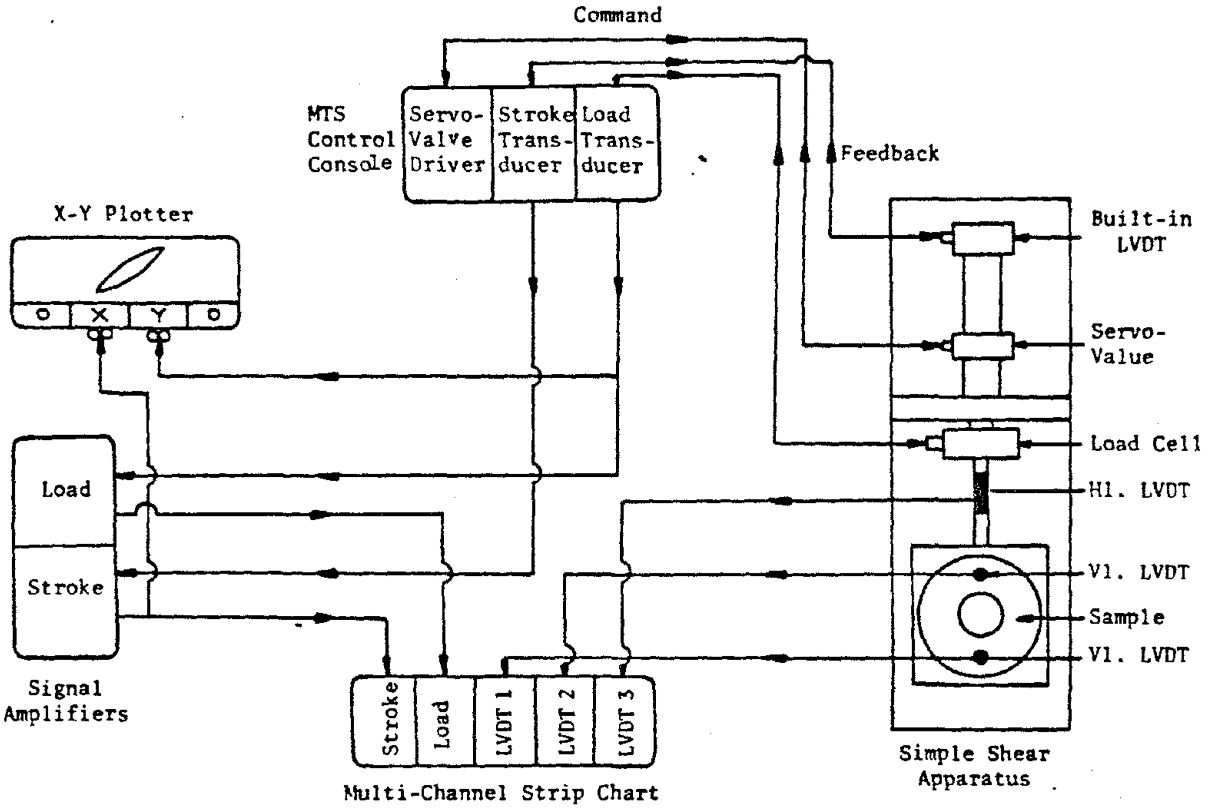


Fig. 3 A Schematic Diagram of the Instrumentation Arrangement

Spreader boxes were used in preparing the samples. Two sizes of the box were made to cover the range of sample sizes used in this study.

Three sample diameters were used during this research. The diameters were 3, 6 and 12 inches. The height was also a variable and changed from 0.25 inches to 4 inches. For each size tested in the testing program, the sand was rained from a zero height several times and the void ratio calculated was considered the maximum (e_{max}) for that specific size (height and diameter). The minimum void ratio was also calculated (e_{min}) from several trials of raining the sand from height of 30 inches. The relative density corresponding to e_{max} was considered as 0% while the one corresponding to e_{min} was considered to be 100%. Both e_{max} and e_{min} calculated from air pluviation were different than those calculated from ASTM-D2049 standards that were 0.67 and 0.47, respectively, in the majority of the cases. This is acceptable due to the differences in the sizes of the molds used in this study and the standard size of the ASTM. A complete description of the sample preparation and its results can be found in (2,3).

2.4 Testing Program

In order to accomplish the objectives of this research an intensive testing program was performed. As stated before samples of uniform sand with different sizes were tested. Sample diameters of 12, 6 and 3 inches with heights varied from 0.25 to 4.0 inches to cover diameter to height ratios (D/H) of 12, 9, 6 and 3 for each diameter were cyclically tested. Beside the size, the samples were prepared at relative densities of 50 and 95 percent (termed as loose and dense respectively). Two vertical pressures were applied to each sample (500 psf and 1000 psf). Tests were run as close to 0.01, 0.1 and 1 percent shear strains as possible. A total of 144 tests were performed during this testing program.

3. TEST RESULTS

After calibrating the electronic recording equipments, the X-Y recorder pen was lowered to record the stress-strain relationship at specific cycles. Hysteresis loops were plotted at a sequence of 1, 10, 50, 100, 200 and 300 cycles for every test.

For the single hysteresis loop shown in Figure 4, the equivalent modulus is defined as the slope of the chord AB connecting the extreme points of the hysteresis loop. This definition was used throughout this study. The same loop was also used to calculate the hysteretic damping using the technique proposed by Jacobsen and Ayre (18).

$$\gamma = \frac{1}{2\pi} \frac{\Delta W}{W} \qquad (1)$$

where ΔW was the total dissipated energy per cycle as represented by the area inside the loop and W was the work capacity per cycle and was defined as the total elastic energy stored in an equivalent perfectly elastic material. The work capacity W was calculated throughout this study as the area of the triangle OAA' and OBB'.

3.1 Analysis of Shear Modulus

3.1.1 Effect of Shear Strain Level (γ)

The shear modulus was fond to decrease with an increase in the shear strain, which was the same result other researchers found. The relation between the shear modulus and shear strain for a cyclic test performed on a 3-in diameter sample and 1-in height is shown on Figure 5. It was found that similar trend occurred regardless of the sample size, the applied vertical pressure, and the relative density of the sand tested under different strain levels. For the purpose of quantitative comparison, the results from a test

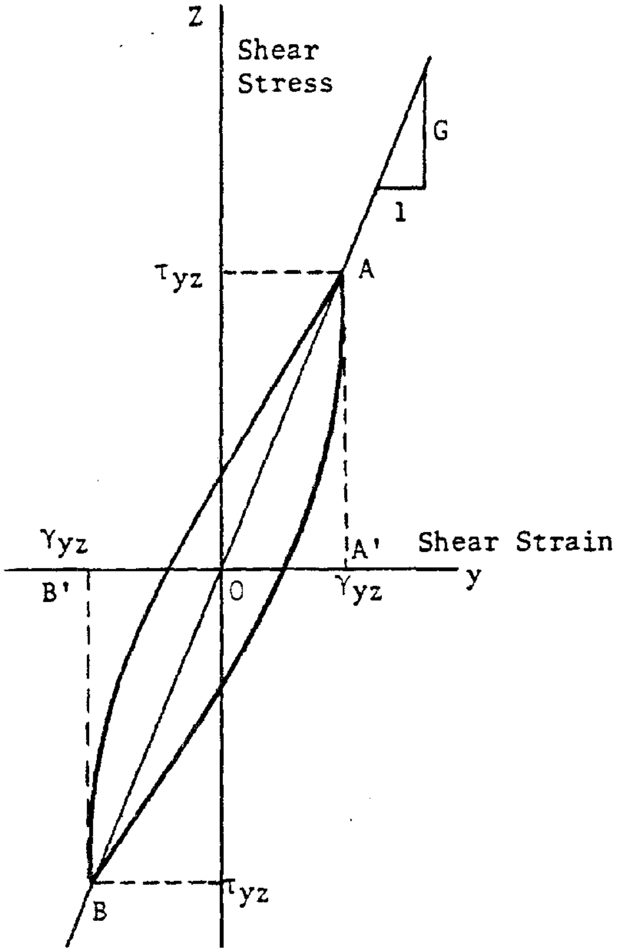


Fig. 4 Stress-Strain Relationship for Sample with no Strain History.

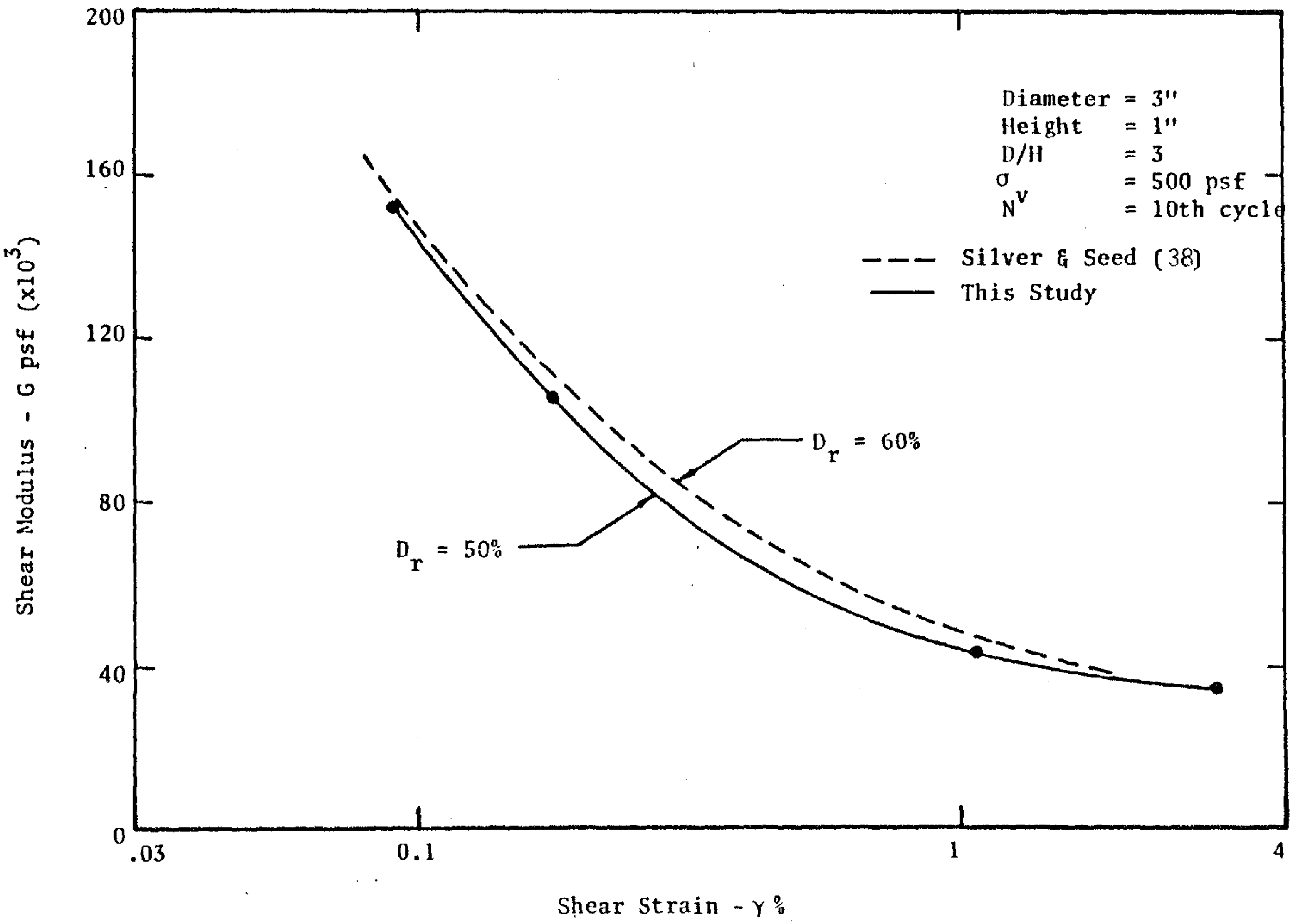


Fig. 5 Shear Modulus vs. Shear Strain: A Comparison with Ref. (38).

performed on a 3-in diameter sample of 1-in height were compared with results from Silver and Seed (38) in which a similar sample size and sand was tested under simple shear conditions. The results agreed very well. A slight difference was observed between the two curves but this may be attributed to the difference, in the relative densities at which the samples of the two studies were prepared.

3.1.2 Effect of Vertical Pressure (σ_v') and Relative Density (D_r)

The effective vertical confining stress was fond to be an important factor influencing the shear modulus of the sand. Increasing the confining stress increased the shear modulus if all other variables remained constant. Figure 6 illustrates the effect of the two vertical confining stresses used in this study on the shear modulus when other variables were the same. It is also shown in Fig. 6 that the higher the density of the sand the larger the shear modulus. Also, Figure 6 indictes the close agreement of the results to the results of Silver and Seed (38) for the same size sample. It is also shown that differences exist among the four relationships plotted on this figure which can be explained again by the differences in the relative densities of the samples tested.

