NBSIR 82-2568

Contribution to the ASTM Resonant Column Round Robin Testing Program

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
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Structures Division
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

Results from National Bureau of Standards (NBS) resonant column tests to determine shear moduli and damping ratios for Monterey No. 0 sand are presented to supplement the ASTM resonant column round robin program. In addition to testing solid specimens as specified for the initial ASTM round robin program, hollow cylindrical specimens were tested to provide an independent check on the validity of the results in shear modulus and damping evaluations.

The NBS test data on shear moduli are consistently lower than the average values obtained from the initial round robin program, but they are within the range of the initial round robin test data. It is believed that, at least in part, the difference between the NBS and the round robin data was caused by the fact the NBS specimens had a lower average relative density which was also closer to 60 percent relative density specified for the round robin tests. Damping ratios obtained by NBS fit rather closely the curve obtained from the initial round robin program.

No significant difference was found between the maximum shear moduli and damping ratios obtained from the testing of solid specimens and hollow cylindrical specimens.

Keywords: Damping; resonant column; round robin tests; shear; shear modulus; soil dynamics; test methods; torsional vibrations.

NOTATION

D_r	Relative density
λ	Damping ratio (expressed as a percent of the critical damping of the system)
e	Void ratio
G	Shear modulus
G_{max}	Maximum shear modulus determined at very small average shear strain amplitude ($\leq 10^{-3}$ percent)
σ_3'	Confining pressure (confining stress)
γ	Average shear strain
γ_{dry}	Dry unit weight of the specimen

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1. INTRODUCTION

In 1978, ASTM Subcommittee 18.09, Soil Dynamics, under the coordination of Professor V. P. Drnevich of the University of Kentucky, initiated a round robin program for determining the dynamic shear modulus and the damping ratio of Monterey No. 0 sands by the resonant column testing technique. In the round robin program, the requirements were set for testing, including the type of material used, type and dimensional requirements of the test specimen, specimen density and method of specimen preparation, procedures for specimen set-up in the testing chamber, and the procedures for determining the dynamic properties.

The geotechnical engineering laboratory at the National Bureau of Standards (NBS) acquired the resonant column testing device in 1980 and had it in operation early in 1981. As part of the NBS pilot testing program, it was decided to follow the procedures specified in the ASTM round robin program in order to determine whether the NBS test results are comparable with available round robin test results. Typical test data were forwarded to Professor Drnevich for review. As the result, Professor Drnevich requested NBS to submit a report so that the NBS data can be included in the final report on the ASTM round robin program. This report contains the test data produced by NBS to supplement the ASTM resonant column round robin program, as well as a discussion of the test procedures used and results obtained. In addition to the tests specified in the round robin program, NBS also performed tests on specimens with different dimensional characteristics (hollow cylinders) to provide an independent check on the validity of the results in shear modulus and damping characteristics evaluations. These test results are also included and discussed in this report.

The body of the report contains a discussion of test results and procedures, as well as plots of the test results. Appendix A contains the test procedure specified initially for the round robin test program. Appendix B contains a draft report by Professor Drnevich on the initial round robin program which includes nine sets of test data and was issued in January 1979. Appendix C contains a tabulation of the NBS test data.

2. TEST EQUIPMENT

The NBS resonant column device is a Drnevich-type apparatus with the specimen fixed at the base and excitation forces applied to the top of the specimen. Two types of specimens were used in testing; one type is a solid specimen, 71.0 mm ± 0.2 mm in diameter and 143.2 mm ± 0.1 mm in height (refer to p. A9 in Appendix A) and the other type is a hollow cylindrical specimen with an inner diameter of 35.2 mm ± 0.1 mm, an outer diameter of 71.0 mm ± 0.2 mm and a height of 76.4 mm ± 0.5 mm. The round robin program specified the use of solid specimens. The hollow specimen data were added since they independently corroborate the solid specimen data and also provide valuable information as to whether the laboratory determined values of shear modulus and damping would be affected by the type of specimens used in the evaluation.

3. TEST MATERIAL

Monterey No. 0 sand was used. A particle size distribution curve and the selected index properties of the Monterey No. 0 sand, obtained by Mulilis, et al., (1)[1/] are shown in figure 1 and table 1, respectively. The sand is a commercially available washed uniform fine to medium beach sand of a group symbol "SP" using the unified soil classification system (2), composed of quartz and feldspar particles. The maximum and minimum dry unit weight determinations were performed in accordance with the ASTM test method (3) and Kolbuszewski's method (4), respectively.

4. TEST PROCEDURES

Oven-dried materials were used in the specimen preparation and all the specimens were prepared to a relative density of approximately 60 percent using a dry tapping method. The amount of material required to fill a known volume was divided into five equal parts. The first part of the material was poured into a funnel which is resting on the bottom platen and then the funnel was raised slowly to allow the material to flow into a space confined by a rubber membrane. which is tightly backed up against a split

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1/ Numbers in parentheses are literature references in Section 9.

mold by vacuum, to form the first layer. Slight tapping on the wall of the split mold was required to reach the calibrated layer thickness which was calculated using Ladd's method (5). Subsequent parts of the weighed material were poured into the same funnel with its bottom resting on top of the layer just being constructed. By dividing the total weight of the specimen into five parts and constructing the specimen in a sequence of five layers, a uniform density distribution throughout the height of the specimen is achieved (5).

After the total weighed material was placed in the split mold, the top platten was put into place and the rubber membrane(s) adjusted around the top platen. The vacuum was then removed from the split mold and a suction of 10 kPa was applied through the bottom platten to hold the specimen in place. The split mold was then removed from the specimen while the suction was maintained in the specimen.

The above described procedure deviates in two respects from the procedure used in the initial round robin tests: (a) specimen density was controlled in five separate layers rather than raining in the material continuously. The NBS procedure is believed to produce a better control of the uniformity of the specimen, (b) the suction applied to the specimen was 10 kPa rather than the 34.5 kPa used in the initial tests. The suction was reduced in order to minimize the disturbance of the specimen fabric, which was a parameter investigated in the NBS tests.

Actual dimensions of the prepared specimen were measured with the suction applied to the specimen. The length of the specimen was determined at two diametrically opposite positions and averaged. The diameters were measured at two elevations and at 90° displacement between the directions of the measurements and averaged . The actual diameter of the specimen is the above measured average value subtracting twice the average membrane thickness. Dry unit weight of the specimen can then be calculated using the actual dimensions of the prepared specimen.

After complete assembly of the apparatus around the top platten, a plexiglass cylinder was placed around the assembly and was enclosed by a top plate in which all the transducers for input driving force and output accelerometer and displacement measurements are housed. A pressure of 10 kPa was then applied in the chamber and the suction within the specimen was slowly released so that the specimen was completely supported by a positive chamber (confining) pressure of 10 kPa. At each stage while the specimen was under a confining pressure of 10 kPa, regardless whether this pressure differential was due to suction within the specimen or confining pressure in the test chamber, a small amplitude torsional shake-down test with the average shear strain amplitude of about 5×10^{-4} percent was conducted to determine the system response. The tests were also used to detect any specimen disturbance due to the assembling operation of the test set-up by observing the Linear Variable Differential Transformer (LVDT) readings which measured the change in specimen height. The confining pressure was then brought up to the desired magnitude for testing.

5. TEST PROGRAM

Summaries of the twelve tests conducted are given in table 2. Maximum shear modulus determinations were conducted for a range of confining pressures from 10 kPa to 300 kPa by applying low amplitude torsional vibrations with average shear strains of less than 10^{-3} percent to the specimen. Large strain testing was also conducted at confining pressures of 50 kPa and 300 kPa, as specified in the initial round robin program. A maximum amplitude of average shear strain amplitude of about 4×10^{-2} percent was obtained using this resonant column apparatus.

6. TEST RESULTS

The mean dry unit weight of the tested specimens was 1578 kg/m^3 with a standard deviation of 4.48 kg/m^3. This unit weight is equivalent to a void ratio of 0.675 and a relative density of approximately 60.2 percent. The range of unit weights for the tested specimens varied from 1573 kg/m^3 to 1585 kg/m^3, as indicated in table 2.

Test results are presented in figures 2 through 7, following the same format of presentation as in the draft ASTM report in Appendix B. Test data in a tabulated form are also included in Appendix C. Figure 2 shows the maximum shear modulus as a function of confining pressure. The dashed lines given in the figure are the boundaries for the upper and lower standard error of estimate from the initial round robin program which were obtained by least square best fit calculations which resulted in a coefficient of correlation of 0.93. Test data points obtained from solid specimen testing are shown with solid symbols. Open symbols are used for data points from the hollow cylindrical specimen testing. Figure 2 indicates that the NBS test data are slightly below the line giving the lower standard error of estimate; however, they are still well within the range of the data points submitted to the round robin program (refer to figure B1 in Appendix B).

Test results on shear modulus vs. shear strain amplitude are shown in figures 3 and 4 for confining pressures of 50 kPa and 300 kPa, respectively. Again, the upper and lower standard error of estimate and least square best fit curves from the initial round robin program are reproduced in both figures to provide a means to qualitatively evaluate the NBS test data. For the case of confining pressure of 50 kPa, the NBS test data are right on the lower curve corresponding to the lower standard error of estimate while the data points from the 300 kPa confining pressure testing are below the lower limit. Larger scatter of test data is also observed from the specimen testing under the higher confining pressure. However, the test data are well within the spread of actual data points used to construct the least square best fit curves (refer to figures B2 and B3).

Damping ratios calculated for the specimen tested at very small average shear strain amplitudes (average shear strains of 10^{-3} percent or less) are plotted in figure 5 as a function of confining pressure. The average (solid line) and the average $\pm$ one standard deviation (broken lines) for the data points in the initial round robin program (refer to figure B7) are also shown in the figure. It should be noted that the data points used for the plot of figure B7 are not the actual points reported, but are calculated from least squares best fit lines for damping vs. average shear strain amplitude for the data submitted by the participating laboratories. This approach, according to Professor Drnevich, is necessary because accurate measurement of damping is extremely difficult when the magnitude of the damping ratio is less than one percent. The NBS test data presented in figure 5 also show considerable scatter. Although the maximum shear moduli determinations in the NBS testing program consistently yielded lower values than those obtained from the initial round robin program as indicated by figure 2, the damping ratio measurements fall between the average line and the average - one standard deviation line for the initial round robin tests.

Damping ratios vs. shear strain amplitudes are plotted in figures 6 and 7 for confining pressures of 50 kPa and 300 kPa, respectively. The least square best fit line and the standard error of estimate lines from the initial round robin program (refer to figures B8 and B9) are also shown in both figures. Once again, the values of damping ratios are following more or less the curves of least square best fit up to a magnitude of average shear strain of about 10^{-2} percent beyond which the NBS test data show consistently slightly higher values for damping ratios.

7. DISCUSSION

At least in part, the generally lower values of maximum shear modulus in the NBS test data, when compared to the initial round robin tests can be attributed to the fact that in the NBS tests the specimen dry unit weights in general were lower than those used in the initial round robin program. In the round robin program, an average specimen dry unit weight of 1588 kg/m^3 was calculated, which is 10 kg/m^3 higher than the average dry unit weight of the NBS specimens. One reason for this difference in unit weight is that the NBS test specimens were subjected to a suction of 10 kPa while in the initial round robin program a suction of 34.5 kPa was used. This suction tended to cause a greater reduction in volume. Note that the average relative density of the NBS specimens was closer to the specified 60 percent than that of the round robin tests.

Maximum shear moduli, determined from the hollow cylindrical specimens appear to be slightly smaller than those determined from the solid specimens, as indicated by the test results presented in figure 2. Damping ratios, determined from the testing of hollow cylindrical specimens at these small average shear strain amplitudes, appear to be slightly higher than those from solid specimen testing. Additional study is required to determine if these findings are statistically significant because of the scatter of the data on damping ratios at small strains.

8. CONCLUSIONS

Several conclusions can be drawn from the NBS pilot testing program:

(a) The NBS test data on shear modulus values are consistently lower than the average values obtained from the initial round robin program; however, they are within the range of the initial round robin test data. At least in part, this difference may be caused by the fact that the average dry unit weight of the NBS test specimens was lower than that of the initial round robin specimens and closer to the specified 60 percent relative density.

(b) The NBS damping measurements closely fit the curve obtained using the least squares best fit method on the test data in the initial round robin program.

(c) There was no significant difference between the shear moduli obtained from the testing of two different types of specimens: solid cylinders and hollow cylinders, even though the shear modulus of the hollow specimens was slightly lower, and the damping ratio slightly higher at small strains. These preliminary findings need to be further evaluated by additional testing.

9. REFERENCES

1. Mulilis, J.P., Chan, C.K., and Seed, H.B. (1975), "The Effects of Method of Sample Preparation on the Cyclic Stress-Strain Behavior of Sands," Report No. EERC 75-18, EERC, U.C. Berkeley, July

2. ASTM D2487-69, "Classification of Soils for Engineering Purposes," Annual Book of ASTM Standards, Part 19, Soil and Rock; Building Stones.

3. ASTM D2049-69, "Relative Density of Cohesionless Soils," Annual Book of ASTM Standards, Part 19, Soil and Rock; Building Stones.

4. Kolbuszewski (1948), "General Investigation of the Fundamental Factors Controlling Loose Packing of Sands," Proc. Second Int. Conf. Soil Mech. and Found. Eng., Rotterdam, Vol. 7, pp. 47-49.

5. Ladd, R.S. (1978), "Preparing Test Specimen Using Under Compaction," Geot. Testing Journal, ASTM Vol. 1, No. 1, March pp. 16-23.

