04 Apr 1995, 10:30 am - 12:00 pm

High Pressure Cyclic Triaxial Tests

Jianren Wang
Law Engineering and Environmental Services, Inc., Atlanta, Georgia

Clay E. Sams
Law Engineering and Environmental Services, Inc., Atlanta, Georgia

John D. Lawrence
Law Engineering and Environmental Services, Inc., Atlanta, Georgia

Harry Johnson
Law Engineering and Environmental Services, Inc., Atlanta, Georgia

Recommended Citation

Wang, Jianren; Sams, Clay E.; Lawrence, John D.; and Johnson, Harry, "High Pressure Cyclic Triaxial Tests" (1995). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 5.
https://scholarsmine.mst.edu/icrageesd/03icrageesd/session01/5

Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume I, St. Louis, Missouri

High Pressure Cyclic Triaxial Tests

Paper No. 1.06

Jianren Wang
Clay E. Sams

John D. Lawrence
Harry Johnson

Law Engineering and Environmental Services, Inc., Atlanta, Georgia

SYNOPSIS: Shear modulus and damping from high pressure (up to 500 psi) cyclic triaxial tests of soils are presented. The test results are compared with published models where low confining pressures were used. The apparatus and test setup for the high pressure tests are also discussed.

INTRODUCTION

In earthquake analyses for buildings and earth structures, it is important to understand how soil deposits supporting the structures respond to earthquake loadings. Different soil deposits will amplify earthquake motions differently when earthquake motions propagate from bedrock through the soil deposits to the ground surface. Usually, soil deposits are modeled as a layered system in the seismic analyses. To analyze how this layered system responds to earthquake loadings, shear modulus and damping ratio of each soil layer is required.

A large data base of shear modulus and damping ratio of different types of soils under various conditions has been generated using in-situ and laboratory testing methods. Many researchers have developed different models for stress-strain relationships for soil under different conditions based on the data generated in-situ and in the laboratory. However, since the data base for shear modulus and damping ratio was generated at confining pressures generally less than 100 psi, it is unknown if these stress-strain models are valid for high confining pressures.

The proposed New Production Reactor (NPR) is located at the Savannah River Site (SRS) near Aiken, South Carolina. The soil deposits at the NPR site are about 1100 feet deep. As part of geotechnical characterization of the site, it was required to estimate site amplification of seismic motions for hazard assessment and general foundation design of reactor plant structures. The seismic analyses required the shear modulus and damping of each soil layer down to bedrock. A deep borehole was extended through the soil and into the bedrock to a total depth of approximately 1200 feet. Thin-walled tube samples were taken within the differing soil layers. Resonant column and cyclic triaxial tests were performed on selected samples taken at different depths to obtain the shear modulus and damping ratio of each soil layer. The project requirements specified that the samples be tested at confining pressures up to 500 psi. This upper limit pressure is approximately five times higher than the pressures used in conventional testing.

This paper presents cyclic triaxial test results of samples subjected to confining pressures generally greater than 150 psi and up to 500 psi. The test results are compared with the Hardin-Drnevich (1972) model and the Seed et. al. (1984) shear modulus and damping curves. Resonant column tests were performed at Purdue University and are not presented in this paper. However, resonant column tests on Ottawa sand are herein presented along with cyclic triaxial tests on the same batch of sand under the same conditions as part of validation testing of the cyclic triaxial equipment.

APPARATUS AND TEST SETUP

The cyclic triaxial test procedures have been well developed and are documented in ASTM Standard D3999-91 (1994). However, these procedures were developed for conventional confining pressures. For higher confining pressure, some of the test procedures and test equipment have to be modified.

One significant modification is the use of specially-made high pressure triaxial chambers. Conventional triaxial chambers are made of acrylic and can only sustain pressures less than 150 psi. To allow pressures up to 500 psi, two metal triaxial chambers were specially made for the project, with a viewing port to allow the observance of the specimen during testing.

A computer-controlled INSTRON 8500 servo-hydraulic loading system was used to apply cyclic loads. The system was capable of applying and maintaining static loads during cyclic loading. This capability allowed application of axial load during saturation, consolidation and cyclic loading to compensate for the uplifting forces due to the attachment of the piston rod to the specimen cap. Axial load, axial deformation, and pore water pressure of the specimen were digitally recorded during testing at a sampling rate of 100 points per second. The frequency of loading was 1 Hz, except for one test where additional loading frequencies of 0.1 and 10 Hz were also used. Cyclic loading (straining) of each specimen was staged beginning at the smallest deformations (0.001 inch). Approximately 15 cycles of each axial deformation were applied in each stage, in an undrained condition.

In cyclic triaxial test setup, axial deformation transducers (LVDTs) are normally attached to the piston rod outside triaxial chamber. As the result, the deformation measured consists of deformation of the specimen and the system (piston rod, cap and porous stones). The deformation of the system (system compliance) is generally on the order of 10^{-4} inch. When the deformation measured is small (less than 10^{-2} inch), system compliance becomes significant. Prior to testing, system compliance was checked by applying static loads in the absence of a soil specimen in steps up to the maximum loads anticipated. Deformation of the system was found to be linear to the load applied and was repeatable. Consequently, the axial deformation measured in all tests was corrected by subtracting the system compliance from the measured deformation at the same load to obtain specimen deformation.