In another qualitative comparison between the results of this study and published data, the following formulas developed by Hardin and Drnevich (16) were used in plotting Figure 7.

$$G_{max} = 11430 \times \frac{(2.973-e)^2}{1+e} (\sigma_v')^{1/2} \tag{2}$$

$$G = \frac{G_{max}}{1 + \frac{\gamma}{\gamma_r}} \tag{3}$$

$$\gamma_r = \frac{\tau_{max}}{G_{max}} \tag{4}$$

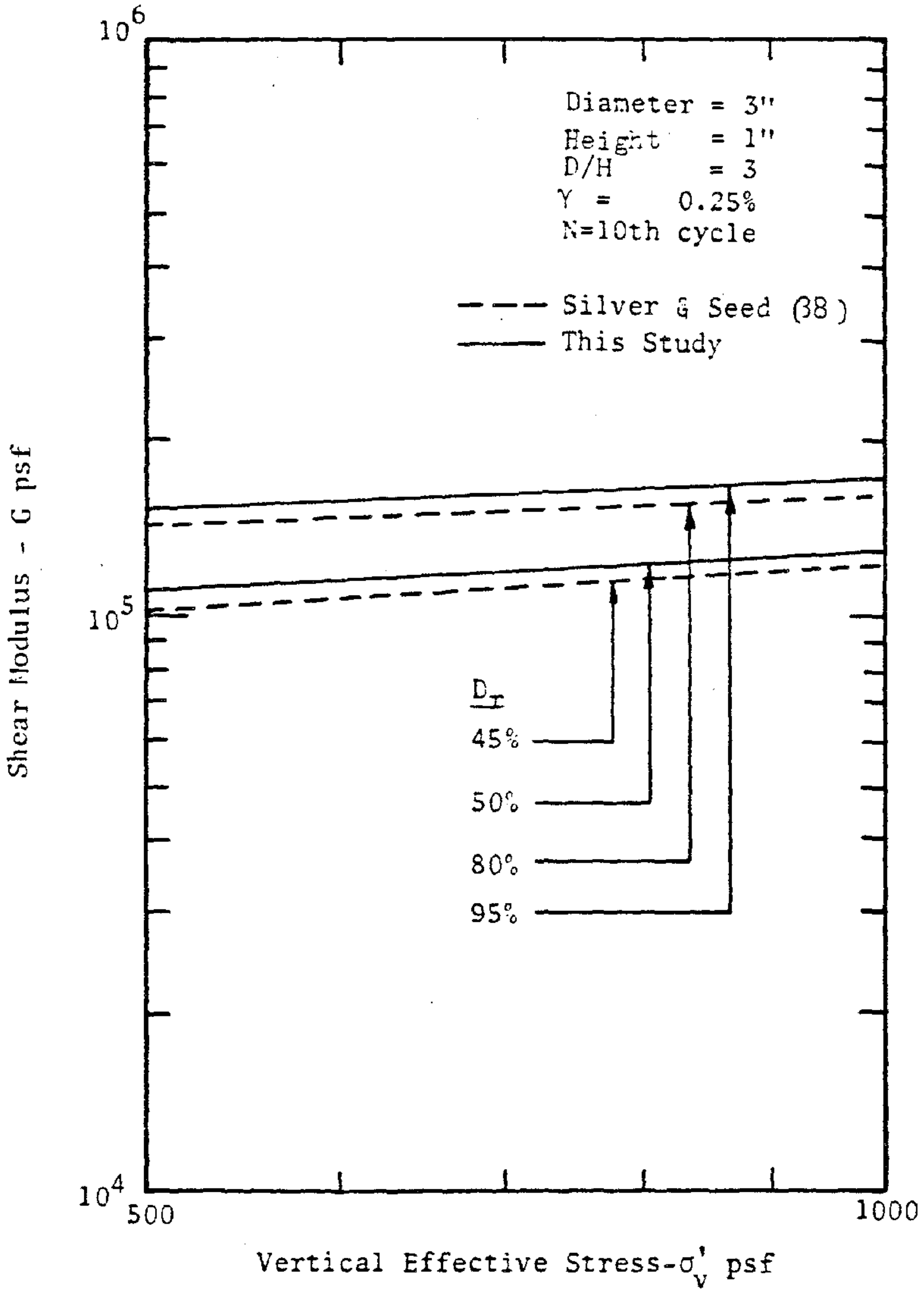


Fig. 6 Shear Modulus vs. Vertical Effective Stress.

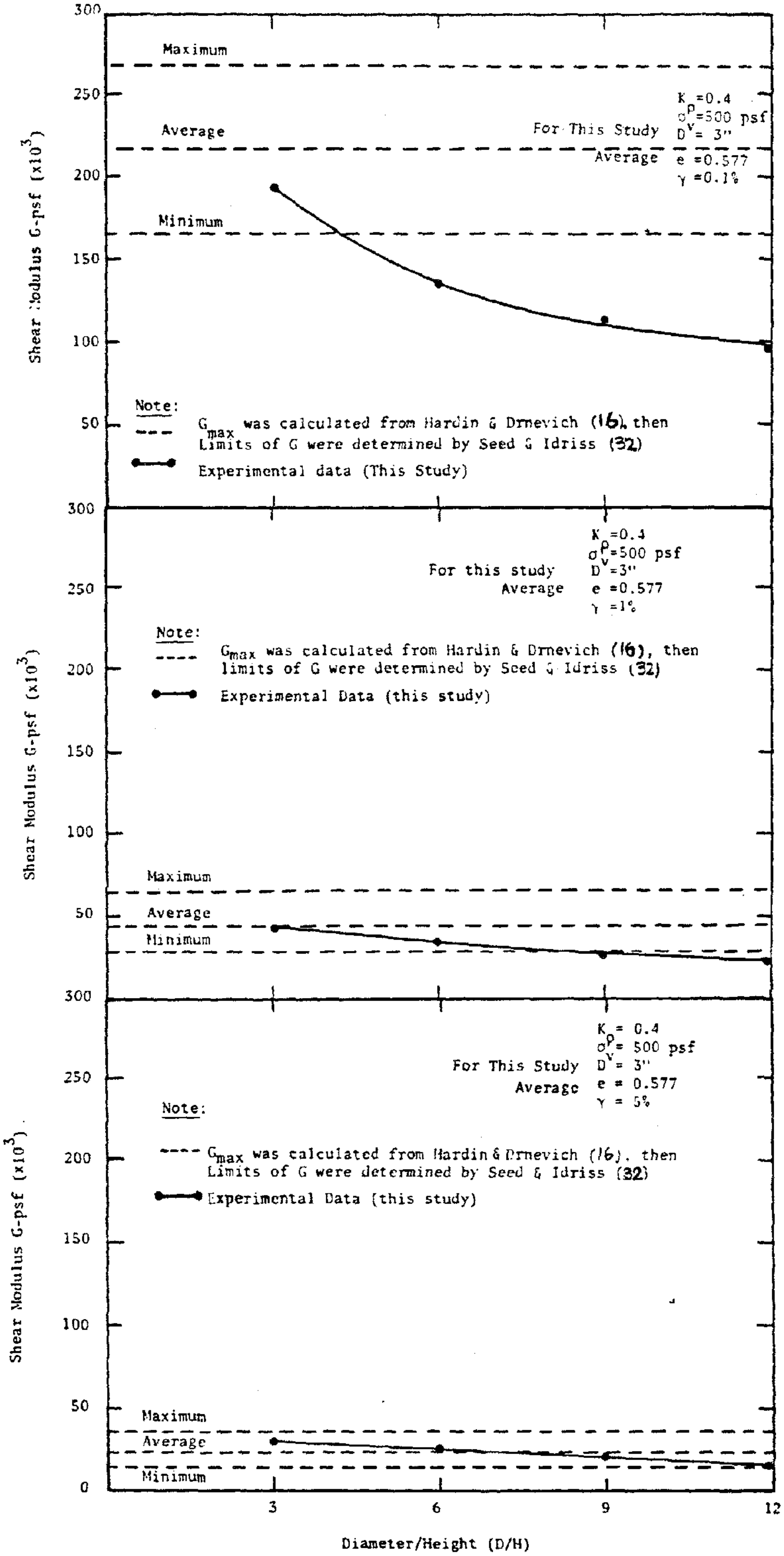


Fig.7 Comparison of Experimental Results with Ref. (16) & (32).

$$\tau_{\max} = \left\{ \left(\frac{1+K_o}{2} \sigma_v' \sin \phi' \right)^2 - \left(\frac{1-K_o}{2} \sigma_v' \right)^2 \right\}^{1/2} \quad (5)$$

Figure 7 was plotted after calculating G_{max} from equation (2) then at the required strain level the maximum, minimum, and average values of G/G_{max} were obtained from Seed and Idriss (32). The data from Hardin and Drnevich (16) and Seed and Idriss (32) agreed well with the data resulting from testing 3-in diameter and 1-in height samples in this study. As shown in Figure 7 for the conventional size sample tested in simple shear, the data from this study lay within the range of the published data at 0.1 percent strain. At a higher strain (1.0 percent) results of other sample sizes were within the range of the calculated limits, Figure 7. The results of all sample sizes existed within the range of the calculated limits for a strain amplitude of 5 percent at which the height seemed to have no significant influence on the results.

3.1.3 Number of Stress Cycles (N)

As reported in the literature by DeAlba, et al. (9), Finn, et al. (13), Kovacs, et al. (21), and many others, the shear modulus was found to increase with an increase in the number of cycles (N). Figure 8 shows how the shear modulus increased with the increase in the number of cycles at different shear strain levels. Between the first and tenth cycles the increase in the shear modulus was more pronounced than for the cycles beyond. In addition, the influence of the number of cycles on the modulus was small at higher strain rates.

3.1.4 Sample Size

Experimental Results

It was found from this study that the shear modulus was dependent on the size of the sample. Both diameter and height has a major influence on the

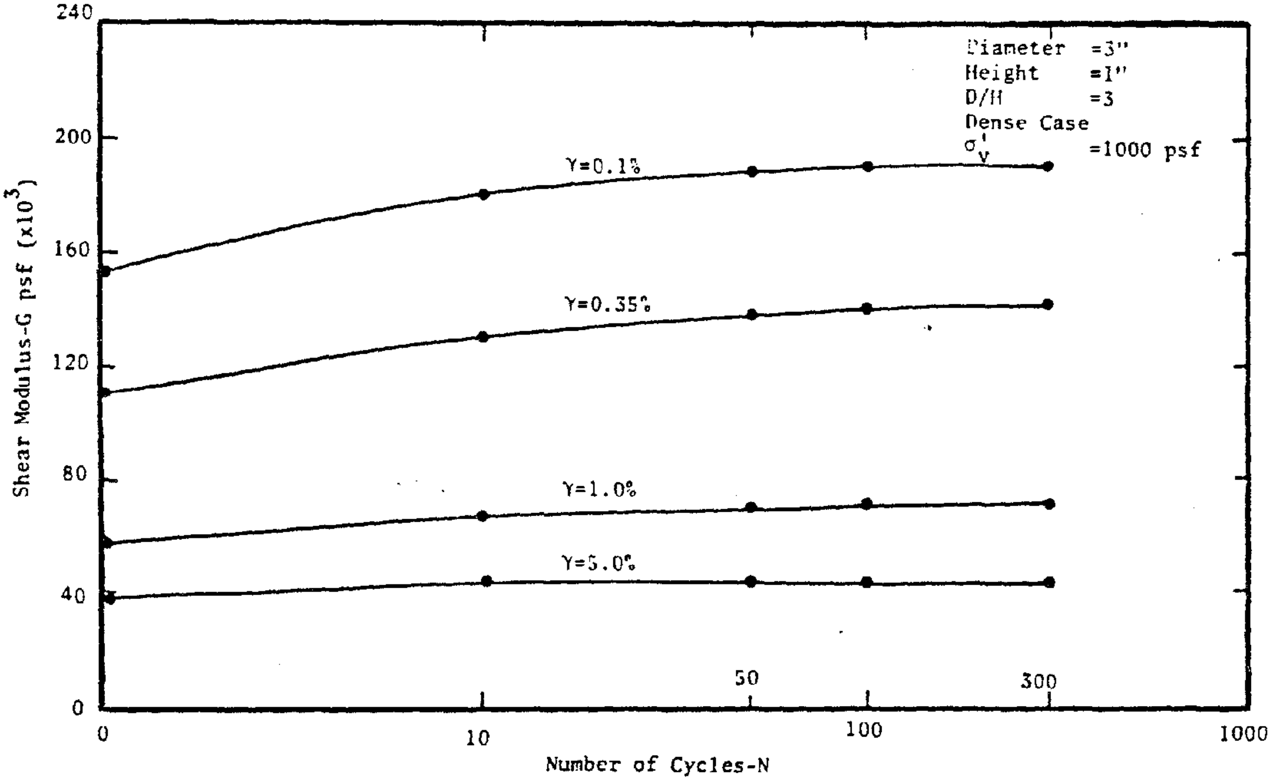


Fig. 8 Variation of Shear Modulus with Number of Cycles.

shear modulus, i.e. for the same sample diameter the shear modulus was found to be affected if the height changed. Also, for the smae height or if the diameter to height (D/H) ratio was kept unchanged, the shear modulus was still diameter dependent. Figure 9 (a) shows the effect of varying the D/H ratio on the shear modulus for the three sizes used in this study (3, 6 and 12-in diameters) at different strain levels for cycle number ten. It shows that increasing the D/H ratio between 3 and 6 resulted in a noticeable reduction in the shear modulus. For a D/H larger than 6 the effect decreased until at about a D/H of 8 or 9 the shear modulus began to stabilize. At a higher strain level and larger sample diameter, the shear modulus did not change much and the D/H ratio had almost no effect at 5 percent shear strain. Similar behavior happened at a higher number of cycles as shown in Figure 9 (b) for cycle number 300.

Cross curves from Figures 9 (a)are plotted in Figures 10 to show the effect of change in diameter on the shear modulus. It is clear that the diameter to height ratio was not the only size factor that affected the shear modulus, the diameter also has a large influence. For a specific value of D/H the shear modulus dramatically decreased with an increase in the sample diameter from 3 to 8 inches then a point of stabilization was reached and the shear modulus began to be independent of the diameter. This behavior was unique for all values of D/H if the sample was tested at a low shear strain of 0.1 percent. At a higher shear strain of 1 percent the effect of the diameter as well as the D/H ratio on the shear modulus decreased, and on increasing the strain to 5 percent the effect of size on the shear modulus decreased further.