TABLE 1: Index Properties for Monterey No. 0 Sand
Mulilis et al. (1975)

Unified Soil Classification System Group Symbol	SP
Mean Specific Gravity	2.65
Particle Size Distribution Data	
D_{50}, mm 1/	0.36
C_c 2/	0.9
C_u 3/	1.5
Dry Unit Weight Data	
Maximum, kg/m^3	1,693.15
Minimum, kg/m^3	1,430.45

1/ D_{50}, mean grain size

2/ $C_c = (D_{30})^2/(D_{60} \times D_{10})$, coefficient of curvature

3/ $C_u = D_{60}/D_{10}$, coefficient of uniformity

TABLE 2: Summary of Resonant Column Pilot Test Program

Sample No.	Symbol	Specimen Type	Dry Unit Weight	Relative Density D_r	Void Ratio e	Test Procedures	
						G_{max} Determination	G vs. γ at σ_3' =
			kg/m^3	percent			kPa
M-101	○	hollow cylindr.	1,579	60.7	0.674	X	-
M-103	◇	hollow cylindr.	1,585	62.9	0.668	X	-
M-104	△	hollow cylindr.	1,573	58.5	0.680	-	50
M-106	▲	solid	1,577	60.0	0.676	-	50
M-107	■	solid	1,573	58.5	0.680	X	50
M-109	□	hollow cylindr.	1,575	59.3	0.678	X	300
M-110	◁	hollow cylindr.	1,583	62.2	0.670	-	300
M-111	▷	hollow cylindr.	1,578	60.4	0.675	-	300
M-113	⊖	hollow cylindr.	1,579	60.7	0.674	-	50
M-114	▼	solid	1,573	58.5	0.680	-	50
M-117	●	solid	1,573	58.5	0.680	X	300
M-118	◀	solid	1,584	62.6	0.668	-	300

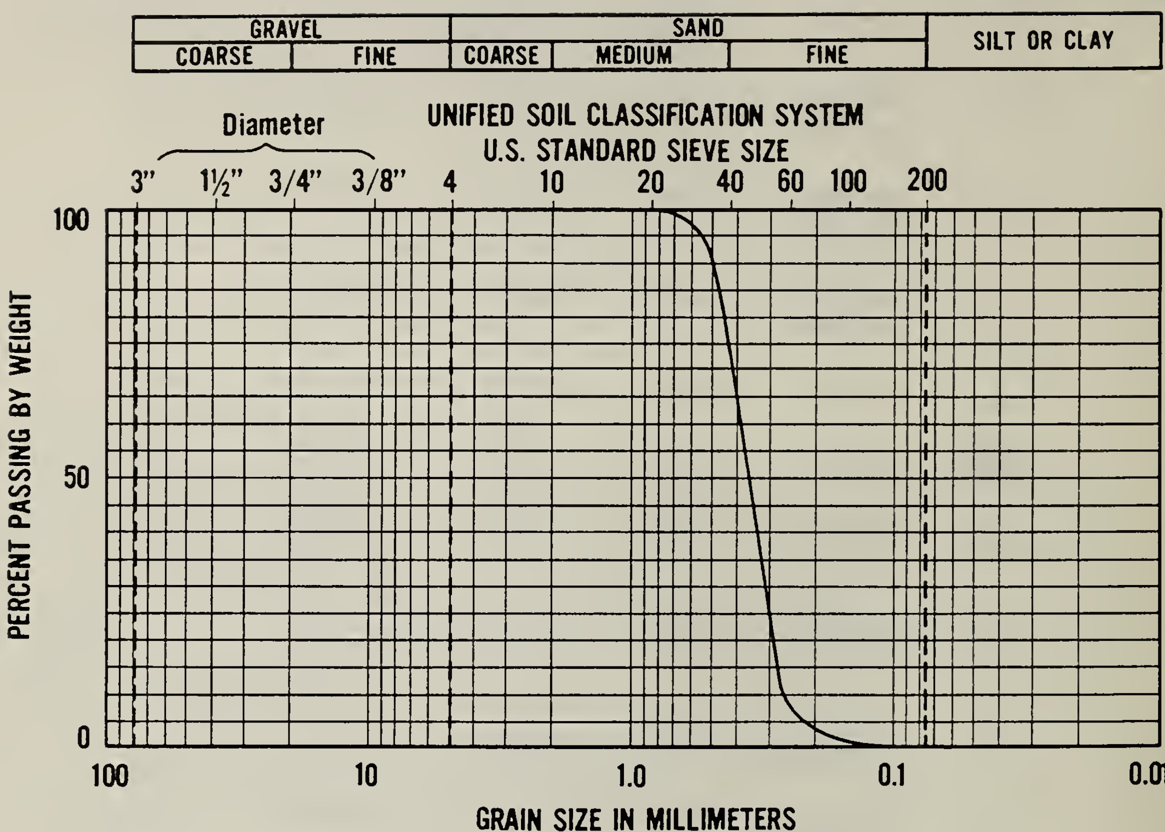


Figure 1 Grain size distribution of Monterey No. 0 sand

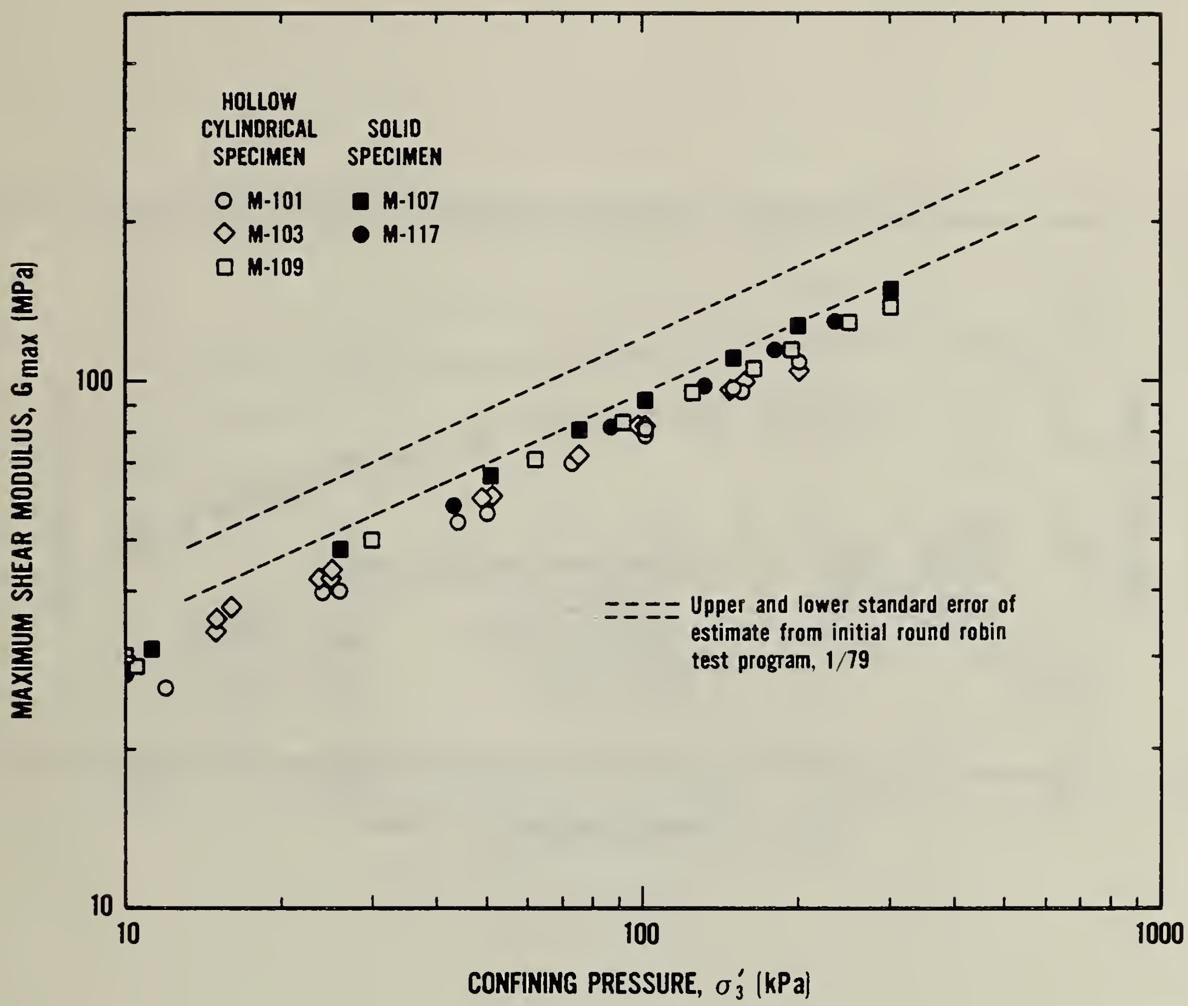


Figure 2 Maximum shear modulus vs. confining pressure

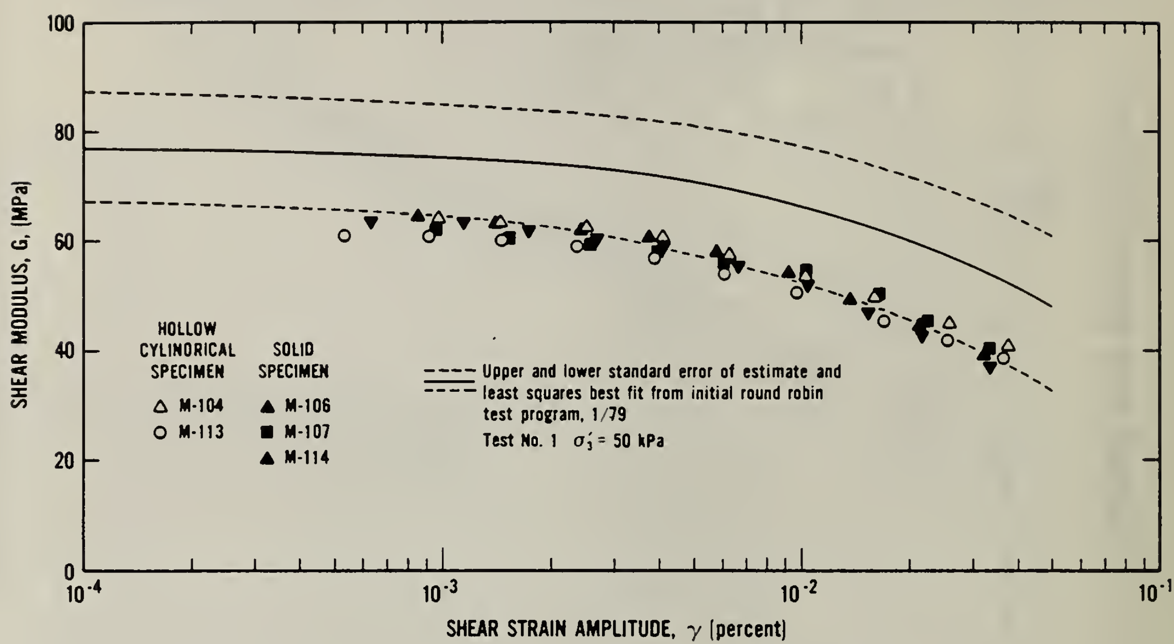


Figure 3 Shear modulus vs. shear strain amplitude, confining pressure at 50 kPa

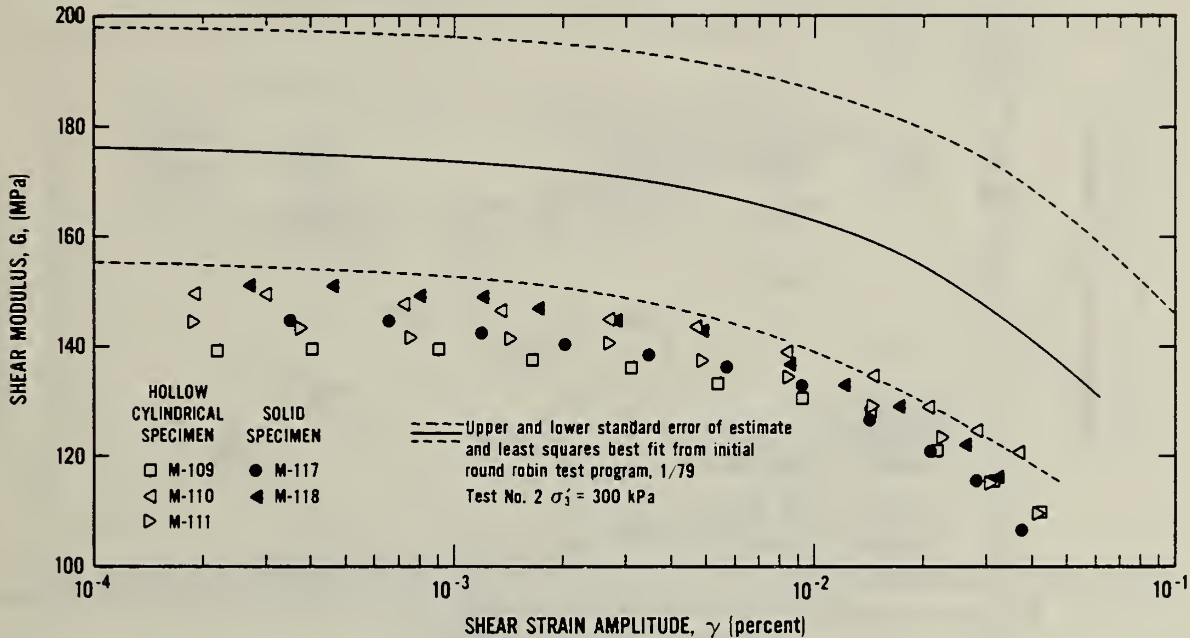


Figure 4 Shear modulus vs. shear strain amplitude, confining pressure at 300 kPa

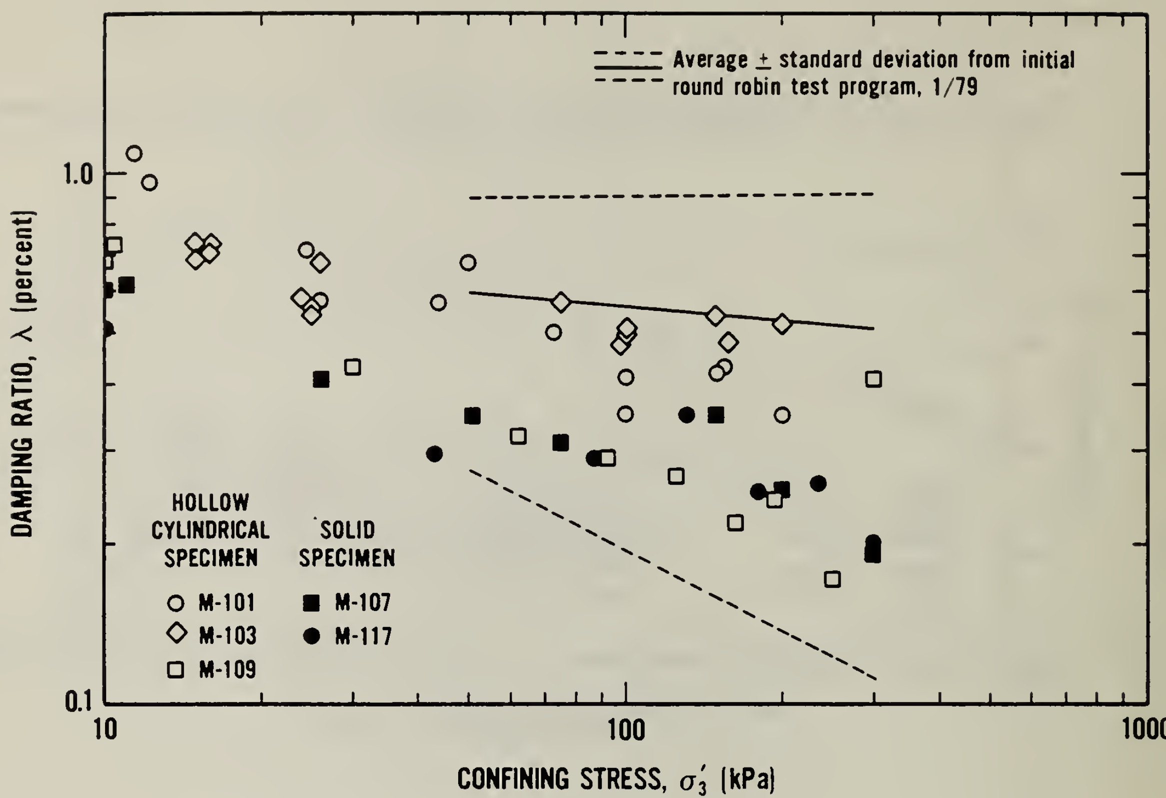


Figure 5 Damping ratio vs. confining stress at shear strain at and less than 10^{-3} percent

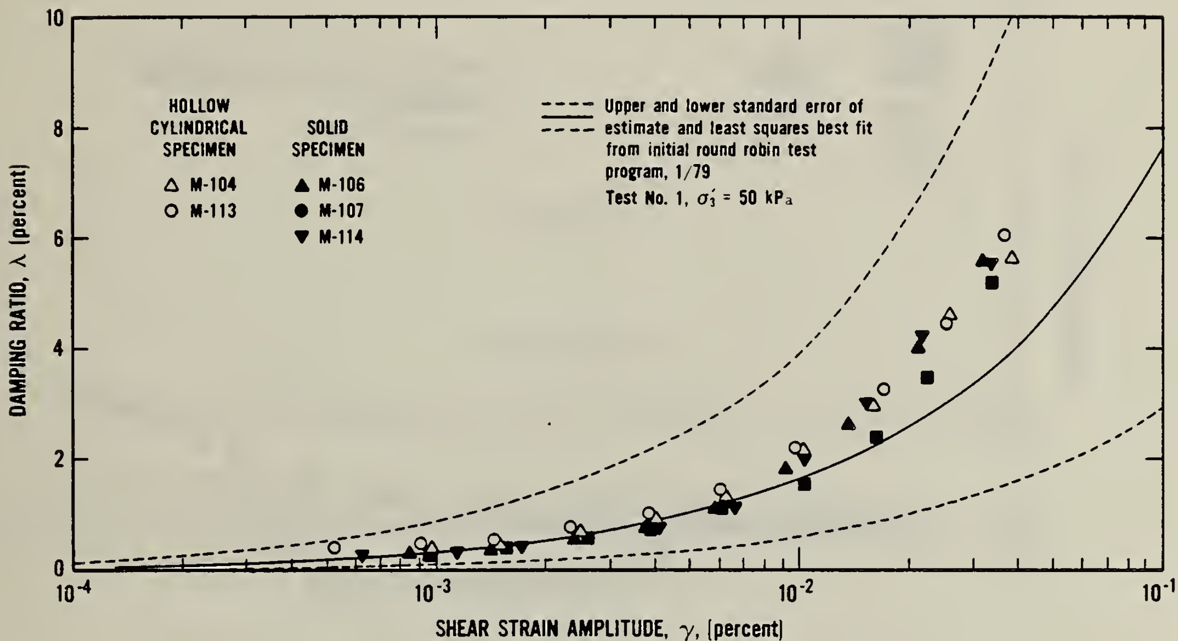


Figure 6 Damping ratio vs. shear strain amplitude, confining pressure at 50 kPa

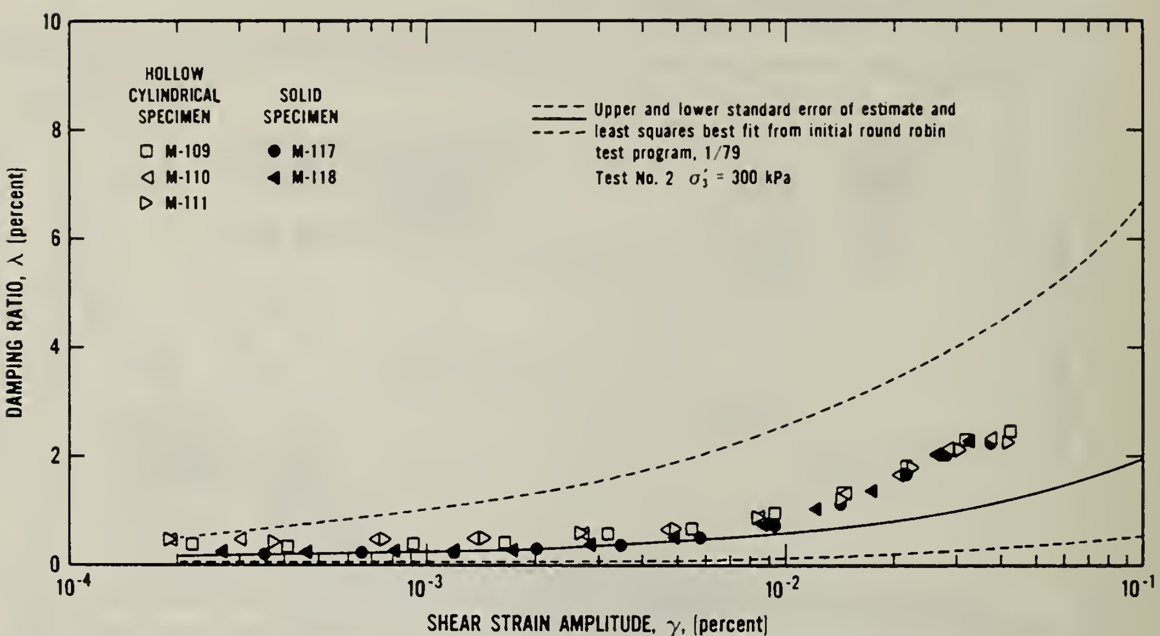


Figure 7 Damping ratio vs. shear strain amplitude, confining pressure at 300 kPa

APPENDIX A

Test Procedure
of
Initial ASTM Resonant Column Round Robin Testing Program

UNIVERSITY OF KENTUCKY
Department of Civil Enginee
Lexington, Kentucky 4050

May 1978

Soil
ASTM

Dear :

We are delighted to have your participation in Resonant Column Testing Program. Enclosed are details of the program and some references on the resonant column testing. The goals of the program center around the possibility of standardizing the test equipment calibration, method of testing, and method of data reduction. The paper by Drnevich, Hardin, and Shippy (enclosed) is an effort toward this standardization. It would be most helpful to ASTM and those involved with the resonant column testing if you evaluated this paper by using it as a guide during this test program.

A second paper (report by Drnevich to WES, Soil Mechanics Series No. 23) is also enclosed. It basically includes the first paper and gives much more detail, data sheets, an example, etc.

If you do not have Monterey No. 0 sand at the present time, you may obtain some by contacting.

Dr. Clarence Chan
Univ. of California at Berkeley
Richmond Field Station
1301 S. 46th Street
Richmond, CA 94804
(415) 231-9406

He will send you a 100 pound bag of the sand by overland freight. You will have to pay the freight charges.

It would be most desireable to perform the tests in a few weeks and return the results to us by early June so that at least a preliminary report can be made to the Soil Dynamics Committee at the ASTM meeting, D-18.09, in late June. As a means of helping us plan our report, complete the attached sheet immediately and return it to us.

If you wish a card deck of the computer program for data reduction, give me a call, and we'll send you one. If you wish, we can run your data through the program here. Be sure to send us the completed data sheets as requested in the procedure.

Thanks again for your willingness to participate. Don't hesitate to call if you have any questions or problems.

Sincerely,

Vincent F. Drnevich

Enclosures

RESONANT COLUMN TESTING PROGRAM
OUTLINE

Number of tests: Two (2) tests are proposed for this program.

Test Material: Monterey No. 0 Sand
Monterey Sand Company
Sand City, California

Sand gradation: D_{50} = 0.36mm

Density limits: (determined by C.K. Chan (1), refer to Figure 1) e_{max} =0.85, γ_{min} = 1430.45 Kg/m^3 (89.3 pcf)

e_{min} =0.56, γ_{max} = 1693.15 Kg/m^3 (105.7 pcf)

Sample Preparation Parameters:

Sample preparation: See attachment for procedure.

Specimen: Uniform circular cross section with ends perpendicular to the axis of the specimen.

Sample Diameter: Minimum diameter of 33mm (1.3in).

Height to diameter ratio: Not less than 2 nor more than 7.

Initial specimen density: Both tests will be prepared dry to 60% relative density.

Testing Parameters:

Strain range: 10^{-4}% to the largest for the apparatus.

Saturation: No saturation, both tests will be run dry.

Confining stress: Both tests will be applying confining stresses of 50, 100, 150, and 300 KPa. See attached page for test procedure.

Stabization Time: Fifteen minutes after application of the load is required.

PROCEDURE FOR PREPARING THE RECONSTITUTED COARSE-GRAINED SOIL SPECIMEN (SAND)

INTRODUCTION

This method of preparing coarse-grained specimens for resonant column testing incorporates procedures for obtaining specimens with uniform density throughout and with minimum tendency for particle segregation.

Specimens can be prepared in a mold as shown in Figure 2. Most samples prepared in a mold at relative densities above about 30% percent will have sufficient strength to allow them to be transported and set up in the resonant column apparatus without any meaningful change in their dry unit weight. The sample should be placed in a rubber membrane lined mold that is placed on the resonant column bottom platen. A vacuum should be applied through the mold to draw the membrane to the mold throughout the placement process.

PROCEDURE

1. Assemble and check out all the necessary apparatus to be used in preparing the test specimen. Determine the average thickness of the membrane by measuring it at two diametrically opposed postions near both ends and average the four values. Measure the mold by determining the I.D. (taking into account the membrane thickness) and height (accounting for the two platens). Calculate the volume based on these measurements.

2. Determine the total required dry weight of the material as follows:

$$W_d = \gamma_d (V)$$

Where:

W_d = Total dry weight of the material
γ_d = Required dry unit weight of the test material
V = Final volume of the placed material before pressurizing

From the definition of relative density and figure 1 for Monterey No. 0 Sand, the required dry density for the testing program is 1577.34 Kg/m^{-3} (98.47 pcf), assuming 60% relative density. With the total known volume of the sample from step 1, the total required dry weight can be obtained for each test.

3. Weigh out the proper amount of material as determined in step 2.

4. A special cylinder with a #10 sieve attached to one end as shown in figure 2a is placed into the mold which has the rubber membrane and bottom platen attached (figure 2b). A vacuum is connected to the mold and retained until the process is complete. The cylinder is filled with the weighed sand from step 1 while it sits on the bottom platen. Then the cylinder is slowly raised, and the mold is tapped as the sand flows out. Several trials may be necessary to determine the amount of tapping required to achieve 60% relative density uniformly throughout the specimen. See figure 2 for the required dimensions and figure 3 for the calculations to determine the correct cylinder height and diameter in accordance with the test requirements.

5. When the total material is placed in the mold, the top platen should be put into place, and the rubber membrane adjusted around the platen. If the specimen was constructed outside the apparatus, it is placed into the resonant column apparatus with vacuum still attached to the mold. When in place, remove the vacuum on the mold and attach a vacuum of 34.5 kPa (5.0 psi) to the bottom platen. (If no vacuum regulator exists for the vacuum system, apply a full vacuum and note it on the data sheet. Step 10 should be skipped for this case.) The mold can then be removed from the specimen when the vacuum has been obtained in the specimen. Extreme caution should be used to prevent disturbance.

6. Measure the dimensions of the specimen. Measure the length at two diametrically opposed postions and average them. Measure the diameters at three elevations and at 90° orientations (if Pi-tape is not used) and average these. Subtract twice the average membrane thickness from the average diameter to get the net specimen diameter.

7. Calculate the dry density of the specimen using the weight of the sand placed and the dimensions determined in step 6 above. This dry density is the one to be reported for the test.

8. Complete the assembly fo the apparatus.

9. Apply a cell pressure of 15.5 kPa (2.25 psi).

10. Reduce the vacuum to the pore space from 34.5 kPa (5 psi) to 17.24 kPa (2.5 psi). Then increase the cell pressure by 17.24 kPa (2.5 psi).

11. Remove the vacuum and increase the cell pressure to 50 kPa (7.25 psi).

TEST PROCEDURE FOR THE RESONANT COLUMN TEST

INTRODUCTION

Two, almost identical, tests will be performed. Both tests will utilize identical dry specimens, prepared according to the instructions of the previous section. Confining pressures will be applied in seven stages 50 kPa (7.25 psi), 100 kPa (14.5 psi), 150 kPa (21.75 psi), 300 kPa (43.5 psi), 150 kPa (21.75 psi), 100 kPa (14.5 psi), and 50 kPa (7.25 psi). Both tests will involve vibrating the specimen, at each stage starting at 50 kPa (7.25 psi). For the first specimen, vibration at each stage will be applied such that the modulus and damping, as a function of strain amplitude, can be determined. For the second specimen during the stages associated with ascending confining stresses (except for 300 kPa), only low amplitude vibrations (strain amplitudes less than 0.001%) will be applied. Hence for both specimens, modulus and damping versus strain amplitude will be determined at the largest pressure and for each stage during descending pressures. For the first specimen, these data will also be obtained for the stages of ascending pressure. For the second specimen, only the modulus and damping at strains less than 0.001% will be obtained for the first three stages.

DETAILS OF TESTING PROCEDURE FOR EACH PRESSURE STAGE

1. Allow a stabilization time of 15 minutes after applying the confining stress.

2. Apply a low amplitude vibration and adjust the frequency of the resonance. (See Drnevich, Hardin, and Shippy (enclosed) for the definition of resonance). Strain amplitudes must be kept below 0.001% for this step. Record the appropriate data. (Enclosed data sheets may be used to record this information).

3. For those stages where the modulus and damping are to be determined versus strain amplitude, the amplitude of vibration is increased by approximately 50% (increasing the power to the oscillator by 50% will accomplish this). Adjust the frequency for resonance and record the appropriate data. Continue increasing the amplitude of vibration by 50 % of the previous value, adjusting the frequency for resonance, and recording the data until the maximum amplitude capability of the apparatus is reached. The time at which each reading is taken should be recorded, and the time between readings should be kept relatively constant. A time interval between readings of two minutes is recommended. After vibration at high amplitudes, vibrate at low amplitude

(strains less than 0.001%). Adjust the frequency for resonance and record the data. Damping may be measured by the magnification factor method (analytical), or the amplitude decay method, or both. It may be desirable to use the magnification factor method throughout, and use the ampitude decay method once, say at strains of 0.01%, as a check on the magnification factor method.

DETAILS OF DATA REDUCTION AND PRESENTATION

Since one of the purposes of this program is to evaluate the paper by Drnevich, Hardin, and Shippy as a potentail ASTM standard, it is asked that the data be reduced using procedures given in the paper. Each laboratory may also wish to reduce the data according to their own established procedures. To aid those who may wish to use the computer program, a card deck will be sent upon request. In the event that access to a computer (or the program) is not convenient, copies of the completed Apparatus and Specimen Information Sheets, Data Sheets, and Intermediate Calculation Sheets may be sent to Vincent Drnevich at the Univeristy of Kentucky where they will be run free of charge.

Reduced data are to be plotted on the enclosed sheets and returned with copies of the Apparatus and Specimen Information Sheets, Data Sheets, Intermediate Calculations Sheets, and Final Calculations Sheets for all the data obtained.