Numerical Analysis

In the experimental program the effect of size, in addition to other variables, on the dynamic behavior of sand, that is, the shear modulus and

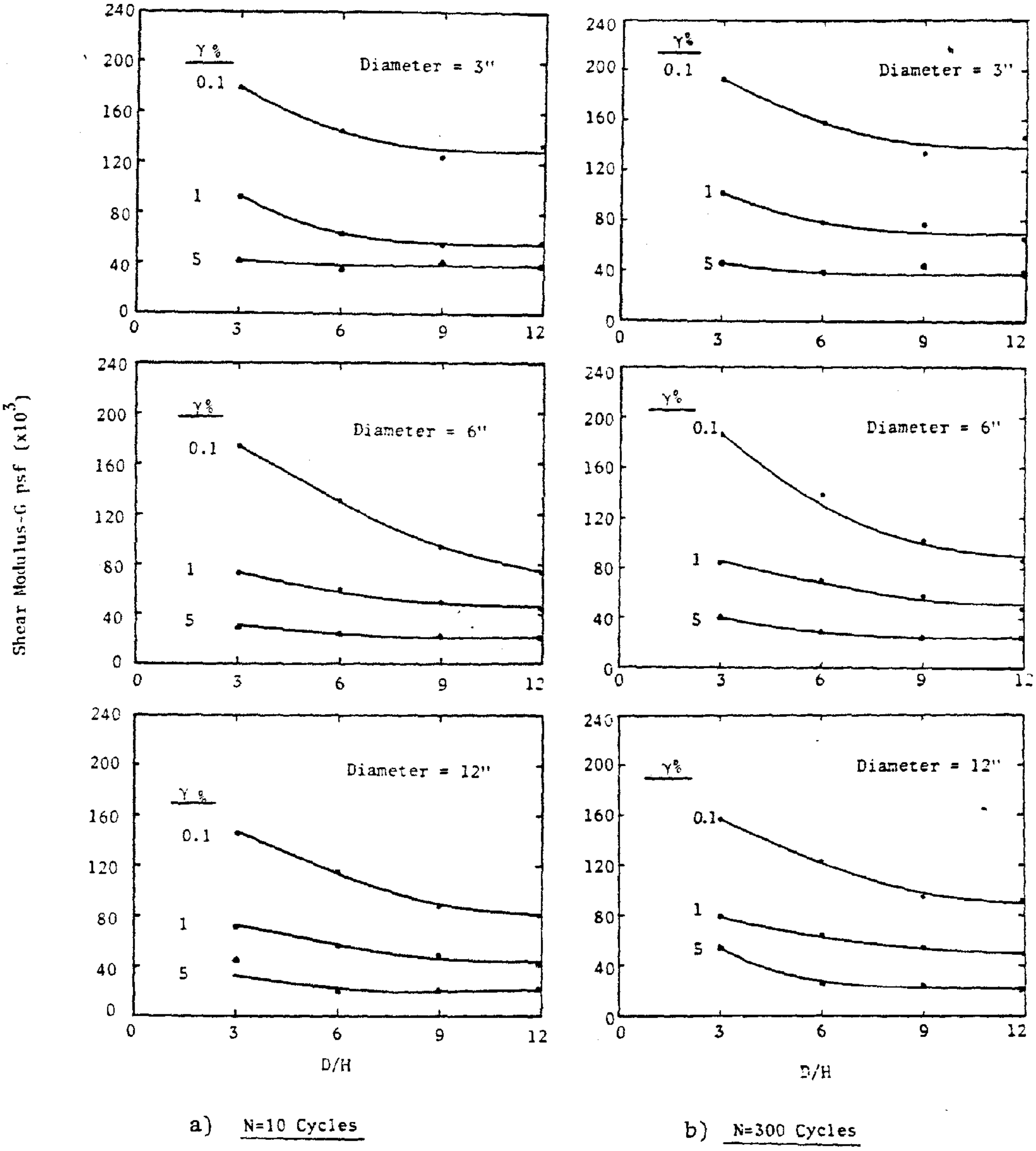


Fig. 9 Shear Modulus Vs. Diameter/Height Ratio Relationships for σ'_v = 1000 psf and Dense Case.

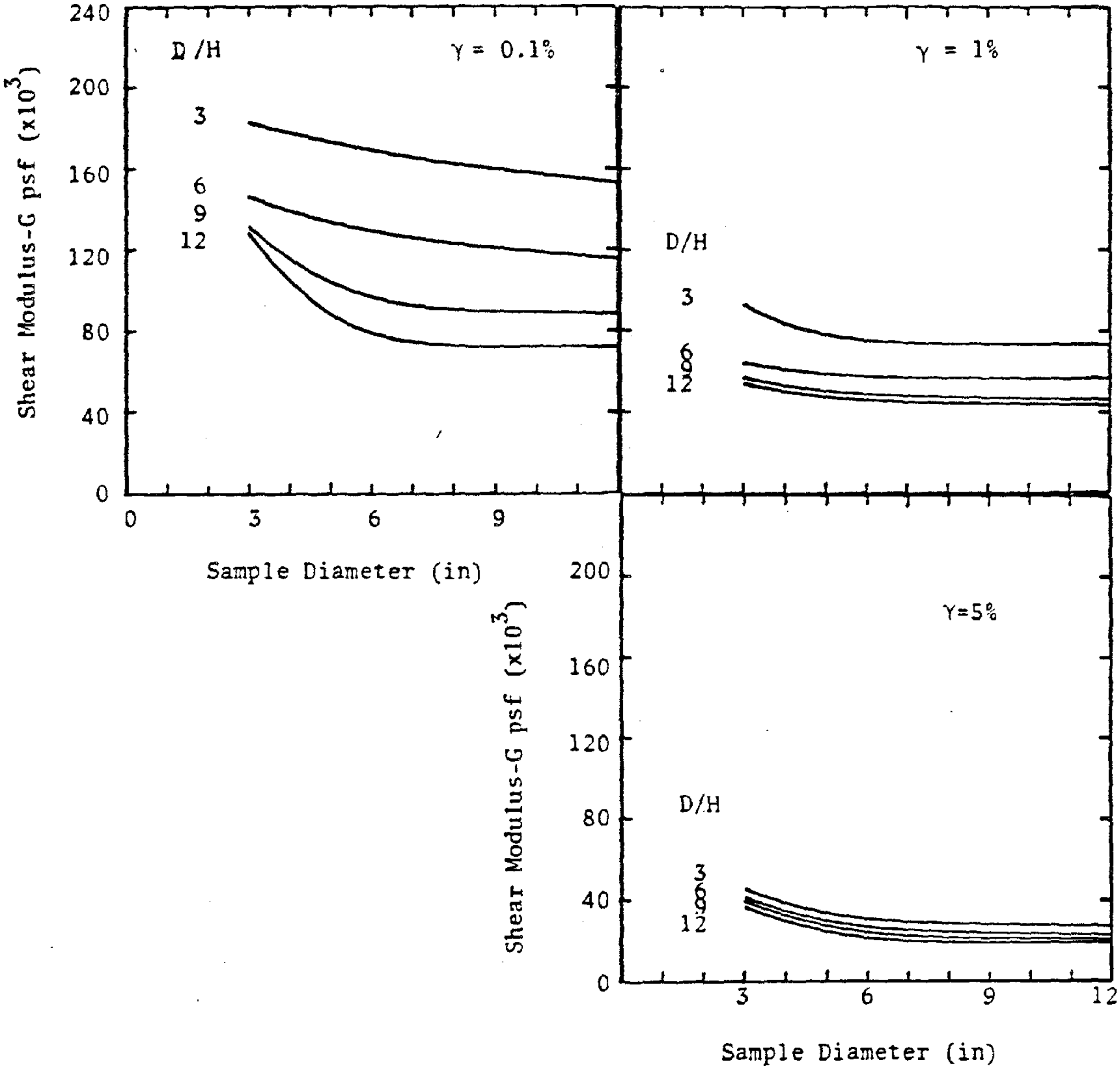


Fig. 10 Shear Modulus vs. Sample Diameter for Different D/H Ratios at N=10 Cycles, σ_v'=1000 psf and Dense Case.

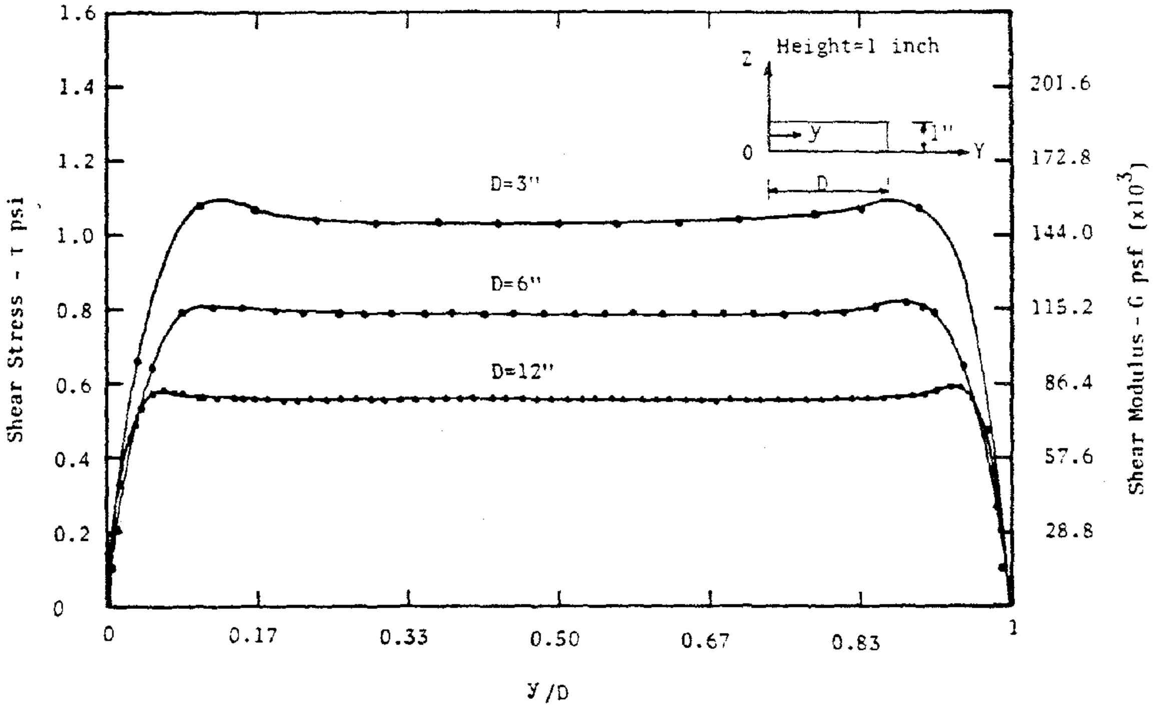
damping ratio, were investigated in detail. The experimental study did not show the stress distribution inside the sample for the different sizes used. However it gave the response of the sample as a whole for a given specified condition.

In general, the objective of laboratory soil testing is to study the behavior of a given soil under conditions similar to those encountered in the field as well as to obtain parameters which describe this behavior. In a laboratory test, the sample is intended and generally assumed to represent a single point in the half space. The validity of this assumption depends on the uniformity of the stress and strain distributions within the soil sample.

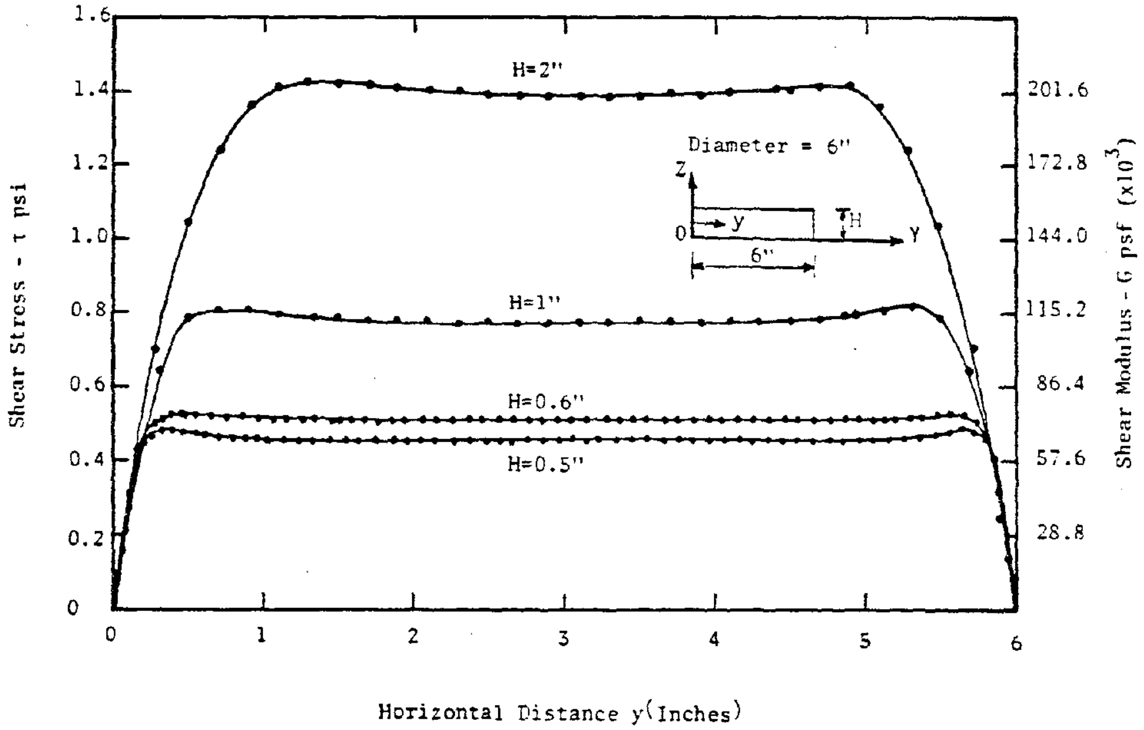
In this research, a theoretical study was undertaken to investigate the shear and normal stress distributions on the boundaries and within the sample and in addition to the experimental study, to determine the ideal sample size at which the shear and normal stresses could be considered to be uniform.

Six cases were investigated to represent the change in the sample size which had already been studied experimentally. To study the effect of sample size on the normal and shear stress distributions, 6-in diameter samples with heights of 0.5, 0.6, 1 and 2 inches were analyzed, as well as 3 and 12 inch diameter samples with heights of one inch. Those are samples chosen from the experimental program. All the cases were analyzed for 0.001 inch/inch shear strain.

Figure 11(a) shows the effect of the bondaries on the shear stress distribution calculated at the mid-height of the central plane for samples having the same height and different diameters. The shear stress calculated at the middle of each sample decreased with an increase in sample diameter. At the same time the area of the sample having uniform shear stresses increased with increasing sample diameter. It is concluded from the figure



a) Effect of Diameter



b) Effect of Height

Fig. 11 Distribution of Shear Stresses over the Sample Diameter for the Same Height and Variable Diameter Computer at γ_{yz} = 0.1% (FEM Analysis).

that the conventional 3-inch diameter simple shear overestimated the shear stress. This is because the behavior of such a small sample size is influenced markedly by the boundaries. Figure 11(b) is drawn to show the effect of sample height, on a sample having a 6-inch diameter. The figure illustrates the increase in shear stresses as the sample height increased for samples having the same sample diameter. When the sample height decreased the uniformity increased for the same sample diameter. It was found that for all samples, at the vertical boundaries over 30% deviation in shear stress occurred and the deviation decresed away from the boundaries. The finite element analysis also showed that the size that indicated the worst stress conditoins had about 70% of the sample subjected to uniform shear stress distributrion, that is less than a ±10% deviation from the stresses at the center of the sample. It was also clear that not just the diameter nor the height was responsible for the nonuniformity of the stresses within the sample but the two together affected the results. The samples of 6 inch diameter and heights of 0.5 and 0.6 inch and the 12 inch diameter sample with a height of 1 inch experienced uniform stresses on over 92 percent of the sample.