On the log-log paper provided, plot the shear modulus obtained at strains less than 0.001% (from the first data of each stage) versus the confining stress. Distinguish between specimen 1 and specimen 2 and between the data obtained during ascending pressure and those during descending pressure. (The unlabelled log-log paper may be used to aid in plotting on the labelled paper).

For each stage where modulus and damping are obtained as a function of strain amplitude, plot the results on the sheets provided. Be sure to label each curve, identifying the specimen number, confining stress, and whether on ascending or descending pressure (for specimen one). (Unlabelled semi-log paper may be to aid in plotting points).

FIGURE A-1

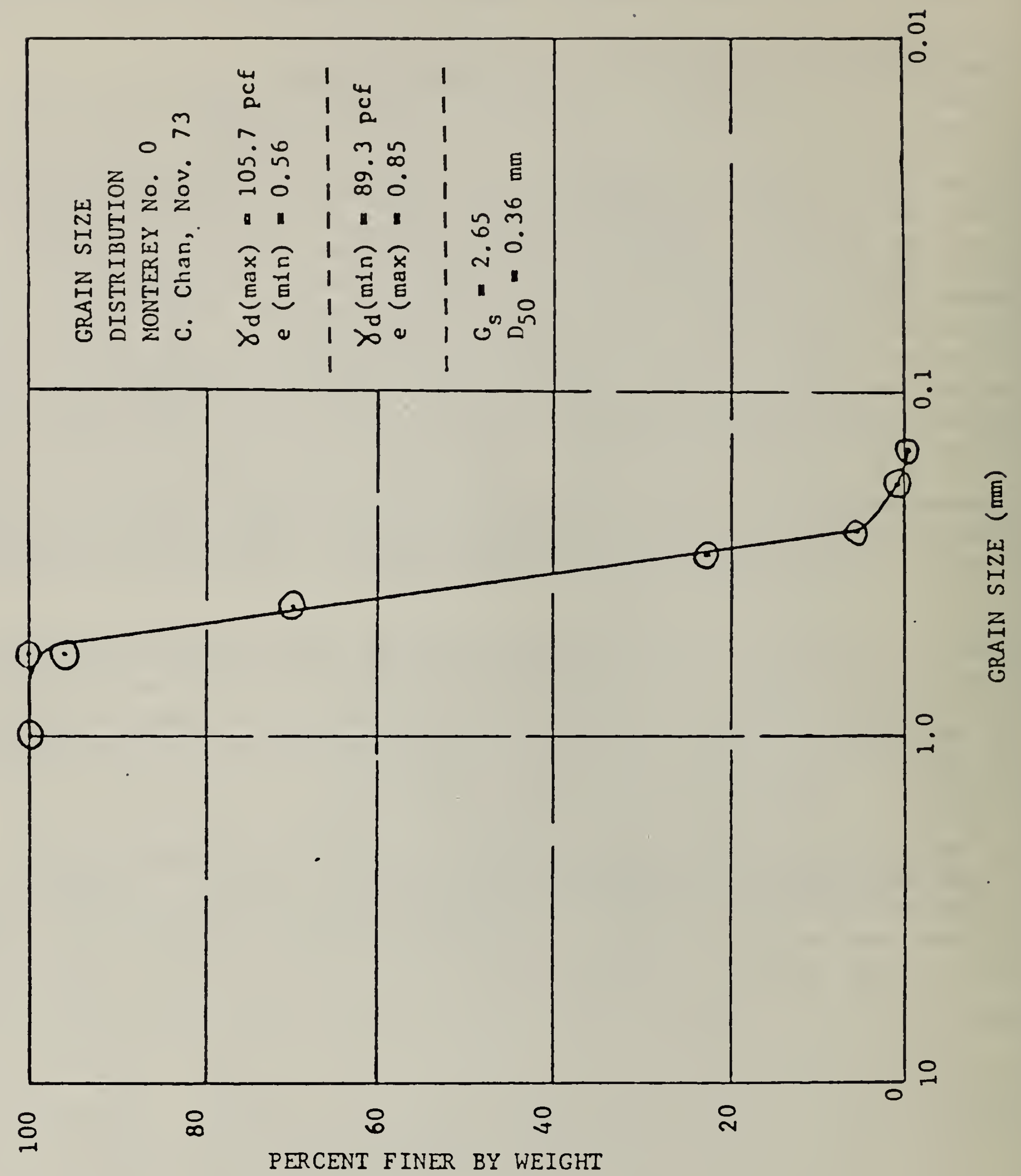
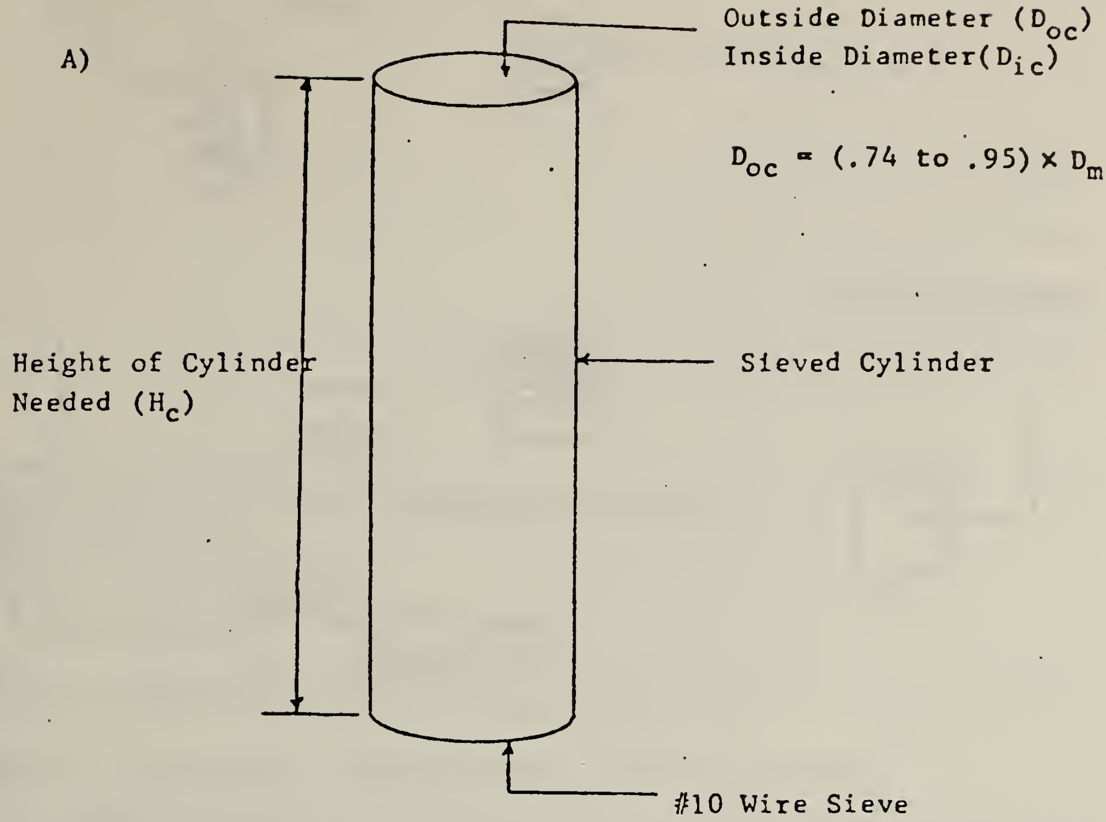

GRAIN SIZE
DISTRIBUTION
MONTEREY No. 0
C. Chan, Nov. 73
γ_d(max) = 105.7 pcf
e (min) = 0.56
γ_d(min) = 89.3 pcf
e (max) = 0.85
G_s = 2.65
D_{50} = 0.36 mm
100
80
60
40
20
0
PERCENT FINER BY WEIGHT
10
1.0
0.1
0.01
GRAIN SIZE (mm)

FIGURE A-2

A)


Outside Diameter (D_{oc})
Inside Diameter(D_{ic})
D_{oc} = (.74 to .95) × D_m
Height of Cylinder Needed (H_c)
Sieved Cylinder
#10 Wire Sieve

B)

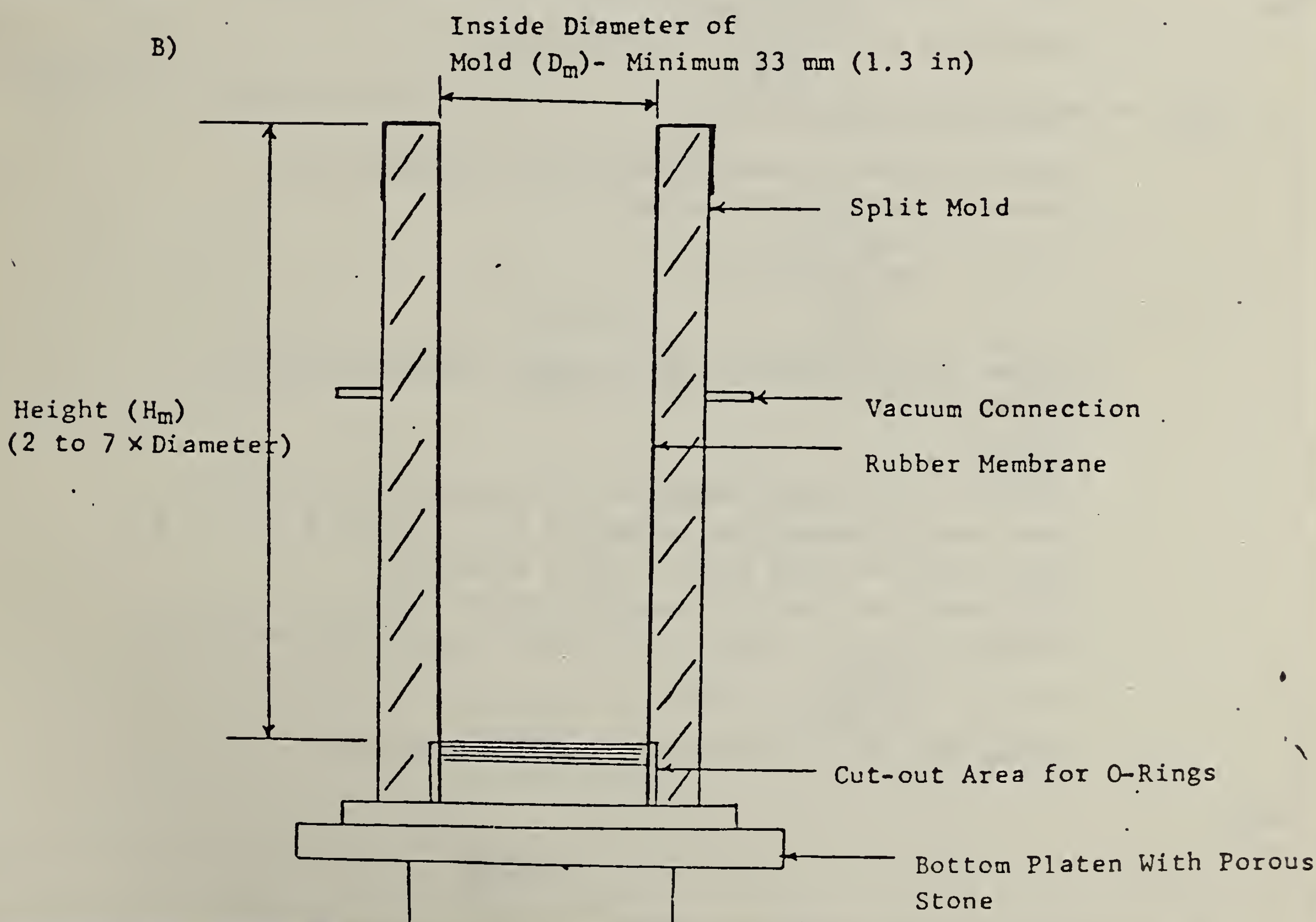
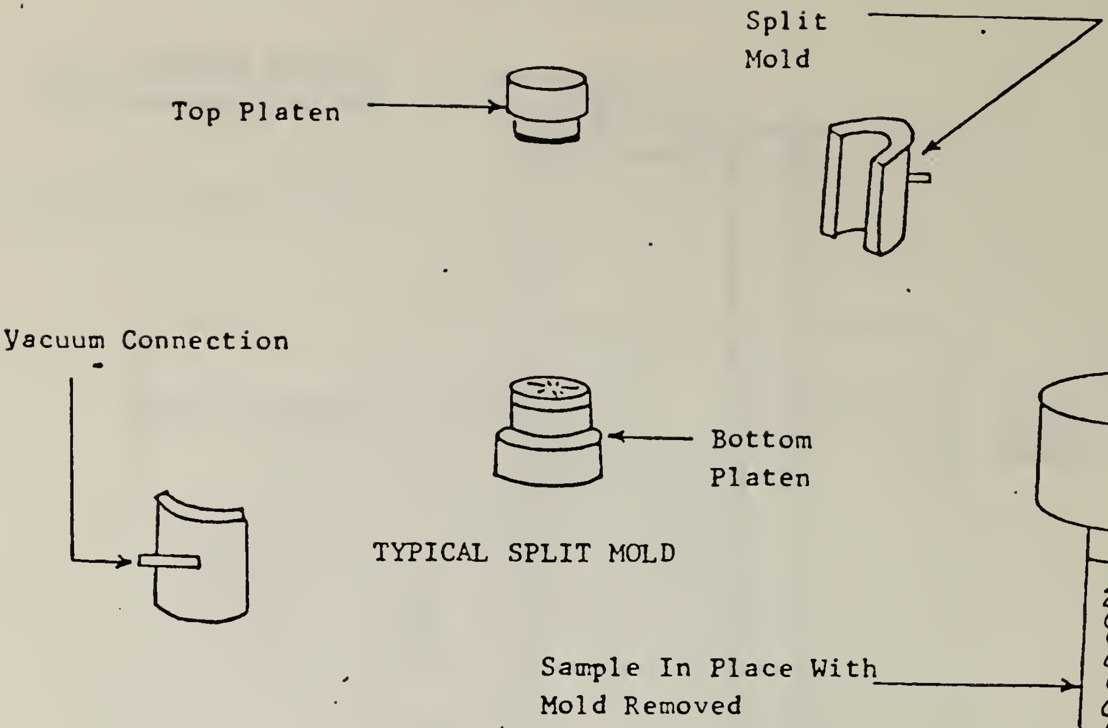
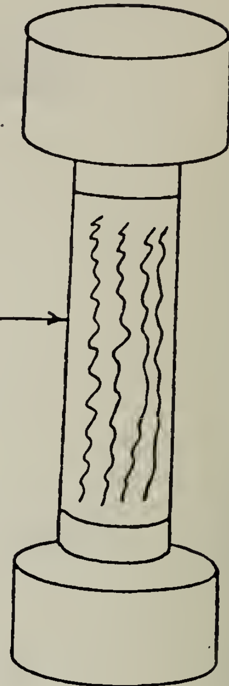

Inside Diameter of Mold (D_m)- Minimum 33 mm (1.3 in)
Split Mold
Height (H_m) (2 to 7 × Diameter)
Vacuum Connection
Rubber Membrane
Cut-out Area for O-Rings
Bottom Platen With Porous Stone

FIGURE A-3



TYPICAL SPLIT MOLD



Assume a 15% area ratio for cylinder wall thickness.

$$\text{Area Ratio} = \frac{D_{oc}^2 - D_{ic}^2}{D_{ic}^2} \times 100\% \leq 15\%$$

Therefore, $D_{ic} \geq 0.93\ D_{oc}$

And the volume of the cylinder must be equal to or greater than the mold volume.

$$\text{So, } H_c = \frac{D_m^2 \ H_m}{D_{ic}^2}$$

Assume an extra 20% for H_c to assure enough cylinder height.