Figure 12 was plotted to demonstrate the relationship between the sample size and the area of the corresponding part of the sample which had a uniform shear stress distribution, i.e., the area which had shear stresses within ±10% of the value at the middle of the sample.

In Figure 13 a relationship between the sample size and the ratio between the computed shear stress at the center of the sample and the applied shear stress on the lower plate was plotted. As shown in the figure, at larger diameters and/or at small heights this ratio tended to become unity. That is, for samples of large diameters and large D/H ratio the measured shear stress value (i.e. the applied shear stress) is almost the same as the shear stress at the middle of the soil sample.

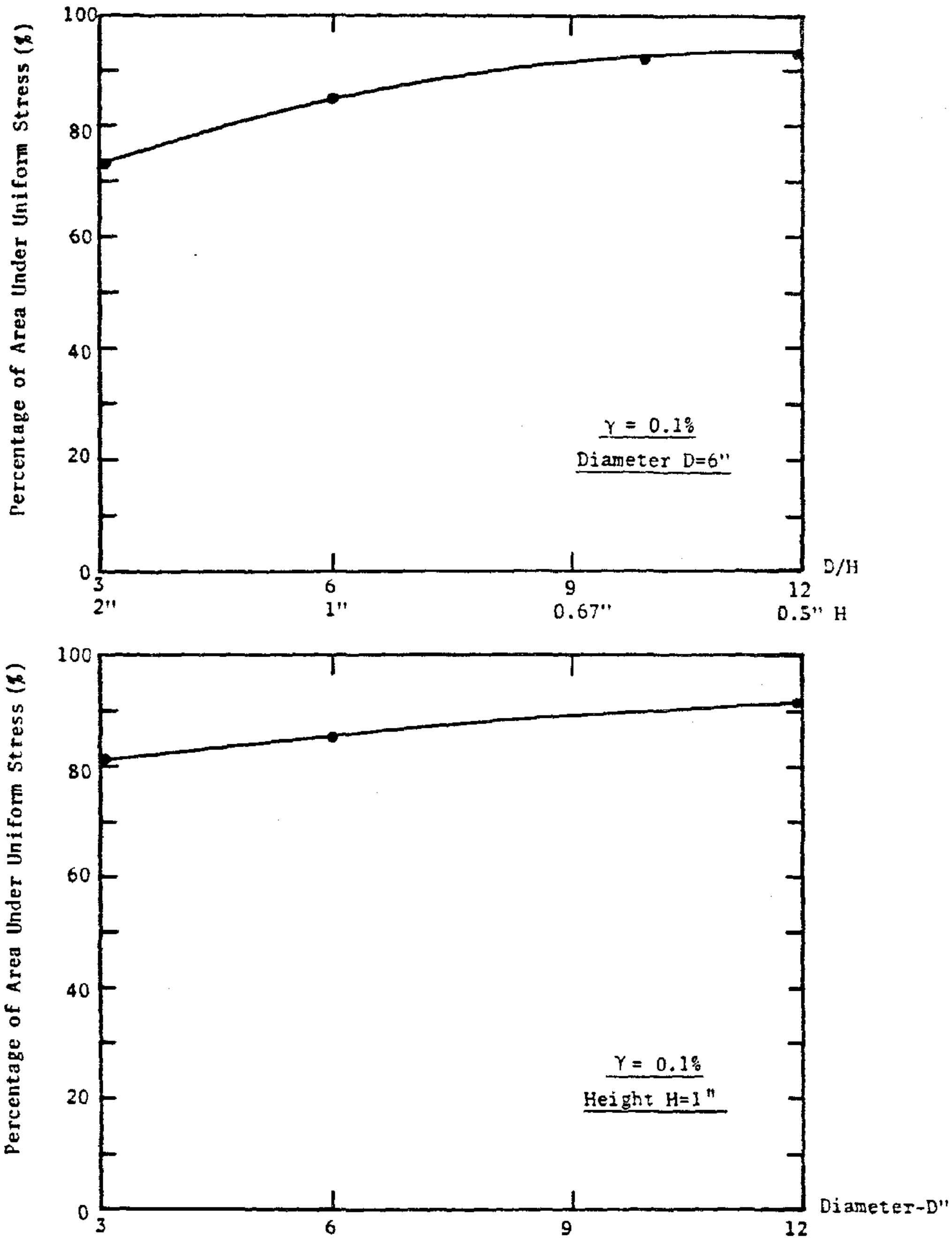


Fig. 12 Ratio of the Area Subjected to a Uniform Shear Stress to the Total Area of Each Sample.

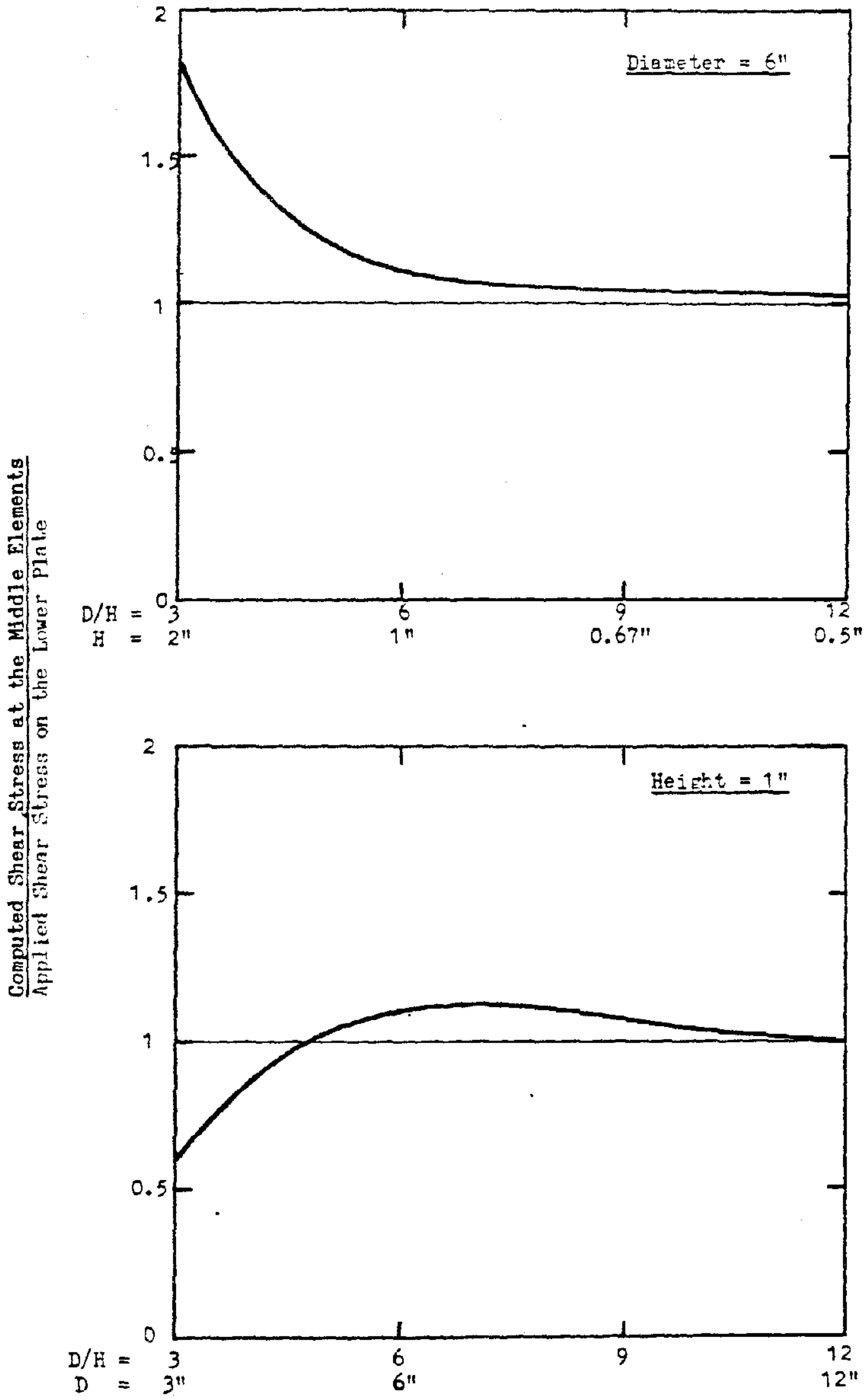


Fig. 13 The Relationship Between Sample Size and the Ratio Between the Computed and the Applied Shear Stresses.

As to the normal stress distribution on the boundaries, it was found that an increase in diameter led to an increasingly uniform stress distribution as shown in Figure 14. Again the uniformity increased with a decrease in sample height for a specific smaple diameter.

Finally, it appeared from the experimental and the theoretical study that the sample having a diameter of 8 inches and height of 1 inch was the minimum sample size at which the shear modulus has a unique value not affected by the bondaries. A sample of this size had uniform normal and shear stresses distributed over 85 percent of the cross sectional area.

For the conventional size simple shear apparatus to be used for the determination of soil behavior a correction factor must then be introduced to correct for the boundary effect. This will be discussed in more detail later in this report.

3.2 Analysis of Damping

Damping values are affected by many factors. The effect of these factors has been studied by many researchers (1,12,15,16,21,32,36,37,38). The most important parameter was found to be the shear strain amplitude. Other parameters were the confining pressure, the number of cycles, and the void ratio (or relative density).

In this study these factors were investigated along with the effect of changing the sample size. Since this research emphasizes study on the effect of sample size on the dynamic properties of sand, and to obtain a better understanding of this effect on damping, it would be worthwhile to compare the aforementioned parameters resulting from testing sand by the cyclic simple shear apparatus used herein with published results in the literature.

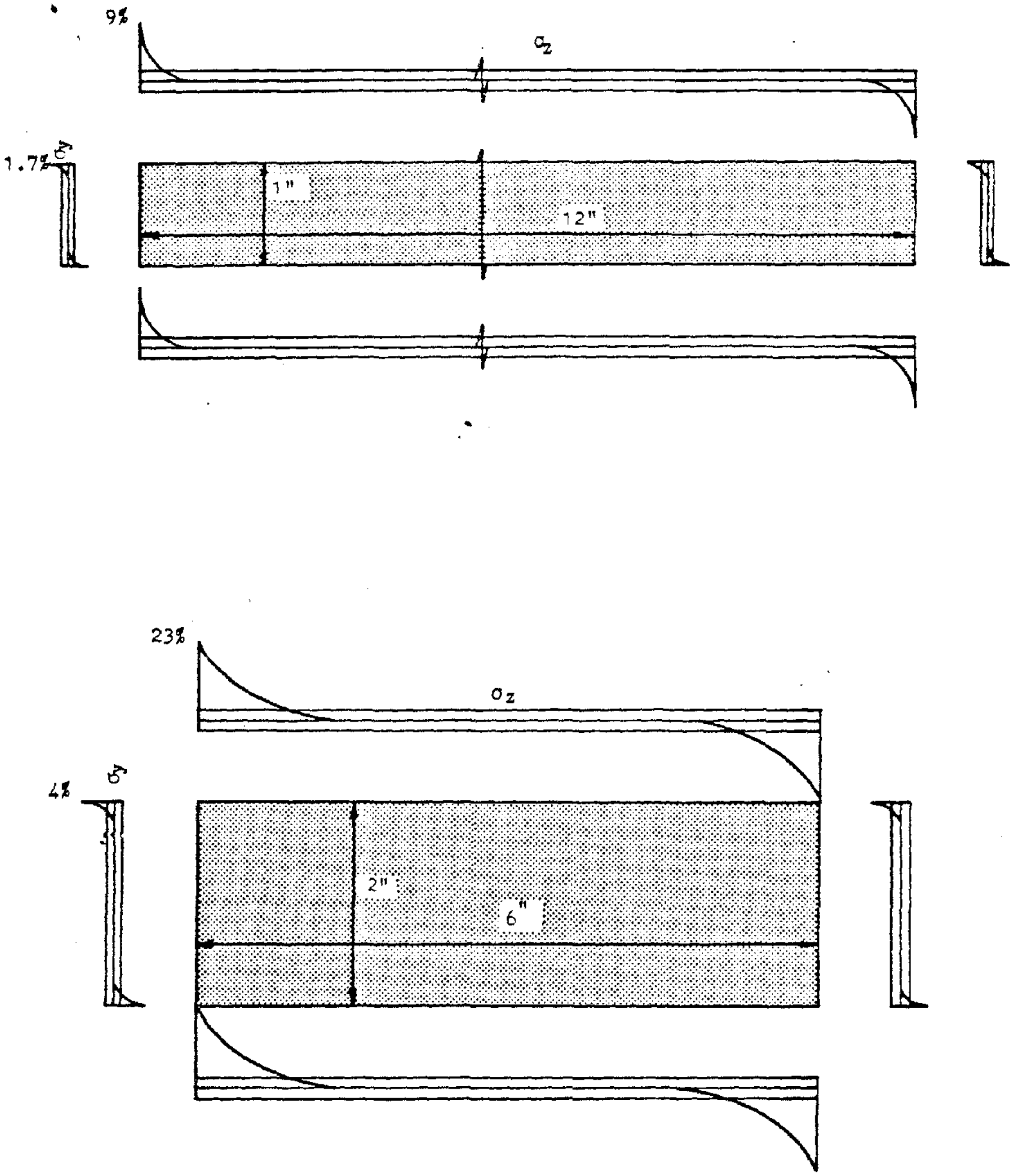


Fig.14 Normal Stress Distribution on the Boundaries.

In the following subsections the findings from studying each parameter will be explained and a comparison with previous studies will be discussed.