EXAMPLE:

Mold I.D. = 2", Mold Height = 4", Cylinder O.D. = 1.9"

Check the Cylinder O.D. to Mold I.D. = 1.05, O.K.

Next Check the Area Ratio: $D_{ic} = 0.93\ D_{oc}$

Therefore, the smallest possible D_{ic} = 1.77"

Assuming the I.D. found to be used is equal to 1.80", O.K.

$$\text{So, } H_c = \frac{(2)^2(4)}{(1.80)^2} = 4.94''$$

Adding 20%, H_c = 5.93" for the cylinder height

From: ________________________________

____

____

____

Tel. No. ____________________________

To: Dr. Vincient P. Drnevich
Dept. of Civil Engineering
214 Anderson Hall
University of Kentucky
Lexington, Ky. 40506

______ We have received all your materials.

______ We have sufficient Monterey No. 0 sand on hand.

We anticipate that testing will begin _________, 1978 and will be completed by __________, 1978. Results will be to you by _________, 1978.

______ We would like to have a card deck of the computer program sent to us.

Signed ____________________.

Date ____________________.

The following material is enclosed for the resonant column "round robin" testing program:

1. Testing Program Outline:
   a) Test Material
   b) Samples Preparation Parameters
   c) Testing Parameters

2. Data Sheets:
   a) Specimen data
   b) Resonant Column Test Sheet
   c) Intermediate Calculations Sheet
   d) Final Calculations Sheet
   d) Amplitude Decay Data Sheet

3. Test Result Reporting Forms (graphs):
   a) Shear Modulus vs Shear Strain
   b) Hysteretic Damping vs Shear Strain
   c) Maximum Shear Modulus vs Effective Normal Stress
   d) Five-cycle Semi-log Paper

4. Drnevich, V.P., 'The Resonant Column Test' Report to the U.S. Army Corps of Engineers, Contract No. DACW 39-77-m-1687, September 1977.

5. Drnevich, V.P., 'Resonant Column Testing-Problems and Solutions', University of Kentucky, Lexington, Kentucky.

6. Drnevich, V.P., Hardin, B.O., and Shippy, D.J., 'Modulus and Damping of Soils by the Resonant Column Method', Paper submitted to the ASTM Symposium on Dynamic Soil and Rock Testing in the Field and Laboratory for Seismic Studies, 1977 Annual Meeting of ASTM, Denver, June, 1977.

If additional information is needed, please contact me at:

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Lexington, Kentucky 40506

(606) 257-1958

1. Drnevich, V.P.,"Resonant Column - Problems and Solutions," ASTM Special Technical Publication, STP 654, October, 1978.

2. Drnevich, V.P.,"Resonant Column Test," Misc. Paper S-78-6, U.S. Army Corps of Engineers, Waterways Experiment Station Contract No. DACW39-77-M-1687, August, 1978, 63 pages.

3. Drnevich, V.P., Hardin, B.O., and Shippy, D.J.,"Modulus and Damping of Soils by the Resonant Column Method," ASTM Special Technical Publication STP 654, October, 1978.

4. Hall, J.R., Jr., and Richart, F.E., Jr.,"Dissipation of Elastic Wave Energy in Granular Soils," J. of the Soil Mechanics and Foundations Div., ASCE, Vol. 89, No. SM6, Proc. Paper 3698, November, 1963, pp. 27-56.

5. Hardin, Bobby O., "The Nature of Damping in Sand," Journal of the Soil Mechanics and Foundations Div., ASCE, Vol. 91, No. SM1, Proc. Paper 4206, January, 1965, pp. 63-97.

6. Hardin, Bobby O.,"Suggested Methods of Test for Shear Modulus and Damping of Soils by the Resonant Column," ASTM Special Technical Publication, STP 479, 1970, pp. 516-529.

7. Hardin, B.O., and Scott, G.D.,"Generalized Kelvin-Voigt Used in Soil Dynamics Study," Journal of the Engineering Mechanics Div., ASCE, Vol. 92, No. EM1, Proc. Paper 4678, February, 1966, pp. 143-156.

8. Shannon, W.L., Yamane, G., and Dietrich, R.J.,"Dynamic Triaxial Tests on Sands," Proc. of the First Pan American Conference on Soil Mechanics and Foundation Engineering, Mexico City, Vol. 1, 1959, pp. 473-489.

9. Stevens, H.W.,"Suggested Method of Test for Some Viscoelastic Properties of Materials, Especially Frozen and Nonfrozen Soils, Under Vibratory Loads," ASTM Special Technical Publication, STP 479, 1970, pp. 530-546.

APPENDIX B

Draft Report
of the
Initial ASTM Resonant Column Round Robin Testing Program

RESULTS OF RESONANT COLUMN ROUND ROBIN TESTING PROGRAM

Dr. Vincent P. Drnevich, P.E.
Department of Civil Engineering
University of Kentucky
Lexington, Kentucky 40506

A) Purpose

1) Evaluate accuracy of the resonant column method;
2) Evaluate the draft standard on this method(Ref. 1);
3) Provide results that other laboratories can use to "calibrate" their apparatus and data reduction techniques;
4) Determine what problems are likely to occur with the method;
5) Check out the results from different apparatus having different boundary conditions and specimen sizes.

B) Scope

1) Perform two tests on Monterey #0 sand, placed by the dry tap method* at a relative density of 60% (dry mass density of 1580 Kg/cu. m);
2) In both tests, confining stresses were staged according to the following sequence: 50 kPa, 100 kPa, 150 kPa, 300 kPa, 150 kPa, 100 kPa, and 50 kPa (7.25 psi, 14.5 psi, 29.0 psi, 43.5 psi, 29.0 psi, 14.5 psi, and 7.25 psi);
3) In test 1, testing was performed over a range of strain

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*See Appendix 1. for details of this method.

amplitudes from low to high for all stages;

4) In test 2, testing at the first 3 stages was carried out only at low strains (less than 0.001 percent). At the highest pressure (300 kPa) and at all subsequent stages (150 kPa, 100 kPa, and 50 kPa), testing was done at strains from low to high as in test 1.

5) Three government, four university, and four consultants laboratories were invited to participate. One university and one consultant did not respond. Further, one university only completed one of the two tests. Their data was not used in the analyses. One government laboratory performed the tests on two different apparatus, having different specimen sizes and boundary conditions. Results of both their tests were used. Another laboratory performed tests using both longitudinal and torsional vibration, sequentially on the same specimens at each stage. Although the test specifications were written to allow for longitudinal excitation, this was the only laboratory to provide results for that excitation mode. No analysis was made of the longitudinal excitation data.

6) The types of apparatus, the boundary conditions, and the specimen sizes are given in Table 1. The apparatus used represent all those in common use. If data from these apparatus and specimen sizes are comparable, then it can be said that the results are device and specimen size independent.

C) Result of Test Program

1) Specimen Densities: The densities reported by each of the laboratories for each of the specimens is given in Table 2. The mean density was 1585 Kg/cubic m (98.9 pcf) with the standard deviation of 12 Kg/cubic m (0.7 pcf). This density corresponds to a void ratio of 0.678 and a relative density of approximately 60%.

2) Initial Tangent Shear Modulus vs. Mean Effective Confining Stress: The results of the ascending pressure stages of test 2 were used for this because only vibrations at low strains were applied to the specimen. The results are shown in Fig. 1. along with the least squares best fit and the upper and lower standard errors of estimate. A 0.93 coefficient of correlation shows that the data fit quite well. As a reference, the Hardin Equation (Ref. 2) is also plotted on this graph. It can be concluded that with the exception of a few outlying points, that initial tangent modulus can be measured with good accuracy and that the Hardin Equation accurately describes the initial tangent modulus of Monterey sand.

If the data from test 1 were used, the scatter would have been significantly worse due to the different amounts of prestraining applied by each laboratory. Prestraining at high amplitude at a given confining stress affects the low amplitude (initial tangent) modulus at other subsequent confining stresses. The magnitude of the effects is dependent on the level and the number of cycles of high amplitude shear strain. From the results of this program, it appears that prestrain effects are not significant if shear strain amplitudes are kept less than 0.01 percent.

3) Shear Modulus vs. Shear Strain Amplitude: These results are best represented by test 1 with the confining stress of 50 kPa (7.25 psi) and by test 2 with the confining stress of 300 kPa (43.5 Psi) because the specimens had not undergone any high amplitude prestraining before these stages. The results are given in Figs. 2 and 3. The scales in both figures are the same but there is a suppressed zero on the ordinate in Fig. 3. The agreement among the laboratories appears to be quite good for the most part. The least squares best fit lines and the upper and lower standard errors of estimate are shown on both figures. The least squares best fit lines for both confining stresses are plotted in Fig. 4 where they are compared with curves that are predicted by use of design equations of Hardin and Drnevich (Ref. 3). Here again it can be said that these design equations can accurately represent Monterey sand.

If the modulus values for both curves are normalized by dividing them by the initial tangent modulus, the two curves given in Fig. 5 result. These curves show that modulus reduction with shear strain amplitude is a function of confining stress. The effects of confining stress can be removed by use of the concept of reference strain (Ref. 3) which normalizes the abscissa values. When normalized modulus is plotted versus normalized shear strain, a single curve results as shown in Fig. 6.

4) Damping Ratio vs. Confining Pressure: Damping ratio versus confining pressure results are shown in Fig. 7. In this figure, only the results from test 1 with confining stress at 50 kPa (7.25 psi) and from test 2 with confining stress at 300 kPa (43.5 psi) are plotted. Actually, the data points in this figure are not the actual ones reported but ones calculated from least squares best fit lines to the damping versus strain amplitude data. This was necessary because accurate measurement of damping when the magnitude of damping ratio is less than one percent is extremely difficult. About the only conclusions that can be drawn from these results is that the damping of Monterey sand at shear strain levels of 0.001 percent is below 1 percent and that damping ratio tends to decrease as confining stress increases.

5) Damping Ratio vs. Shear Strain Amplitude: These results are given in Figs. 8 and 9. Again the data are for test 1 at 50 kPa (7.25 psi) and test 2 at 300 kPa (43.5 psi). The least squares best fit lines and the standard error of

estimate lines are also given. Data scatter in damping values are greater than in modulus values.

D) Discussion of Results

1) The method of specimen construction for density control appears to be quite good.

2) For non-prestrained specimens, shear modulus at low strain amplitude (shear strain = 0.001 percent) can be measured accurately and may be described by use of the Hardin equation.

3) Good correlations among laboratories exist for shear modulus versus shear strain amplitude for non-prestrained specimens. This behavior may also be described by the design equations of Hardin and Drnevich.

4) It is very difficult to obtain accurate damping ratio measurements when damping is below one percent. Several possible reasons for this may include: improper apparatus damping determination in calibration (or disregarding apparatus damping altogether), effects of membranes, and wind and eddy current damping in the torque producing components of the apparatus.

5) It is the opinion of the author that much of the data

scatter in all of the results presented herein could have been reduced if all of the laboratories had followed the calibration and data reduction according to the proposed standard (Ref. 1). Although each laboratory was explicitly asked to do this, a review of the data indicates that several of the laboratories ignored this request and simply ran the tests and reduced the data using old calibrations and data reduction techniques.

E) Conclusions

1) The round robin testing was a most worthwhile activity demonstrating that the resonant column test provides accurate quantitative measurement of shear modulus and shear damping.

2) The test results appear independent of apparatus type and specimen size.

3) The results compare very well with currently available design equations and curves.

REFERENCES

1. Drnevich, V.P., Hardin, B.O., and Shippy, D.J.,"Modulus and Damping in Soils by the Resonant-Column Method," ASTM Special Technical Publication STP 654, ASTM, 1978, pp. 91-125.

2. Hardin, B.O., and Richart, F.E., Jr.,"Elastic Wave Velocities in Granular Soils," J. of the Soil Mechanics and Foundations Div., ASCE, Vol. 89, No. SM 1, February 1963, pp. 33-65.

3. Hardin, B.O. and Drnevich, V.P.,"Shear Modulus and Damping in Soils Design Equations and Curves," J. of the Soil Mechanics and Foundations Div., ASCE, Vol. 98, No. SM 7, July, 1972, pp. 667-692.

Appendix I.

The details for specimen preparation are as follows:

1) Attach a membrane to a bottom platen and place a mold about the membrane.
2) Use a vacuum to pull the membrane to the mold.
3) Place into the mold a special cylindrical tube slightly smaller in diameter than the membrane lined mold with a #10 sieve attached to the lower end.
4) Fill the cylinder with the amount of sand required for the completed specimen.
5) The cylinder is slowly raised and the mold is gently tapped as the sand flows out.
6) The top surface of the sand is leveled off and the top platen is attached.
7) The membrane is pulled up over the top platen, O-rings are used to complete the seal and specimen measurements are made.