3.2.1 Shear Strain Amplitude (γ): Among the conventional parameters affecting damping (shear strain, confining pressure, number of cycles, and void ratio), the shear strain amplitude was found to be the strongest influencing factor. This was also indicated by the other researchers who investigated damping, such as Al-Sanad (1) Edil and Luh (12), Hardin and Drnevich (15,16), Kovacs, et al. (20,21), Seed and Idriss (32), Sherif and Ishibashi (36) and Silver and Seed (37,38). The damping was found to increase with increasing shear strain level for all values of relative densities and confining pressures when measured at any specific cycle. Figure 15 shows the effect on the damping values from increasing shear strain.

3.2.2 Vertical Applied Pressure (σ_v): The applied vertical stress (σ'_v) was found to have a considerable influence on the damping ratio within the range investigated. The values for the damping were found to decrease as the vertical pressure increased from 500 to 1000 psf. Figure 16 shows the effect of vertical pressure on the relationship between damping and shear strain at different numbers of cycles.

3.2.3 Number of Cycles(N): The number of cycles was also found to affect the damping ratio in all cases studies in this research. Hysteresis loops became narrower as the number of cycles increased. Thus, the area inside the loops decreased indicating a subsequent decrease in dissipated energy. Figure 15 shows the relationship between the damping ratio and shear strain as a

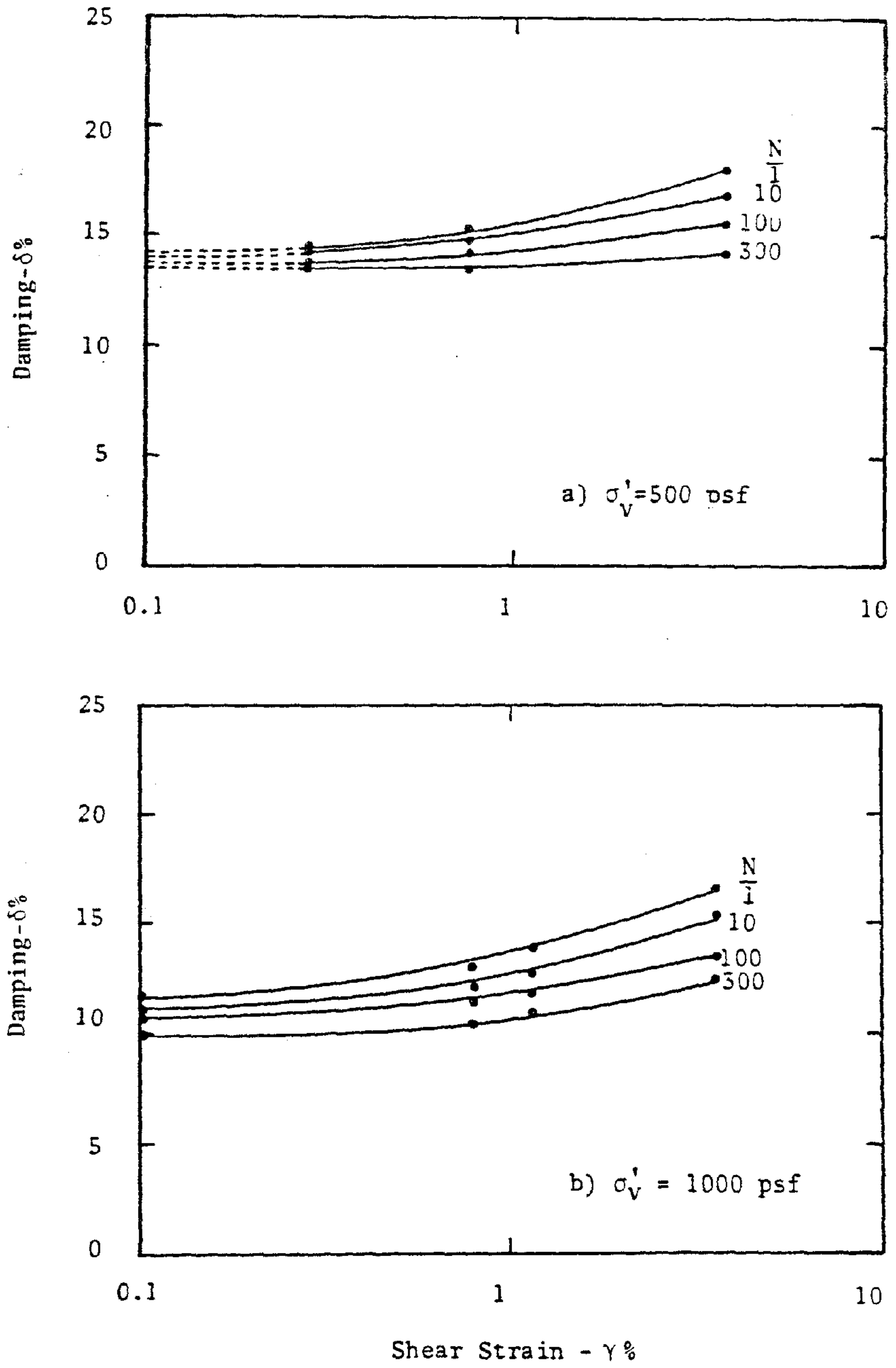


Fig. 15 Effect of Shear Strain and Number of Cycles on Damping Ratio for 3-in Diameter Sample and 1-in Height.

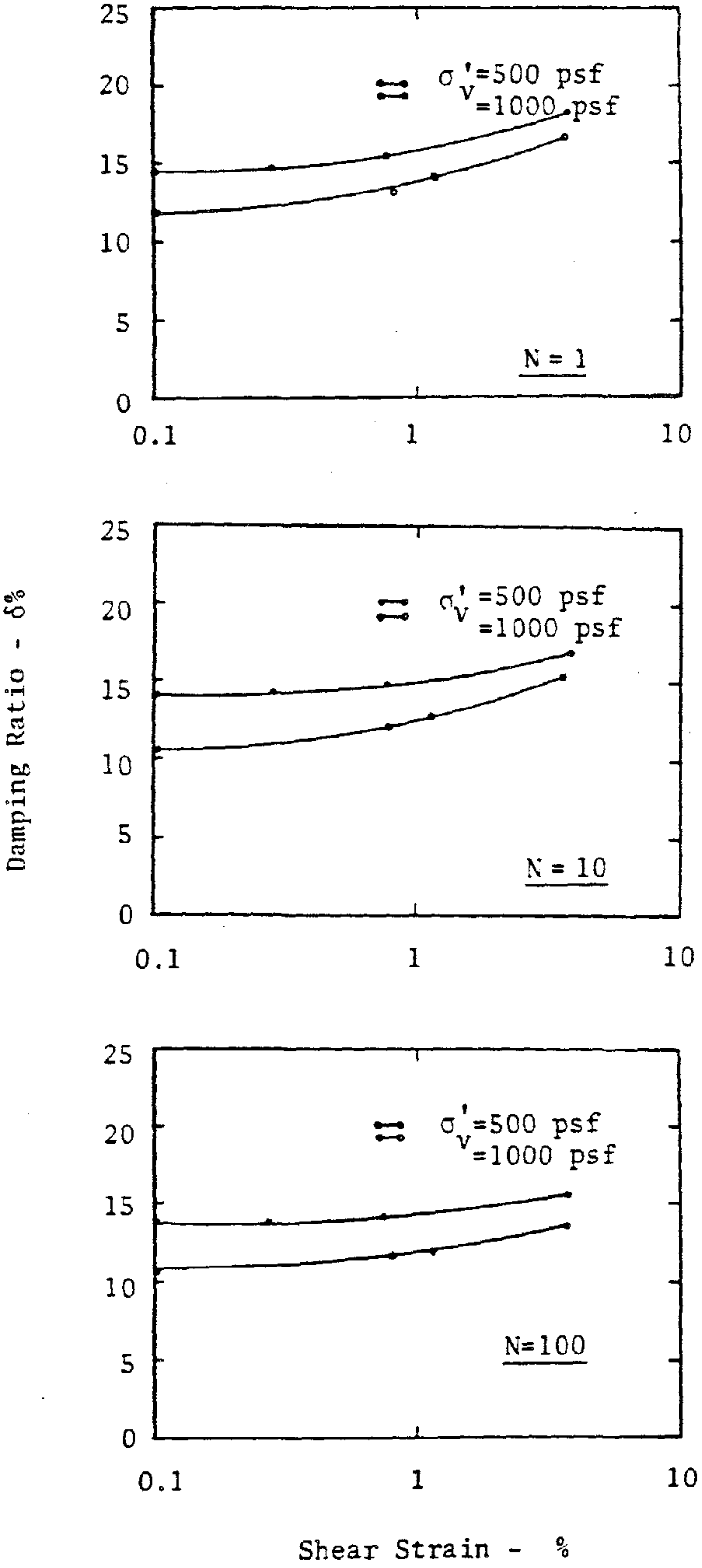


Fig.16 Effect of Vertical Pressure on Damping Ratio for 3-in Diameter Sample and 1-in Height.

function of the number of cycles. These curves show a smaller damping as the number of cycles incresed. Figure 17 shows the damping ratio as a function of number of cycles at different strain levels, on a semi-log plot this relationship was found to be a straight line sloping downward.

3.2.4 Density Condition: The state of density can be expressed by void ratio and/or relative density. In this research, the tests were performed at two different states of density. Each test sample was prepared either at 50 or 95 percent relative density and named loose and dense, respectively. As shown in Figure 18 the effect of density on damping values was found to be negligible for the range of values investigated in this study.

3.2.5 Sample Size Effect: It was found in this study that the shear strain amplitude was not the only important factor affecting damping. The sample size was determined to have equal importance. Not only the sample diameter, but also the height (or the diameter to height ratio) were found to have substantial influence on damping values. For a specific sample diameter, the damping ratio decreased when the diameter to height ratio increased. The decrease in damping ratio was pronounced up to a diameter to height ratio of about 8 then became negligible. This behavior was found to be applicable for the three sample diameters within the range of the shear strain used in this study. This behavior is illustrated in Figure 19 which shows the damping ratio versus the diameter to height ratio at different strain levels for sample diameters of 3,6 and 12 inches. Each testing point on Figure 19 is the average of four tests, two at different densities and two at different values of vertical pressure. If only one curve averaging all the variables was plotted, the result would be as shown in Figure 20 which shows a better fit

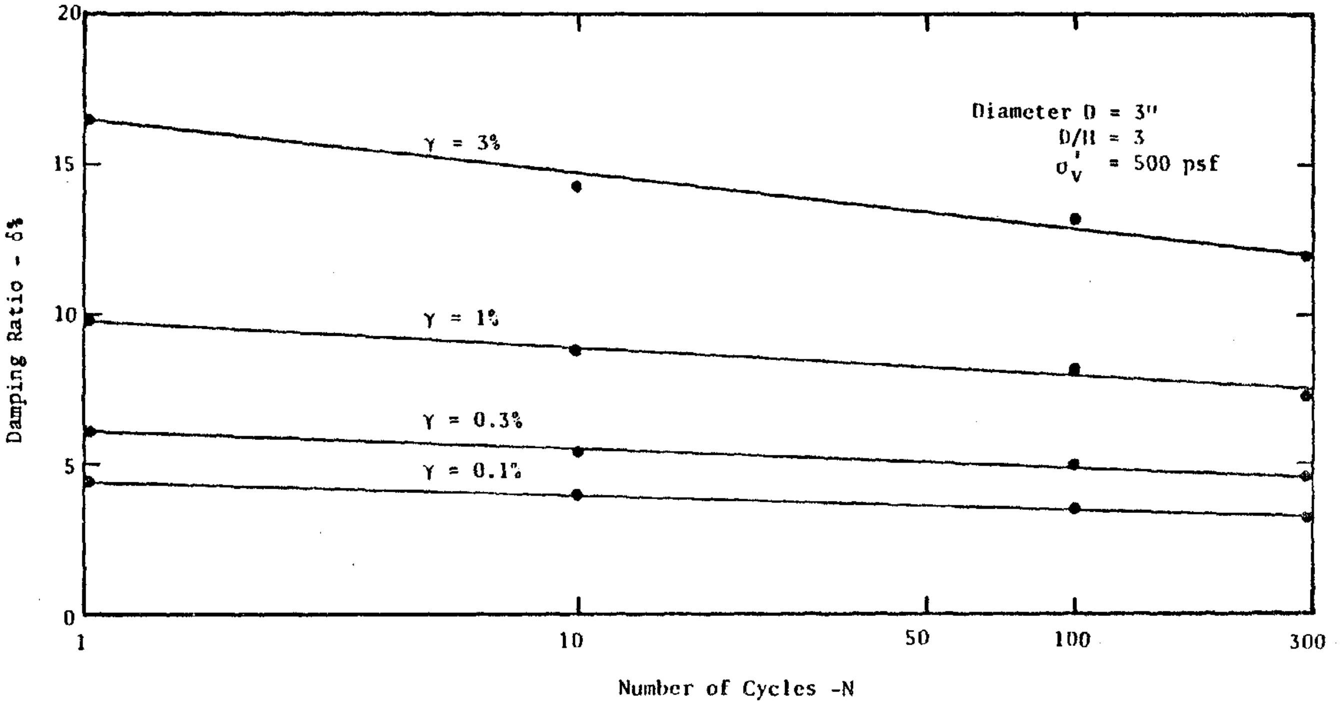


Fig.17 Damping Ratio Vs. Number of Cycles

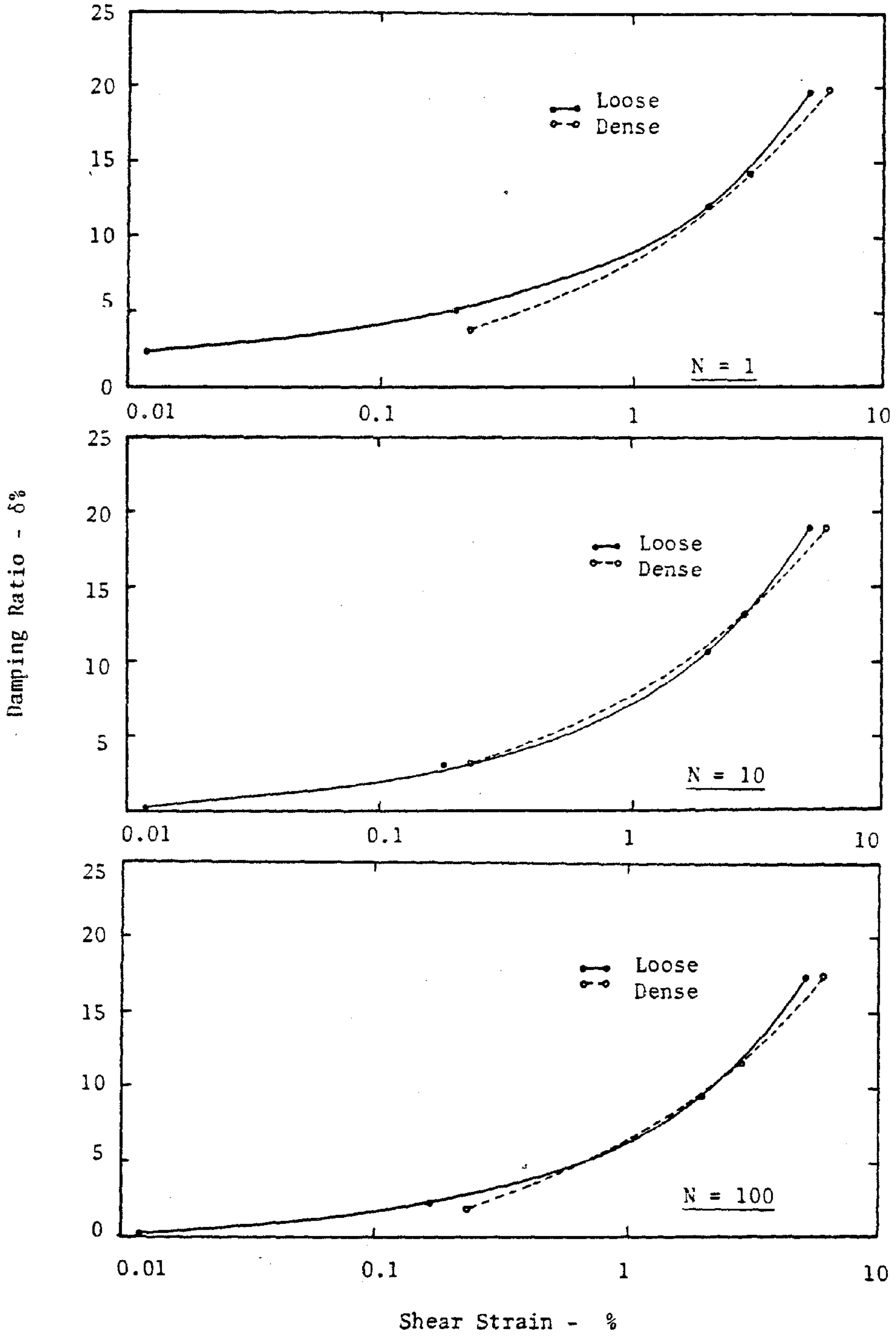


Fig. 18 Effect of Density on Damping for 6-in Diameter Sample and 1-in Height at 500 psf Vertical Pressure.

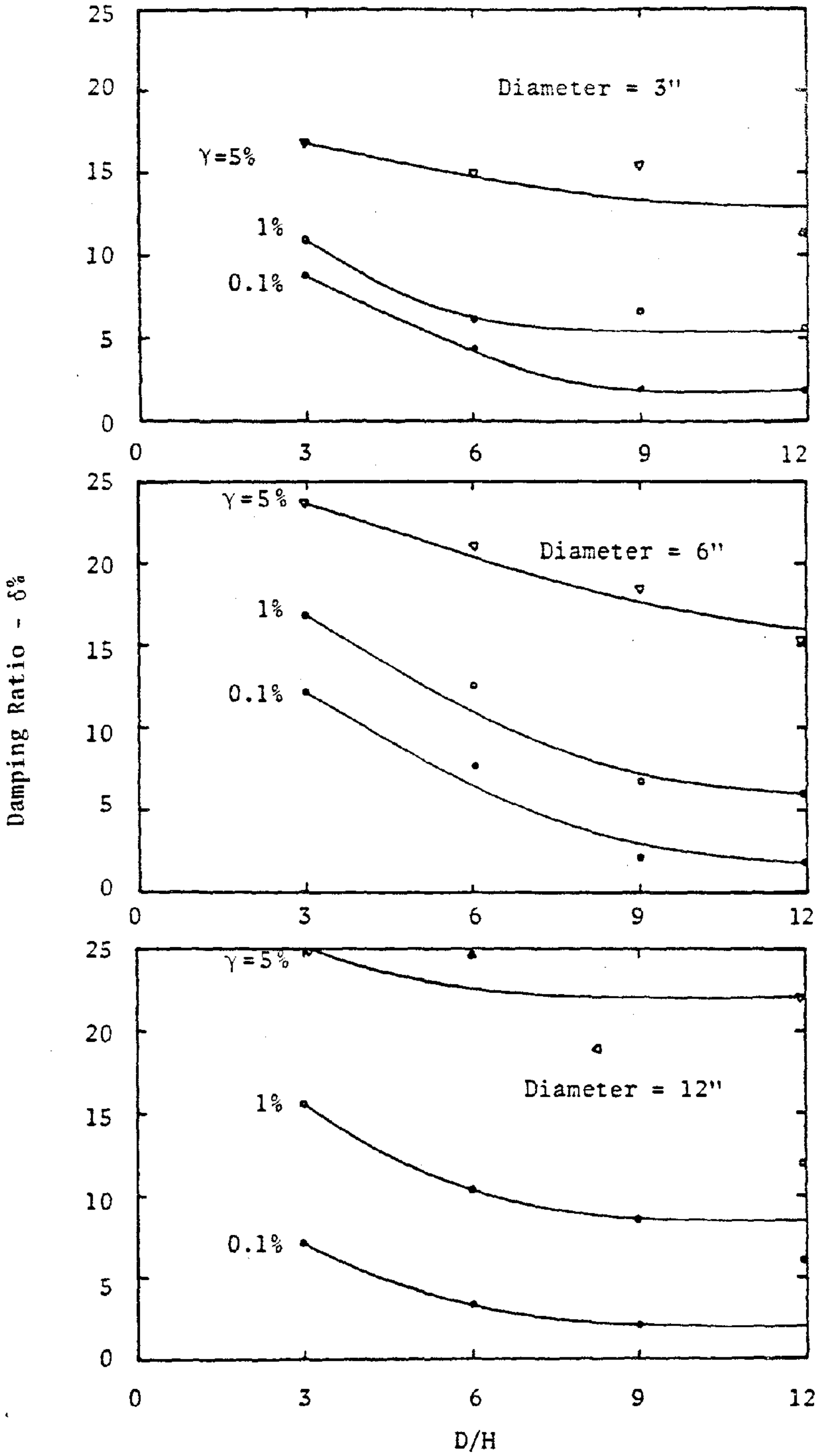


Fig.19 Damping vs. Diameter to Height Ratio at N=10 Cycles.

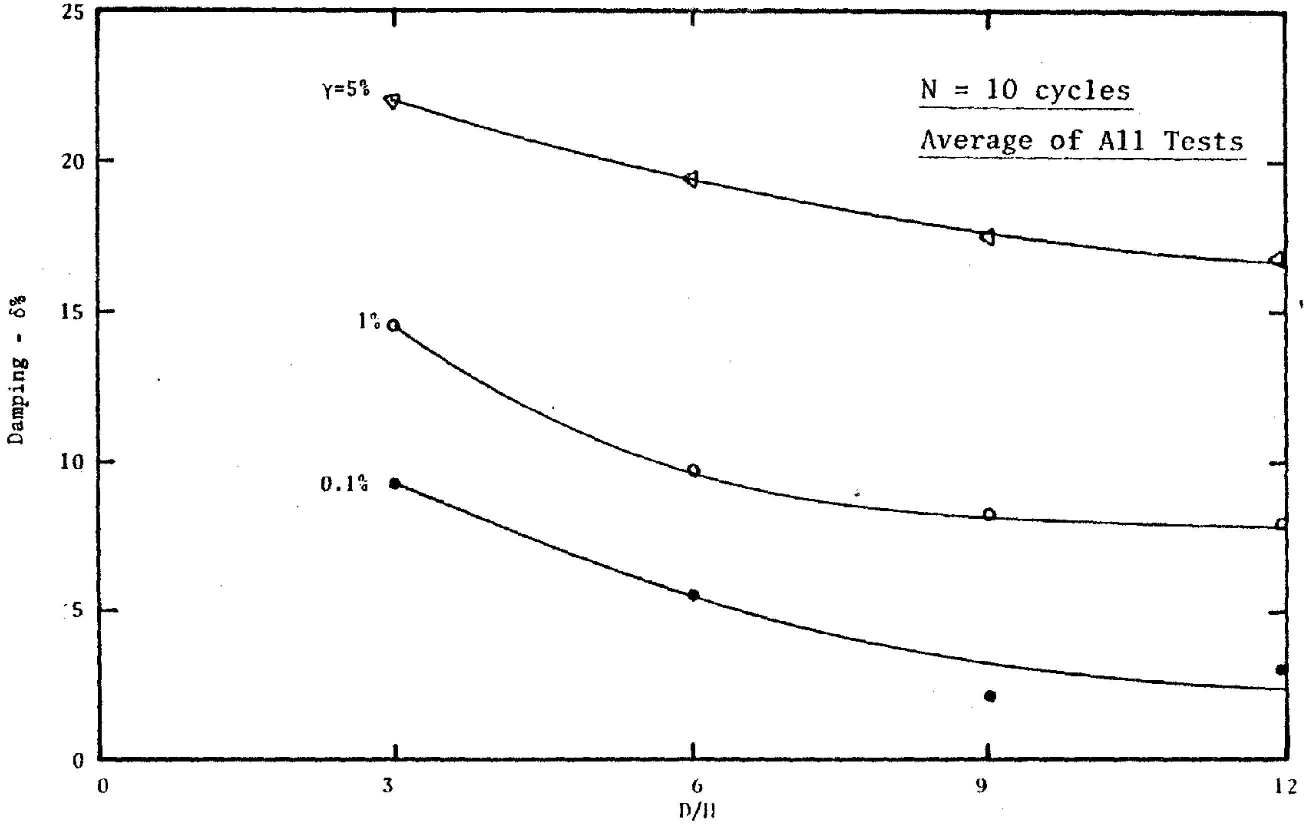


Fig. 20 Damping Vs. Diameter to Height Ratio

for the data points. Figures 21and 22 were plotted to show the effect of the diameter on damping values at different heights and the effect of height on damping values at different diameters, respectively. In Figure 21 all the damping values tended to approach one unique value for a large diameter. This was so for all shear strain levels. When the shear strain amplitude increased this unique value increased. Also shown is that the damping versus diameter relationship was a straight line for each height. The slope of this straight line decreased (i.e. the variation in the damping values lessened) when the height decreased. That is, when the diameter of the sample increased and its height decreased the values for the damping ratio would be less dependent on the size. For further understanding of the effect of sample size on damping values, Figure 22 which shows the damping ratio versus sample height relationships for different sample diameters at various shear strain levels was plotted. These relationships were found to be straight lines on semi-log plots. It is shown that these lines approach each other as the sample height decreases except for a shear strain of 5 percent for which that trend was not clear.

Before getting into a conclusion concerning the effect of sample size on damping results all the values of damping obtained from this study were plotted on one plot, shown in Fig. 23. In this figure and between the upper and lower bounds, a dashed curve was plotted as an interface between the results obtained from bulky samples, defined as samples with diameter to height ratios of three (shown above the line) and those values obtained from testing samples of higher values of D/H (shown below the dashed line). It is believed that the damping values obtained from testing the bulky samples are not representative of only internal damping.