TABLE B1

Information on Apparatus, Boundary Conditions and Specimens

Apparatus	No. Used in Program	Boundary Condition	Specimen Sizes (Dia.xLength in mm)
Hardin	4	Fixed Base-Spring Top	36x75, 60x150 70x140
Drnevich	2	Fixed Base-Free Top	50x100 70x140
Shannon & Wilson	1	Spring Base-Free Top	70x150
Stokoe	1	Fixed Base-Free Top	36x75
Soil Dyn. Instr.	1	Spring Base-Free Top	150x300

Table B2

Specimen Sizes and Densities

Laboratory Code	Nominal Specimen Size (Dia.xLgth.) (mm)	Density for Test No. 1 (Kg/cu.m)		Density for Test No. 2 (Kj/cu.m)
1	50.x100.	1590.8		1624.6
2	70.x150.	1579.6		1579.6
3	60.x150.	1587.8		1585.2
4	70.x140.	1581.5		1580.6
5	70.x140.	1587.2		1582.2
6	40.x 75.	1583.6		1595.3
7	60.x150.	1580.4		1568.0
8	36.x 75.	1566.4		1583.4
9	150.x300.	1578.3		1574.0
Mean Values for Each Test		1581.7		1583.1
Standard Deviation for Each Test		7.1		14.9
Mean Value for Program			1584.9	
Standard Deviation for Program			11.8	

Fig. B1

Maximum Shear Modulus vs. Confining Stress
Test No. 2

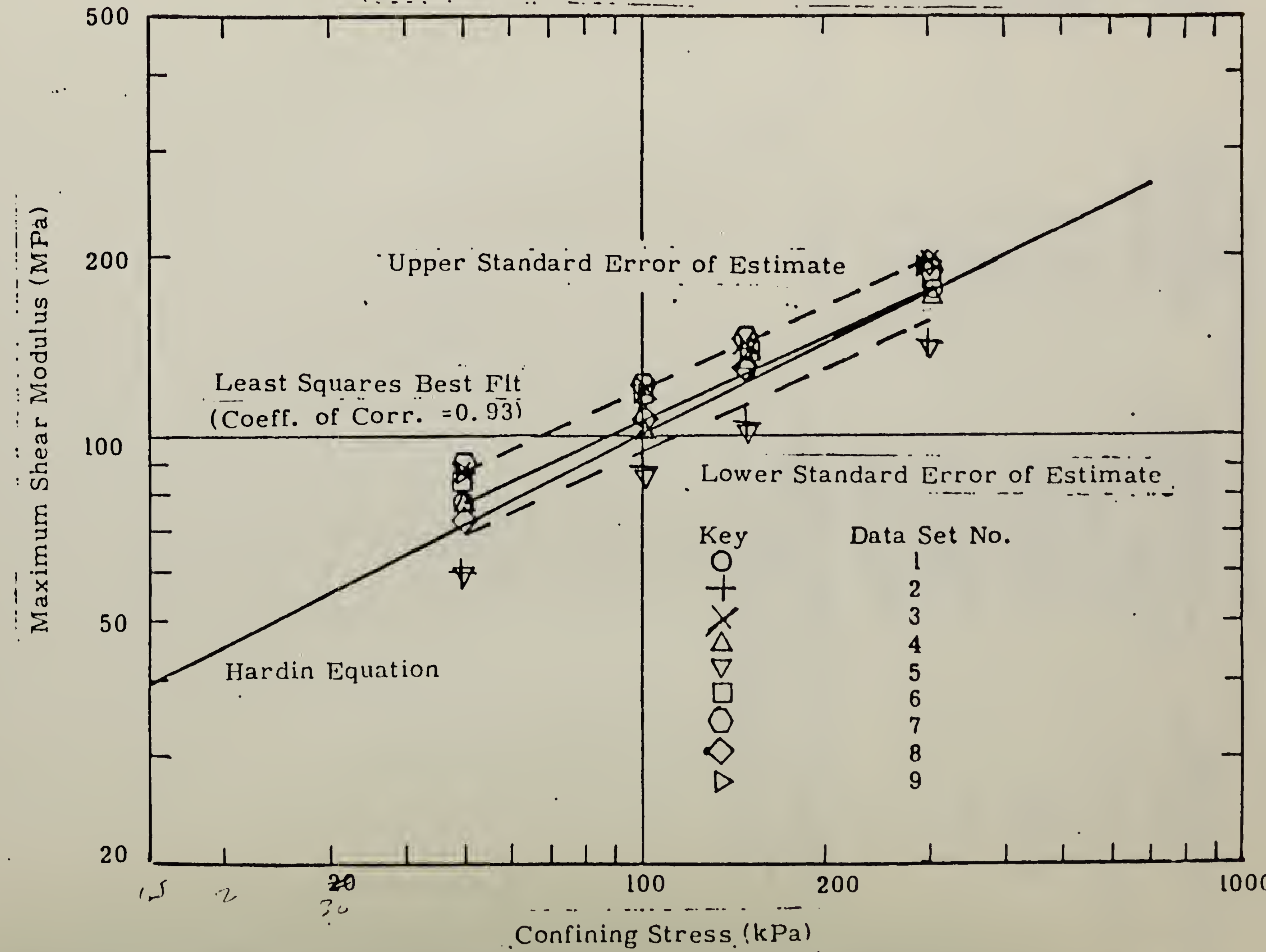


Fig. B2

Shear Modulus vs. Shear Strain Amplitude

Test No. 1, 50 kPa Confining Stress

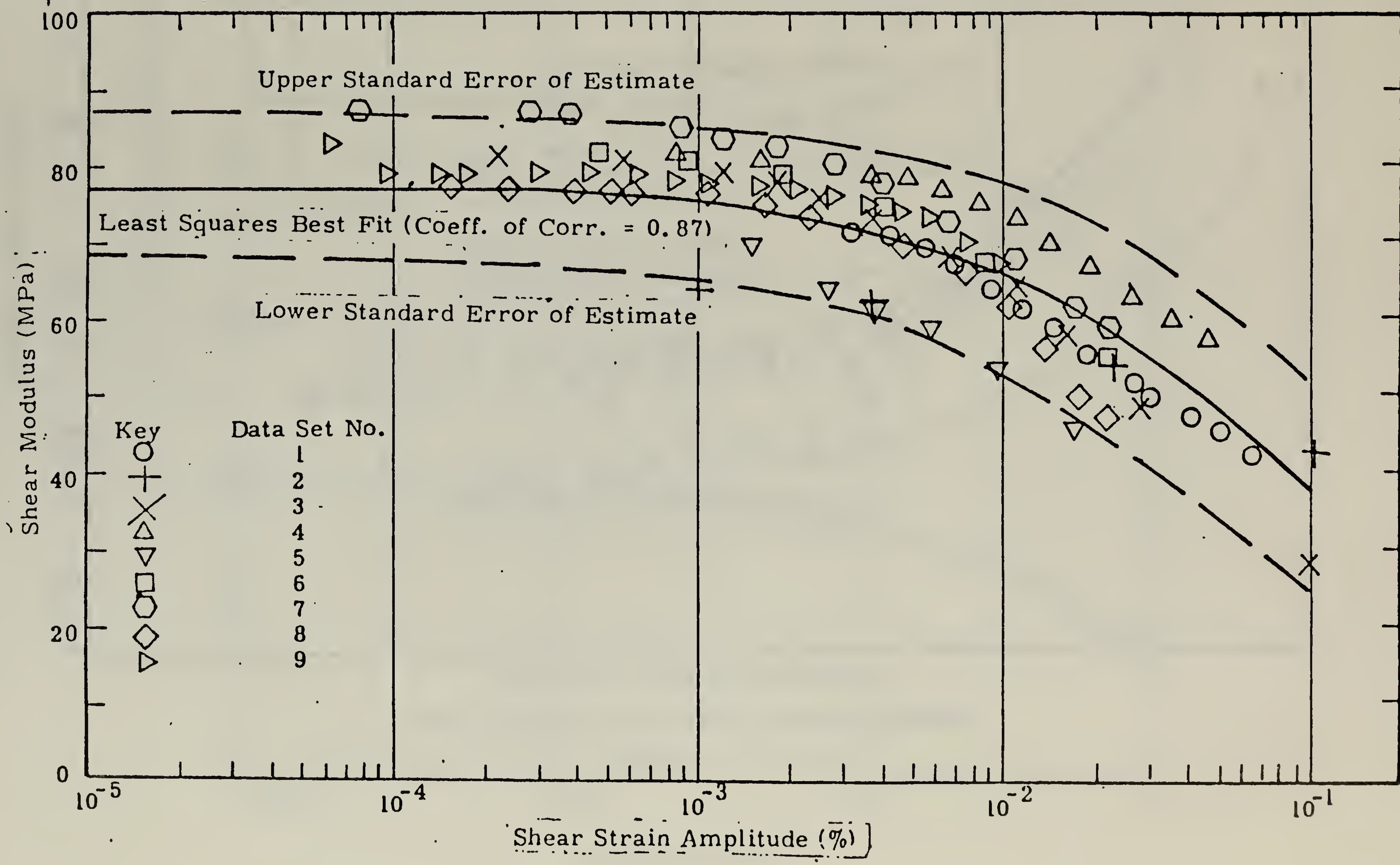


Fig. B3

Shear Modulus vs. Shear Strain Amplitude

Test No. 2, 300 kPa Pressure

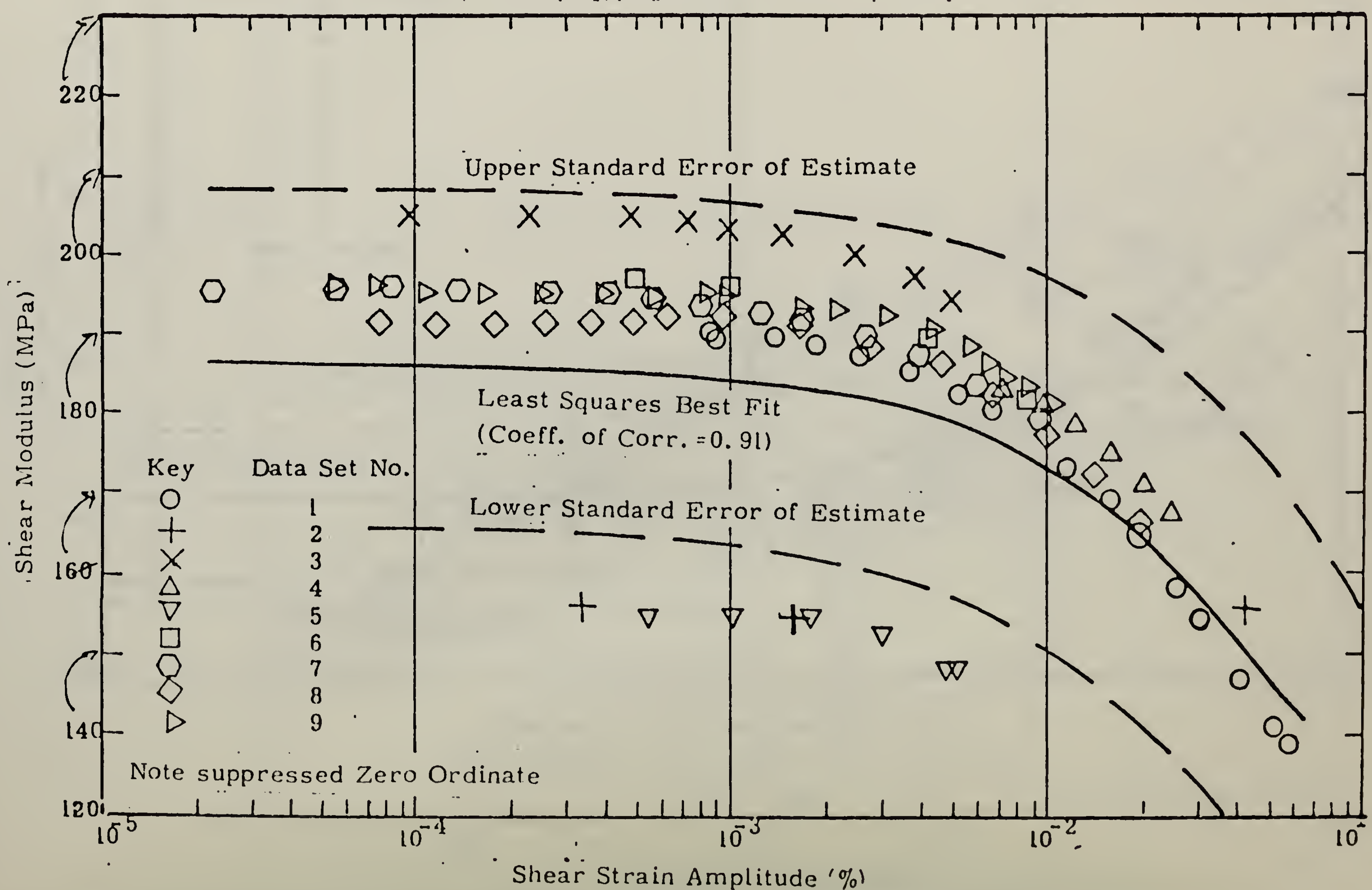


Fig. B4

Comparison of Least Squares Best Fit of ASTM Program with Hardin-Drnevich (1972)