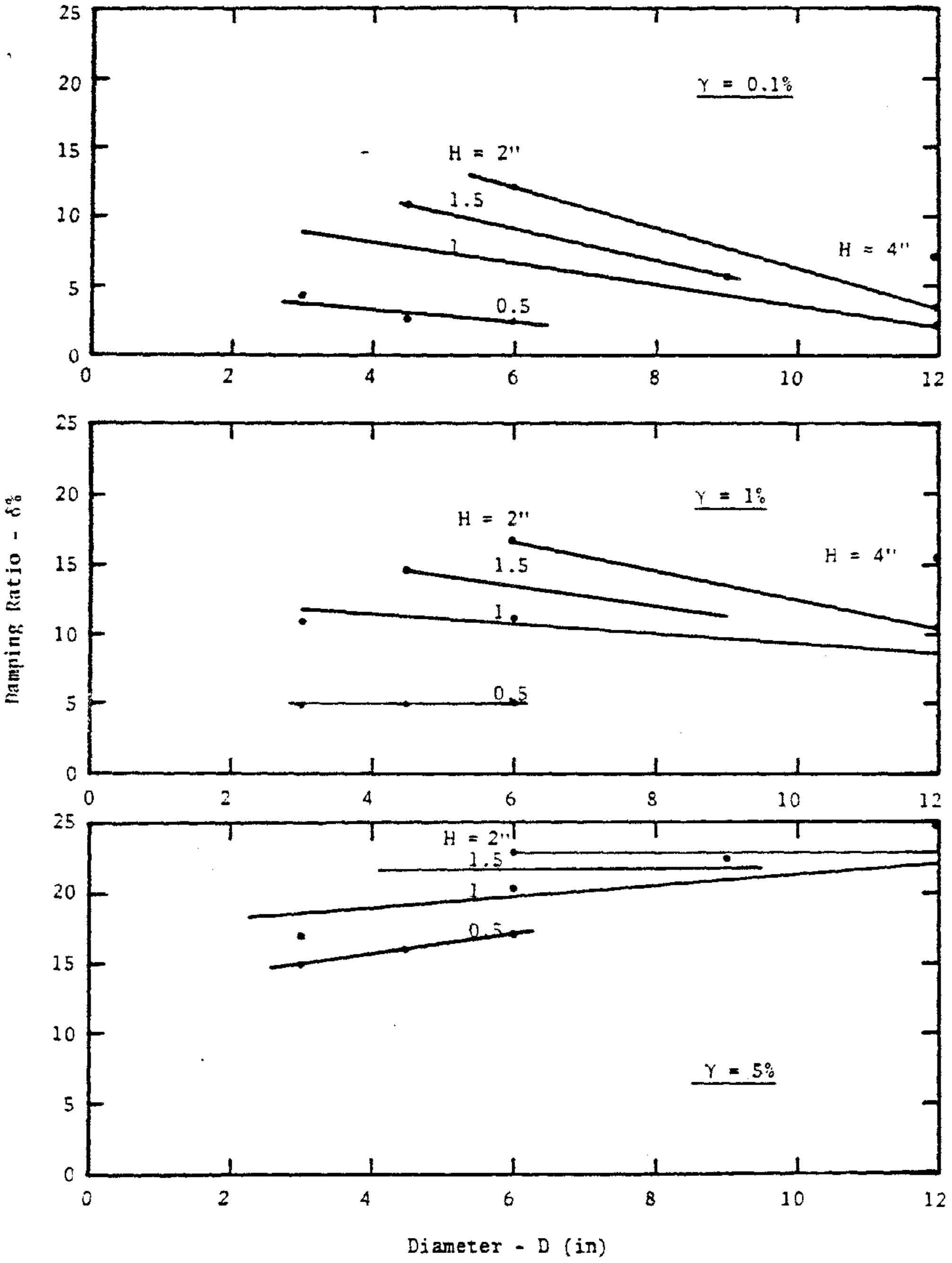


Fig. 21 Effect of Sample Diameter on Damping

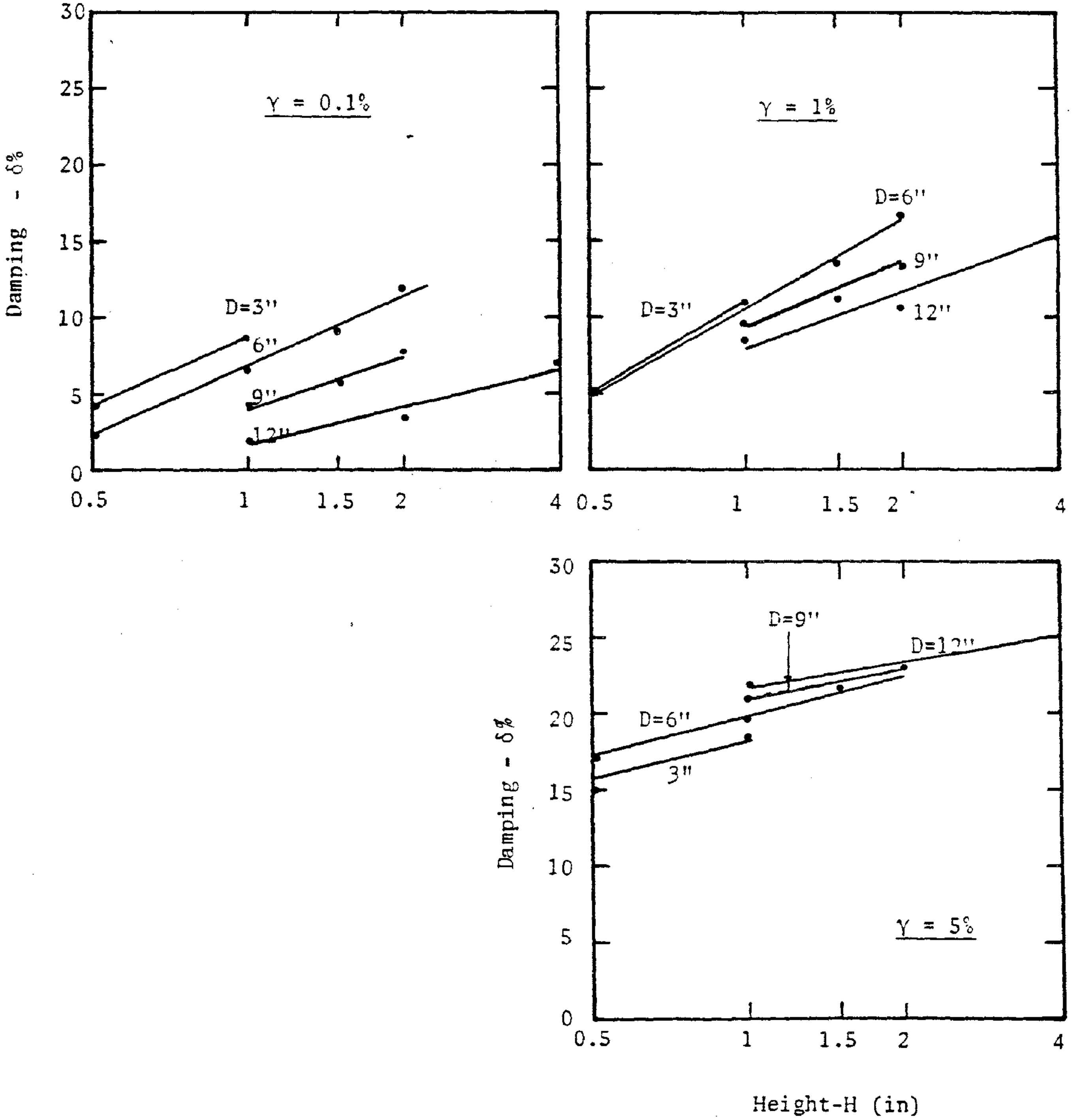


Fig. 22 Effect of Sample Height on Damping.

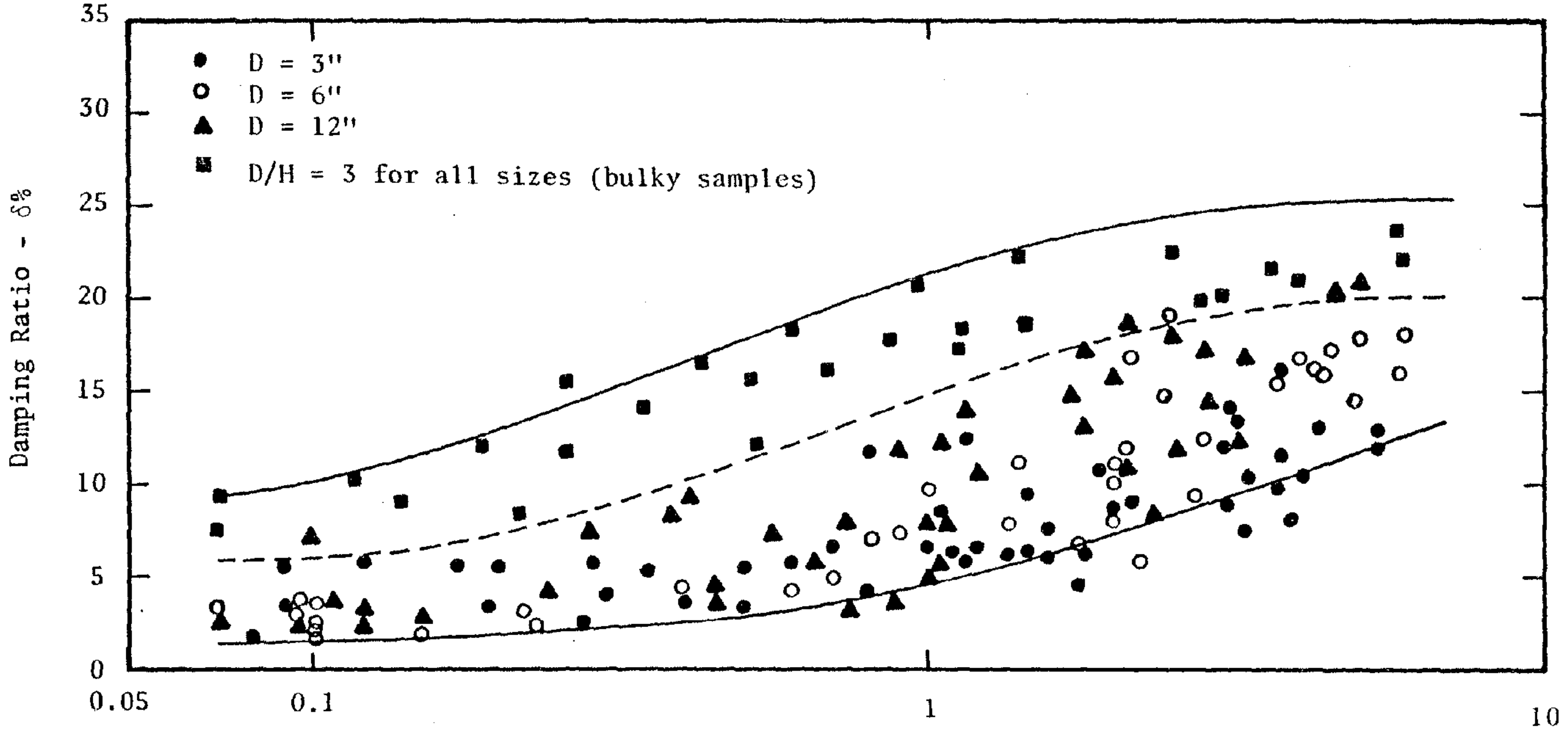


Fig. 23 Damping Ratio for All Cases Tested in This Study.

Plotting the range of damping values obtained from this study with the range of data plotted by Seed and Idriss (32) and also with data from Al-Sanad (1) in one figure gives a further comparison as presented in Figure 24. The range of data in this study appears to be an extension of the range presented previously by Al-Sanad (1). Since the data presented by Al-Sanad (1), represents a more accurate determination of damping values than those presented by Seed and Idriss (32), the extension of Al-Sanad's data in this work is a further demonstration of the validity of the data obtained. In addition, the fact that the data obtained are in the low range indicates that the measurements represent the damping of the soil and very little effect, if any, from the apparatus itself.

It can now be concluded that in the study of the effect of smaple size on damping, the larger the diameter (and keeing the height constant) the less the energy is dissipated and subsequently the lower the damping values. The same conclusion was drawn when decresing the height of the sample but keeping the diameter constant. Samples having smaller diameter to height ratios (bulky samples) showed higher damping values (Figure 19) which increased noticeably with the increase in the sample diameter.

It thus seems that damping becomes more size independent when increasing the sample diameter and decreasing the height. This was the same conclusion obtained from the study of the sample size effect on the shear modulus.

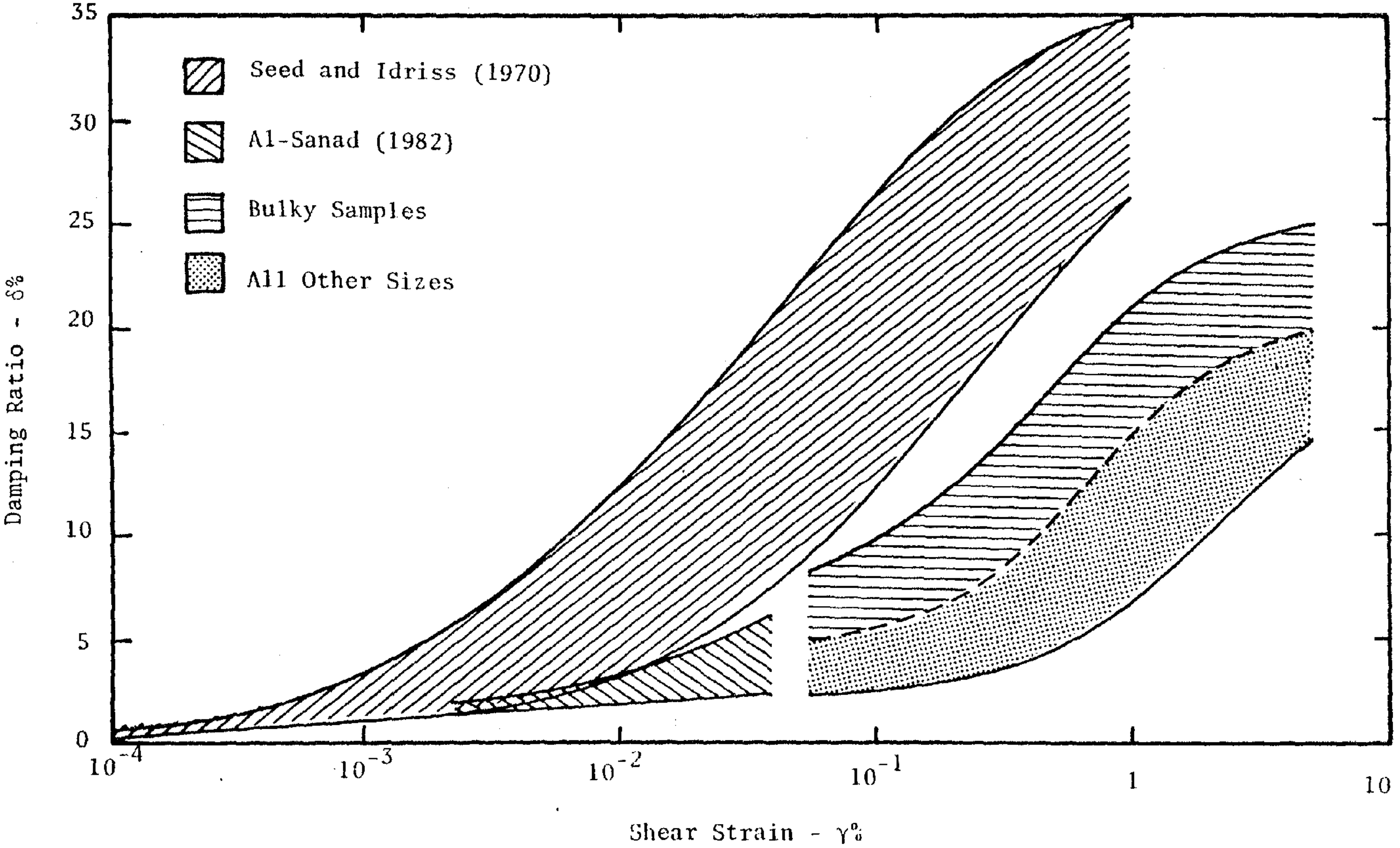


Fig. 24 Range of Damping Ratio.