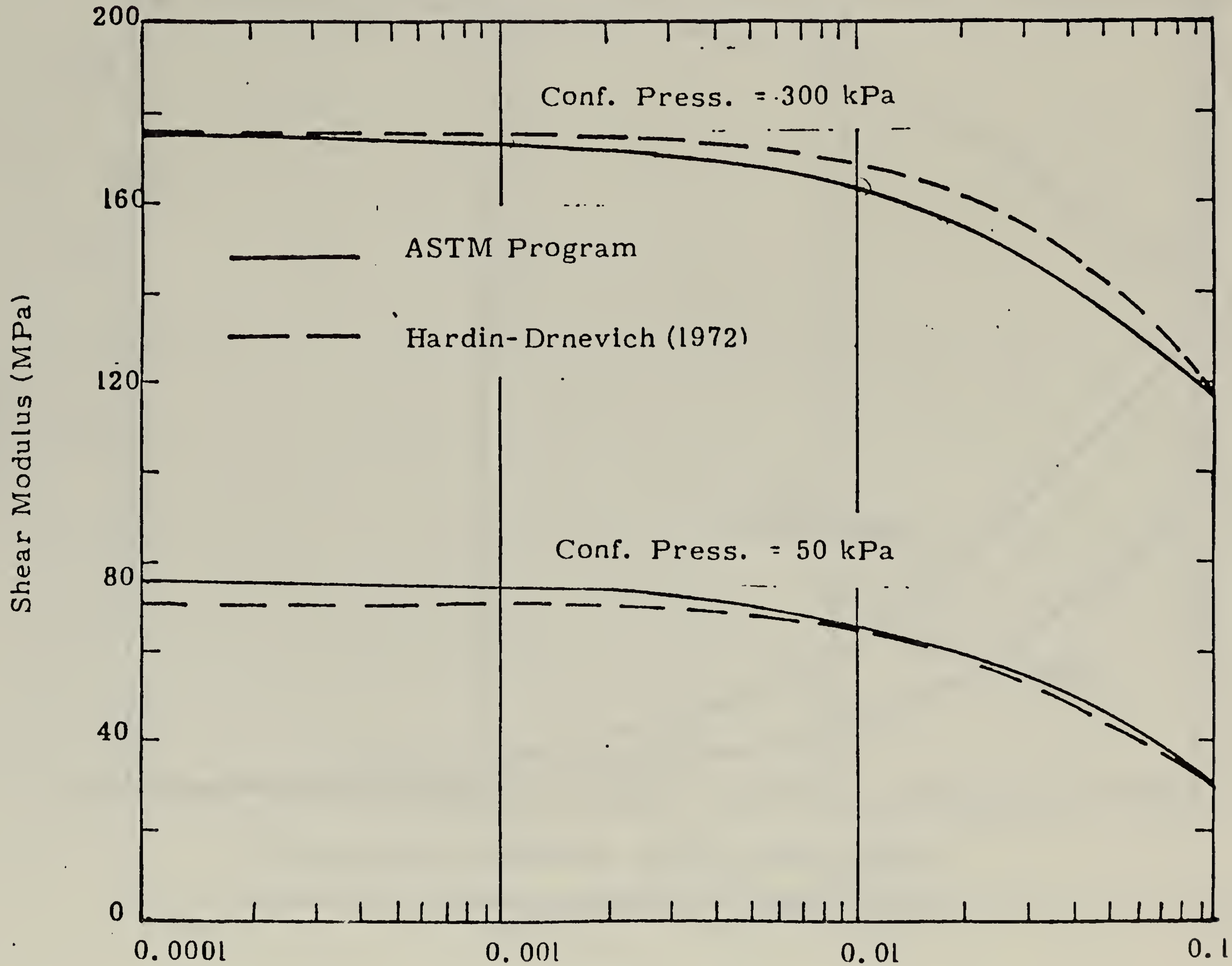
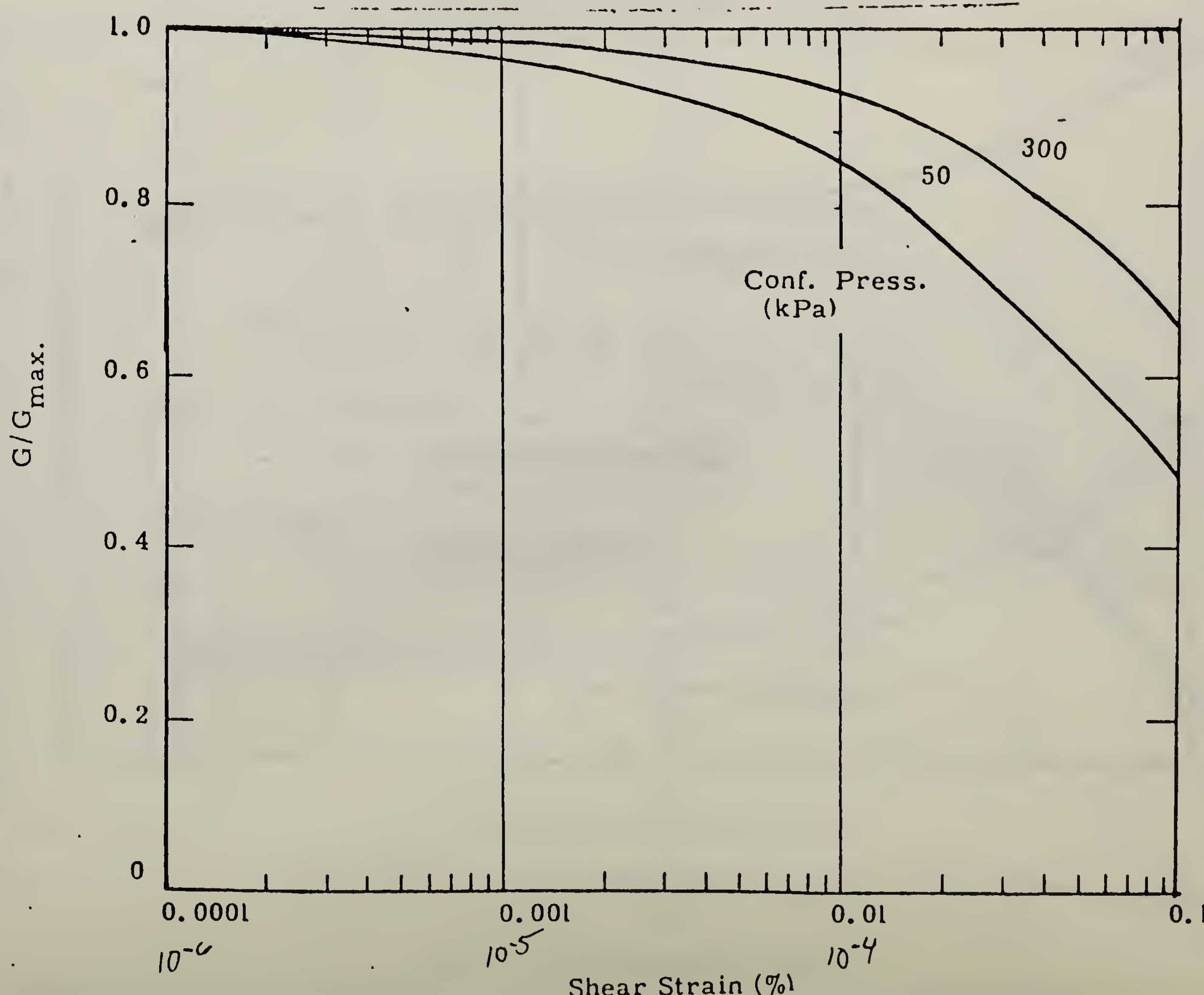


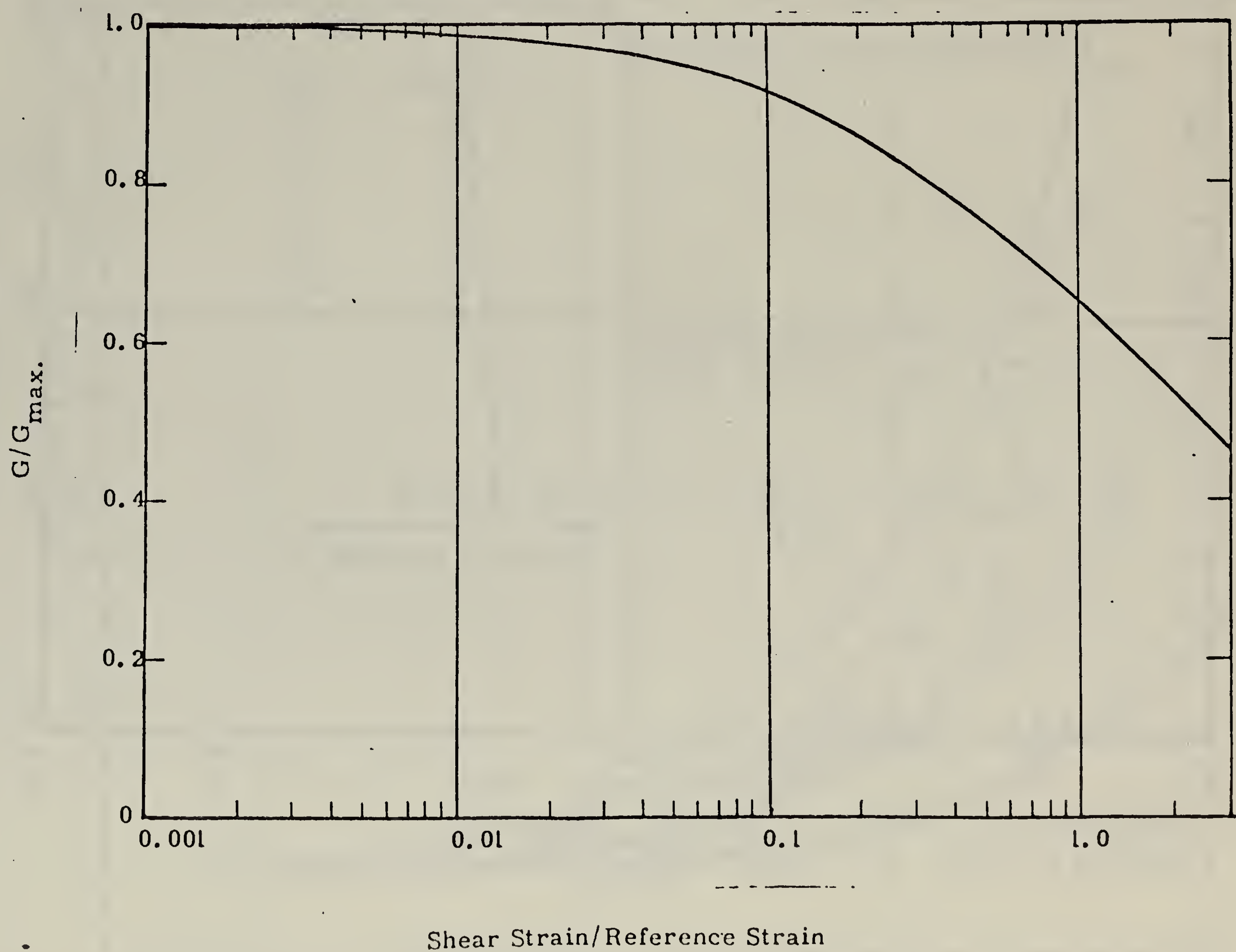
Fig. B5

Normalized Shear Modulus vs. Shear Strain

Least Squares Data Fit, ASTM Test Program



Normalized Shear Modulus .vs. Normalized Shear Strain
Least Squares Data Fit, ASTM Test Program
Confining Stress = 50 kPa and 300kPa



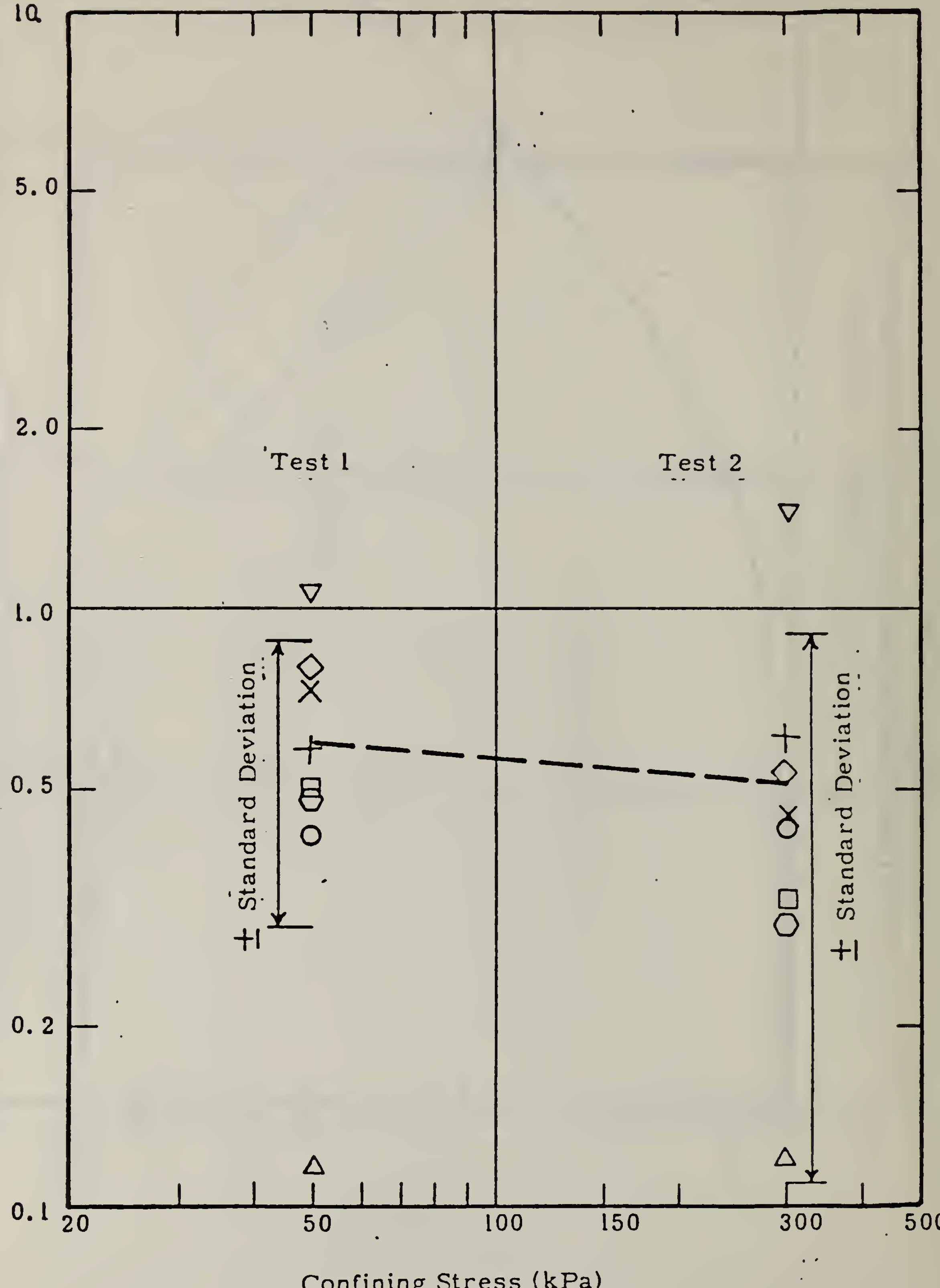


Fig. B7 Damping Ratio at Shear Strain of 0.001% vs. Confining Stress Data Derived from Least Squares Fit Applied Independently to Each Laboratory

Fig. B8
Damping vs. Shear Strain
Test No. 1, 50 kPa Pressure

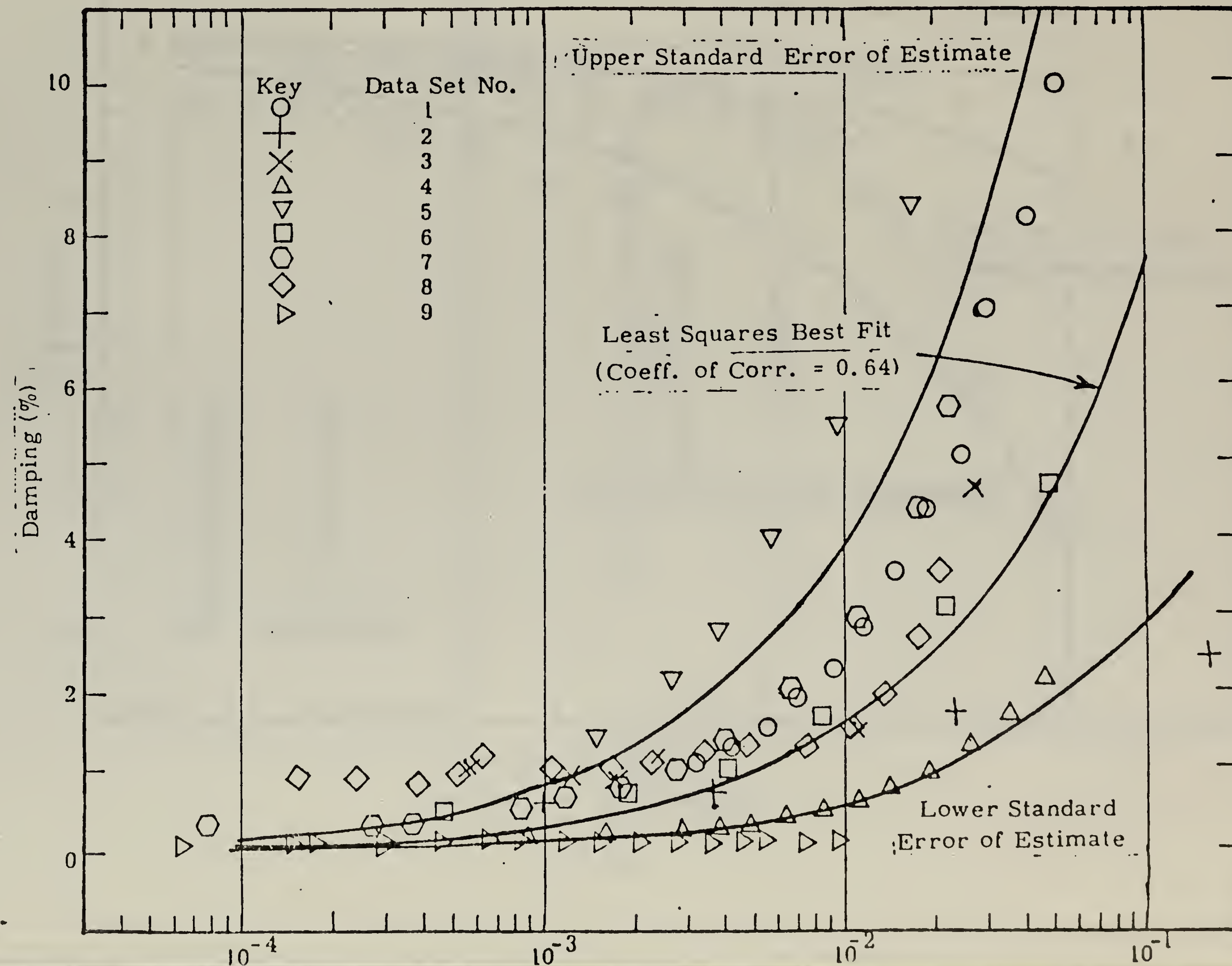
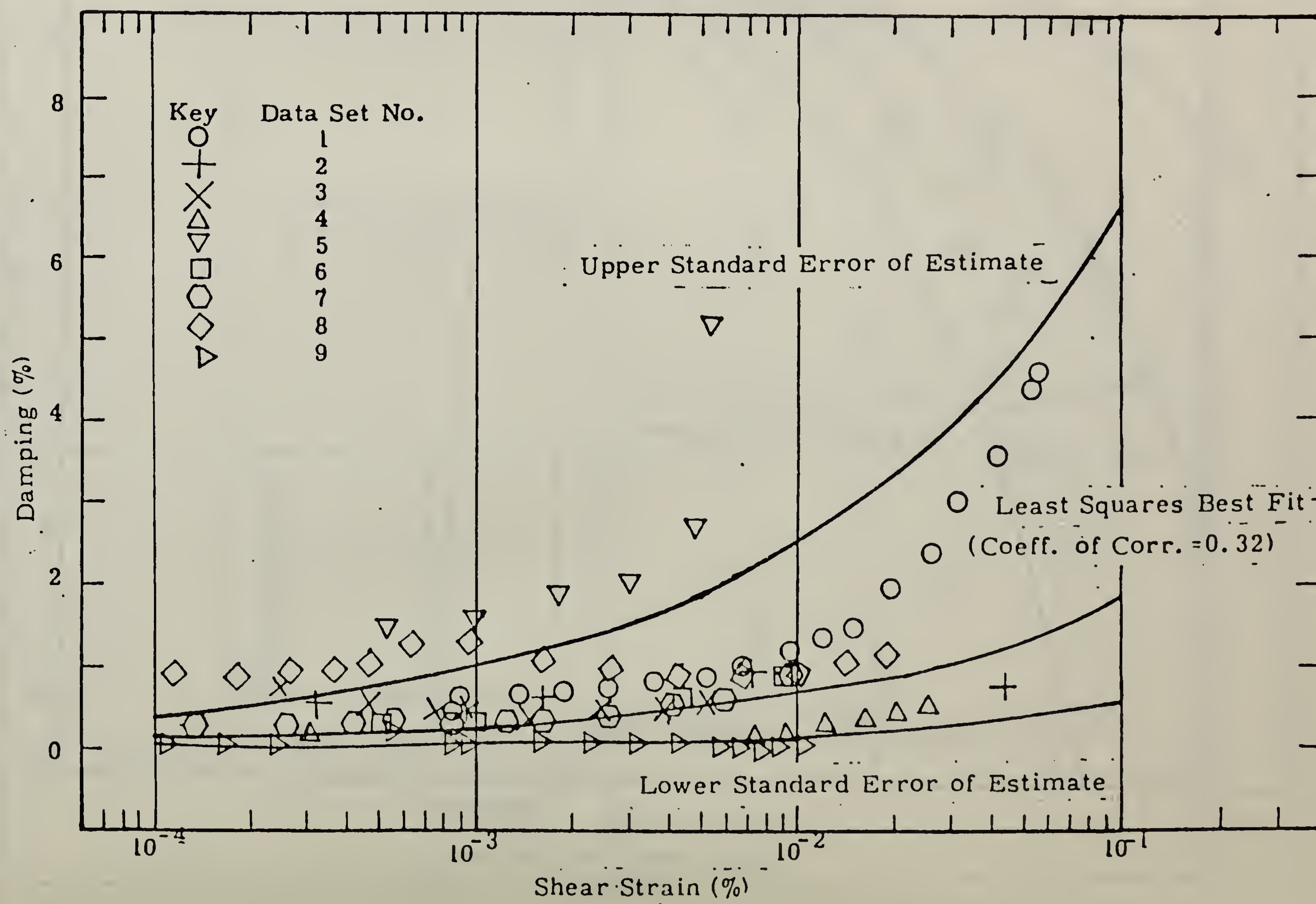


Fig. B9

Damping vs. Shear Strain

Test No. 2, 300 kPa



APPENDIX C

Tabulated Dest Data
from the
NBS Resonant Column Pilot Test Program

Table C.1: G_{max} and Damping Measurements in Resonant Column Testing

Sample No.	Symbol	Specimen Type	Confining Stress, σ_3'	Shear Strain	G_{max}	Damping Ratio, D_T
			kPa	γ, %	MPa	%
M-101	○	hollow cylindrical	11.4	1.20-3	19.6	1.062
			24.3	1.05-3	40.0	0.695
			43.7	8.25-4	53.8	0.561
			72.6	7.28-4	69.6	0.491
			101.1	7.78-4	80.6	0.397
			154.7	6.07-4	96.0	0.427
			199.3	9.90-4	108.8	0.347
			150.2	6.30-4	97.2	0.409
			100.9	7.70-4	79.4	0.405
			49.9	7.90-4	55.6	0.665
			26.4	1.11-3	40.0	0.561
			12.3	1.01-3	26.2	0.936
			101.2	9.10-4	80.5	0.339
M-103	◇	hollow cylindrical	16.0	9.60-4	37.2	0.701
			25.0	8.80-4	42.8	0.665
			15.0	1.00-3	35.7	0.688
			25.0	8.60-4	44.4	0.545
			16.0	9.60-4	36.5	0.714
			25.0	8.70-4	44.4	0.536
			75.0	6.30-4	72.1	0.552
			101.0	6.10-4	82.0	0.497
			149.0	4.90-4	96.3	0.523
			200.0	4.60-4	106.4	0.509
			157.0	5.50-4	98.8	0.473
			99.0	6.80-4	82.0	0.446
			24.0	1.04-3	42.0	0.568
			15.0	1.02-3	33.5	0.726
			100.0	6.30-4	82.0	0.485

Table C.1: G_{max} and Damping Measurements in Resonant Column Testing (cont'd)

Sample No.	Symbol	Specimen Type	Confining Stress, σ_3' kPa	Shear Strain γ, %	G_{max} MPa	Damping Ratio, D_T %
M-107	■	solid	11.1	1.03-3	31.2	0.622
			10.0	1.11-3	29.3	0.612
			26.0	1.01-3	48.0	0.408
			51.0	8.76-4	66.0	0.345
			75.0	7.97-4	80.5	0.311
			74.0	7.97-4	80.5	0.311
			100 .0	5.11-4	91.5	0.426
			149.0	5.20-4	110.5	0.348
			200.0	6.22-4	126.7	0.253
			300.0	6.02-4	148.5	0.186
M-109	□	hollow cylindrical	10.4	1.30-3	29.1	0.714
			10.0	1.25-3	29.8	0.665
			30.0	9.67-4	50.3	0.424
			62.0	9.46-4	70.7	0.309
			92.0	1.05-3	83.9	0.281
			125.0	8.23-4	95.8	0.262
			162.0	9.12-4	105.9	0.214
			193.0	9.00-4	115.1	0.239
			251.0	9.59-4	129.0	0.167
			300.0	2.20-4	139.2	0.400
M-117	●	solid	10.0	6.84-4	28.4	0.512
			43.0	5.89-4	57.9	0.292
			87.0	4.23-4	81.9	0.287
			131.0	2.84-4	97.9	0.358
			180.0	3.51-4	113.6	0.249
			233.0	3.92-4	128.5	0.263
			300.0	3.53-4	144.3	0.195

Table C.2: Shear Modulus, G, and Damping, D_T, Measurements at Confining Stress, σ'_3 = 50 kPa

Sample No.	Symbol	Specimen Type	Shear Strain γ, %	Shear Modulus, G MPa	Damping Ratio, D_T %
M-104	△	hollow	9.77-4	64.3	0.393
		cylindrical	1.45-3	63.3	0.439
			2.51-3	62.4	0.657
			4.08-3	60.4	0.884
			6.30-3	57.5	1.283
			1.02-2	53.7	2.060
			1.60-2	50.1	2.802
			2.61-2	45.0	4.399
			3.85-2	40.9	5.389
M-106	▲	solid	8.46-4	64.6	0.304
			1.41-3	63.3	0.373
			2.40-3	61.9	0.537
			3.77-3	60.6	0.772
			5.86-3	58.0	1.126
			9.20-3	54.2	1.810
			1.37-2	49.3	2.682
			2.13-2	44.7	4.024
			3.20-2	39.2	5.591
M-107	■	solid	9.50-4	62.0	0.339
			1.53-3	60.6	0.395
			2.60-3	59.3	0.561
			3.94-3	58.0	0.756
			6.06-3	56.7	1.044
			1.03-2	54.2	1.549
			1.63-2	50.5	2.373
			2.26-2	45.8	3.503
			3.35-2	40.3	5.168

Table C.2: Shear Modulus, G, and Damping, D_T, Measurements at Confining Stress, σ'_3 = 50 kPa (cont'd)

Sample No.	Symbol	Specimen Type	Shear Strain	Shear Modulus, G	Damping Ratio, D_T
			γ, %	MPa	%
M-113	⊖	hollow	5.25-4	60.9	0.386
		cylindrical	9.06-4	60.9	0.446
			1.46-3	60.0	0.514
			2.37-3	59.0	0.704
			3.87-3	57.1	0.984
			6.07-3	54.3	1.405
			9.79-3	50.7	2.142
			1.70-2	45.5	3.163
			2.53-2	42.2	4.370
			3.68-2	39.0	5.935
M-114	▼	solid	6.31-4	63.4	0.250
			1.15-3	63.4	0.320
			1.72-3	62.1	0.405
			2.63-3	60.8	0.562
			4.15-3	59.4	0.728
			6.68-3	55.6	1.102
			1.05-2	51.9	2.003
			1.55-2	47.1	2.979
			2.18-2	42.6	4.220
			3.35-2	37.2	5.525

Table C.3: Shear Modulus, G, and Damping, D_T, Measurements at Confining Stress, σ'_3 = 300 kPa

Sample	Symbol	Specimen Type	Shear Strain	Shear Modulus, G	Damping Ratio, D_T
			γ, %	MPa	%
M-109	□	hollow	2.22-4	139.2	0.400
		cylindrical	4.08-4	139.2	0.364
			9.12-4	139.2	0.390
			1.66-3	137.7	0.416
			3.17-3	136.2	0.526
			5.43-3	133.3	0.667
			9.32-4	130.4	0.945
			1.45-2	127.6	1.272
			2.18-2	120.6	1.762
			3.17-2	115.1	2.248
			4.22-2	109.8	2.406
M-110	◁	hollow	1.93-4	149.5	0.426
		cylindrical	3.02-4	149.5	0.454
			7.37-4	147.9	0.451
			1.38-3	146.4	0.467
			2.73-3	144.9	0.549
			4.74-3	143.4	0.652
			8.53-3	139.0	0.879
			1.48-2	134.6	1.272
			2.10-2	128.9	1.632
			2.87-2	124.7	2.130
			3.73-2	120.5	2.287

Table C.3: Shear Modulus, G, and Damping, D_T, Measurements at Confining Stress, σ'_3 = 300 kPa (cont'd)

Sample	Symbol	Specimen Type	Shear Strain γ, %	Shear Modulus, G MPa	Damping Ratio, D_T %
M-111	▷	hollow	1.88-4	144.7	0.457
		cylindrical	3.70-4	143.2	0.389
			7.48-4	141.7	0.467
			1.43-3	141.7	0.488
			2.66-3	140.2	0.565
			4.81-3	137.3	0.676
			8.39-3	134.4	0.891
			1.41-2	128.6	1.224
			2.22-2	123.0	1.764
			3.06-2	114.8	2.124
			4.11-2	109.5	2.205
M-117	●	solid	3.53-4	144.3	0.195
			6.59-4	144.3	0.209
			1.19-3	142.2	0.235
			2.02-3	140.2	0.293
			3.46-3	138.2	0.388
			5.72-3	136.2	0.527
			9.28-3	132.3	0.756
			1.43-2	126.5	1.183
			2.11-2	120.9	1.683
			2.86-2	115.4	2.039
			3.73-2	106.5	2.239

Table C.3: Shear Modulus, G, and Damping, D_T, Measurements at Confining Stress, $'_3$ = 300 kPa (cont'd)

Sample	Symbol	Specimen Type	Shear Strain , %	Shear Modulus, G MPa	Damping Ratio, D_T %
M-118	◀	solid	2.71-4	151.1	0.239
			4.65-4	151.1	0.232
			8.20-4	149.0	0.240
			1.20-3	149.0	0.255
			1.74-3	147.0	0.293
			2.87-3	144.9	0.377
			4.93-3	142.9	0.510
			8.69-3	136.9	0.765
			1.23-2	133.0	1.017
			1.75-2	129.1	1.384
			2.67-2	121.6	2.021
			3.26-2	116.1	2.301

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Results from National Bureau of Standards (NBS) resonant column tests to determine shear moduli and damping ratios for Monterey No. 0 sand are presented to supplement the ASTM resonant column round robin program. In addition to testing solid specimen as specified for the initial ASTM round robin program, hollow cylindrical specimens were tested to provide an independent check on the validity of the results.

The NBS test data on shear moduli are consistently lower than the average values obtained from the initial round robin program, but they are within the range of the initial round robin test data. It is believed that, at least in part, the difference between the NBS and the round robin data was caused by the fact the NBS specimens had a lower average relative density which was also closer to 60 percent relative density specified for the round robin tests. Damping ratios obtained by NBS fit rather closely the curve obtained from the initial round robin program.

No significant difference was found between the maximum shear moduli and damping ratios obtained from the testing of solid specimens and hollow cylindrical specimens.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Damping; resonant column; round robin tests; shear modulus; soil dynamics; test methods; torsional vibrations

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