4. CORRECTION FACTORS

4.1 Proposed Ideal Sample Size

It has been shown experimentally and theoretically that the values of the shear modulus and damping ratio varied when sand was tested in different sample sizes even when all conditions were kept the same. It was found that both the shear modulus and damping ratio were affected by the sample diameter up to a diameter of 8 inches after which the change in their values could be, practically, neglected. The values of shear modulus and damping ratio stabilized at a diameter of 8 inches. The dynamic soil properties were also found to decrease with a change in the diameter to hegith ratio up to a value of about 8 to 9. Between diameter/height ratios of 8 to 12 the change in the values of shear modulus and damping ratio were very small and for practical purposes could be considered as being the same.

Actually, the dynamic properties of a sand tested (under simple shear conditions) in a sample of diameter equal to 12 inches and a height of 1 inch reflected the true soil properties without any influence by the sample size. Sand tested in samples of 8 inch diameter and 1 inch height gave very close results to those obtained from samples of 12 inch diameter and 1 inch height. The difference between both results were minimum and for design and practical purposes could be considered identical. In addition, the 12 inch diameter samples required some physical effort in handling, transporting and placing the sample into the simple shear frame and if considerable care was not observed the smaple could easily be disturbed.

Therefore, it was decided to choose (based upon the results of this research) a sample size of 8 inch diameter and 1 inch height to represent an ideal size for meaningful and practical results in both research and commercial areas.

4.2 Correction Factors for Shear Modulus

After justifying the experimental results using the finite element method, a statistical analysis was performed on the experimental data. The purpose was to find empirical equations correlating the shear modulus to the sample size (diameter and height) at various shear strains, densities and vertical pressures. The statistical analysis was performed using the Biomedical Computer Programs P-series, BMDP-79 developed at the University of California, Los Angeles (10). From this series, the P2R program to compute estimates of the parameters of a multiple linear regression equation in a stepwise manner, (Stepwise Regression) was used. That is, the variable entered the equation one at a time according to their individual importance.

A total of twelve cases were analyzed and regression equations were developed. Each case was studied at a specific shear strain, density and vertical pressure. The shear modulus at D = 8 inches and H = 1 inch was used as the basis for calculating a relationship for the correction factor at each case and some of the results are shown in Fig. 25. More results are presented elsewhere (2,4,5). As shown in Fig. 25 it seems that a factor of 0.5 should be consider if sample of size 2.5" or 3" diameter was used in order to eliminate the bondary effect.

4.3 Correction Factors for Damping

Unlike shear modulus, it was found that the vertical pressure and density state did not affect the damping values significantly. For this reason the statistical analysis for the damping ratio included the diameter and height at different strain levels only. Table 1 shows the cases analyzed for damping. The regression equations as well as the formulas developed for the correction

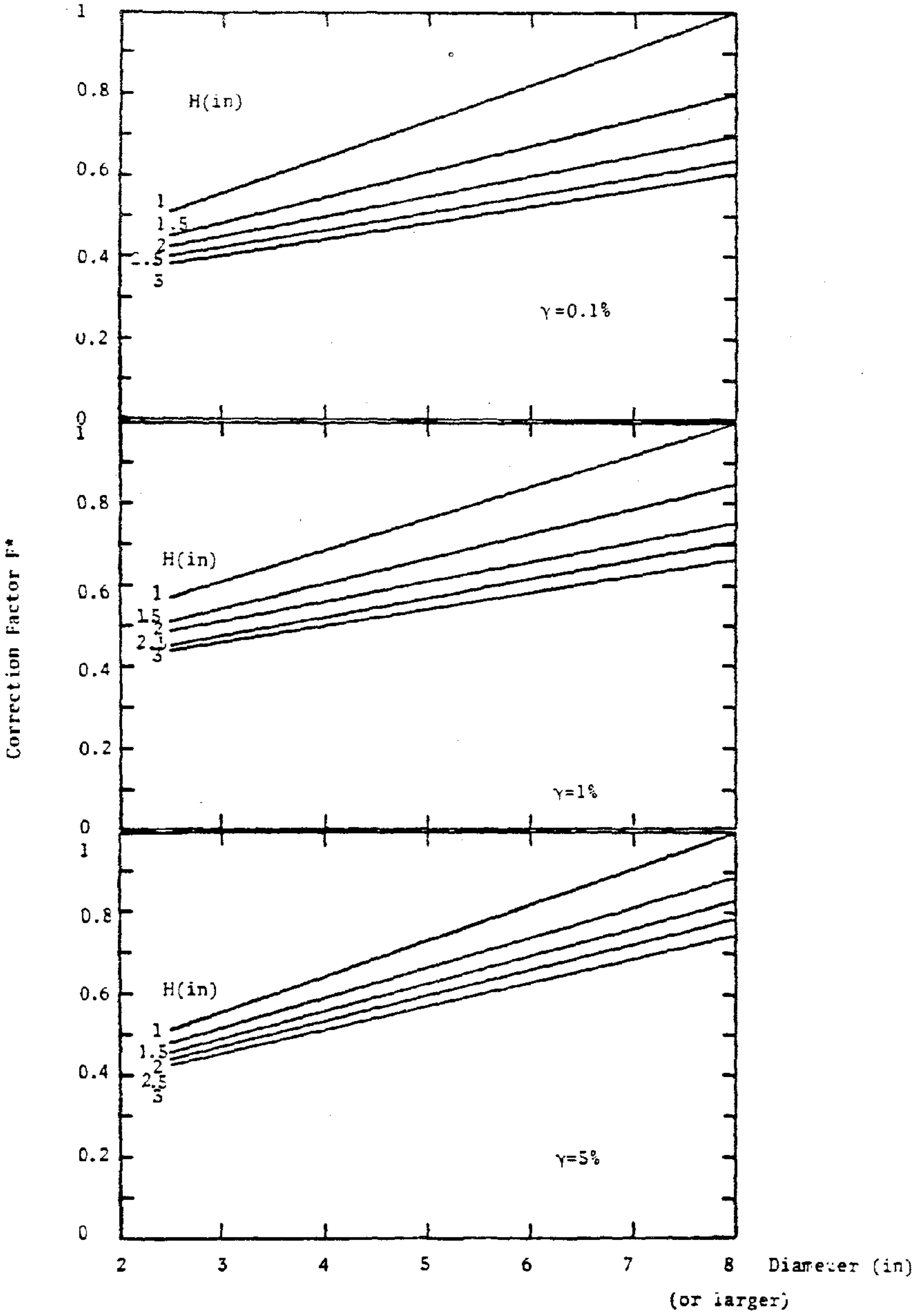


Fig. 25 Size Factor Correcting Shear Modulus
(σ_v' = 1000 psf and Dense Case).

Table 1 : Cases Analyzed For Damping.

Case	Shear Strain %	Regression Equation and Correction Formula	Correlation Coefficient R^2	Damping at D=8" & H=1" %
DAMP(1)	0.1	$\delta = 12.0 - 0.96\,D + 13.4 \log H$ $F_d = 2.78 - 0.22\,D + 3.10 \log H$	0.908	4.32
DAMP(2)	1	$\delta = 13.4 - 0.55\,D + 16.7 \log H$ $F_d = 1.49 - 0.06\,D + 1.86 \log H$	0.918	9.0
DAMP(3)	5	$\delta = 18.2 + 0.24\,D + 8.80 \log H$ $F_d = 0.90 + 0.01\,D + 0.44 \log H$	0.939	20.12

factors are also shown in Talble 1. The same principle followed for determining the correction formula for shear modulus was used in damping determination, that is, the damping for the sample size of 8-in diameter and 1-in height was used as a basis for correction factor calculations and the results are shown in Fig. 26 and Fig. 27.

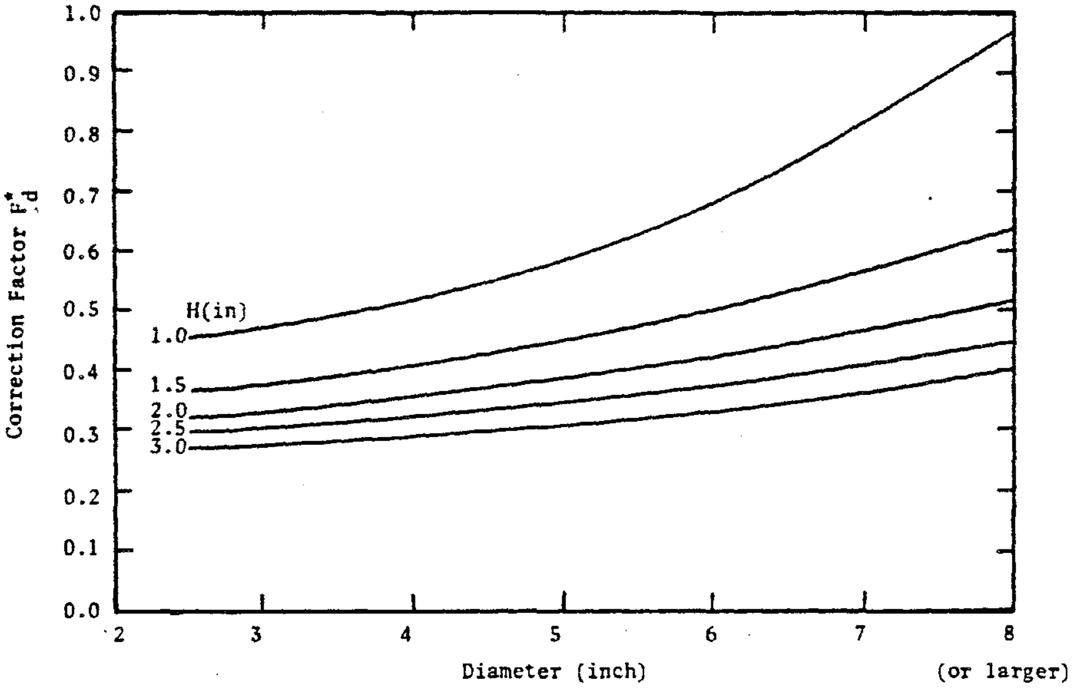


Fig. 26 Size Factor Correcting Damping at Shear Strain of 0.1%.

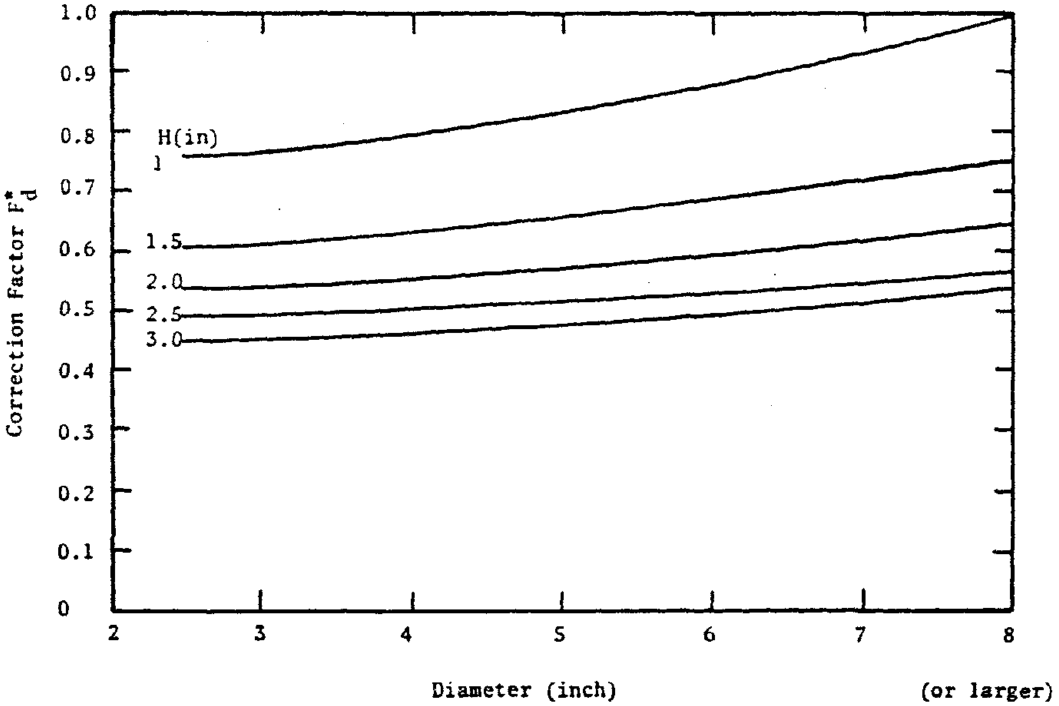


Fig. 27 Size Factor Correcting Damping at Shear Strain of 1%.

5. CONCLUSION

The following major conclusions have been drawn regarding the effect of sample size, based on the experimental results and justified by the numerical analysis.

1. The sample size (both diameter and height) had a major influence on both shear modulus and damping at small shear strains.
2. The effect of the sample size decreased at higher strain levels.
3. The shear modulus decreased as the sample diameter increased up to a diameter of about 8 inches where the shear modulus stabilized and became independent of the diameter.
4. For a specific diameter the shear modulus values were found to decrease with increasing diameter to height ratios up to a ratio of 8 after which the modulus also stabilized.
5. The damping values were found to decrease with an increase in sample diameter.
6. At larger diameters the damping values approached each other regardless of the sample height.
7. At samller heights the damping values also approached each other.

Based on the above conclusions, a sample size of 8 inches in diameter and one inch height was chosen as the ideal size at which 85 percent of the sample cross sectional area is subjected to uniform stresses. At this ideal size the applied shear stress is also a true measure for the stress inside the sample. Therefore, using the chosen ideal size in cyclic simple shear testing gives results that can be considered to be independent of the sample configuration.

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September 19, 1984

Dr. E. V. Leyendecker
Earthquake Division
Center of Building Technology
National Bureau of Standards
Washington, D.C. 20234

Dear Dr. Leyendecker:

According to the agreement between you, Dr. Aggour, Dr. Kovacs and myself, I am enclosing the report requested from me concerning my Ph.D. research titled "Size Effect in Simple Shear Testing", by Amer, Aggour and Kovacs.

Thank you for the assistance I have received throughout the experimental work and during the preparation of this report.

The report is in the Civil Engineering Dept. word processing if you need it, please contact Dr. Aggour.

Sincerely

Mohamed Amer
Faculty Research Assistant

MA:emc

cc: ✓Dr. R. Chung
Dr. M.S. Aggour
Dr. W.D. Kovacs