During the course of testing, punctures in membranes surrounding the specimens were found due to the rough surface of the specimens in conjunction with high confining pressure. This problem occurred more frequently at higher pressures and when the soil grains were medium to coarse sand. Two, and sometimes three membranes were used to reduce the occurrence of this problem.

To validate the testing systems, two tests were performed on Ottawa sand at confining pressures of 235 and 504 psi, respectively. Ottawa sand was sampled from the same batch tested in the resonant column.

TEST RESULTS

Cyclic triaxial tests were performed on two samples of Ottawa sand and on twenty thin-walled tube samples. In cyclic triaxial tests, Young's modulus and axial strain are directly calculated from measured axial load, axial deformation and specimen dimensions. Young's modulus and axial strain can be easily converted to shear modulus and shear strain, respectively, using the theory of elasticity. Poisson's ratio was assumed to be 0.5 in all data conversions, representing fully saturated, undrained conditions. All data was reduced at the 10th cycle of loading.

Ottawa Sand Remolded Samples

Results from two tests on Ottawa sand are shown in Figures 1 and 2, along with the results from resonant column tests and the Hardin-Drnevich hyperbolic model.

Figure 1 shows shear modulus versus shear strain at confining pressures of 235 and 504 psi. Shear moduli from both resonant column and cyclic triaxial tests were normalized with shear modulus at very small strain level (10^{-5} %), G_{max}, measured in resonant column tests. A good correlation is shown between these two tests. The Hardin-Drnevich hyperbolic model for sand without using the hyperbolic strain (Hardin and Drnevich, 1972) is also shown in these figures. The effective friction angle of 30° is assumed for the Ottawa sand in the Hardin-Drnevich model. It can be seen that the Hardin-Drnevich model fits fairly well to the Ottawa sand test data even though the model was developed based on the data at relatively low confining pressure.(≤ 100psi)

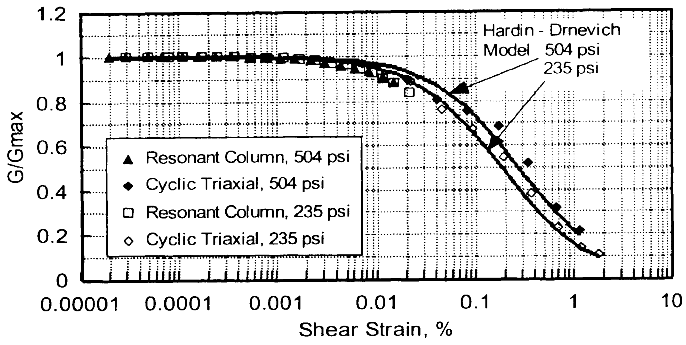

Figure 1. G/G_{max} versus Shear Strain for Ottawa Sand

Figure 2 summarizes damping ratios measured from the two Ottawa sand tests. Again, a good correlation is shown between cyclic triaxial and resonant column tests. It was found that the Hardin-Drnevich hyperbolic model for sand using hyperbolic strain fits the damping data better than the hyperbolic model without using hyperbolic strain.

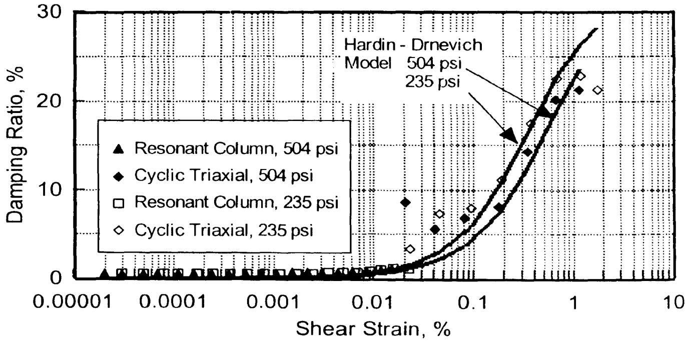

Figure 2. Damping Ratio versus Shear Strain for Ottawa Sand

Thin-Walled Tube Samples

Cyclic triaxial tests were performed on twenty thin-walled tube samples at confining pressures ranging from 40 to 500 psi. The majority of the samples was classified as silty sand or clayey sand. Two samples were classified as clay. Shear moduli and damping ratios from 14 silty or clayey sand samples and the previously mentioned two Ottawa sand samples are plotted in Figures 3 and 4. These samples were tested at confining pressures ranging from 185 to 504 psi, except for sample S39 which was tested at a confining pressure of 85 psi. Four tests performed on silty or clayey sand samples at confining pressures less than 100 psi and two tests on clay samples are not presented in Figures 3 and 4. In these plots, measured shear moduli are normalized with G_{max} calculated using Hardin's equation (1989). Based on high confining pressure resonant column tests on Ottawa sand, Hardin, Drnevich, Wang and Sams (1994) concluded that G_{max}

calculated using Hardin's equation is fairly close to the measured G_{max}. Seed's shear modulus reduction curves and damping ratio curves for sands (Seed, et. al., 1984) are also shown in these plots. The Seed's curves were generated from test data at relatively low confining pressures. The majority of measured shear moduli are found to be above Seed's upper bound curve, whereas measured damping ratios are mostly between Seed's lower and upper bounds of damping ratio curves.

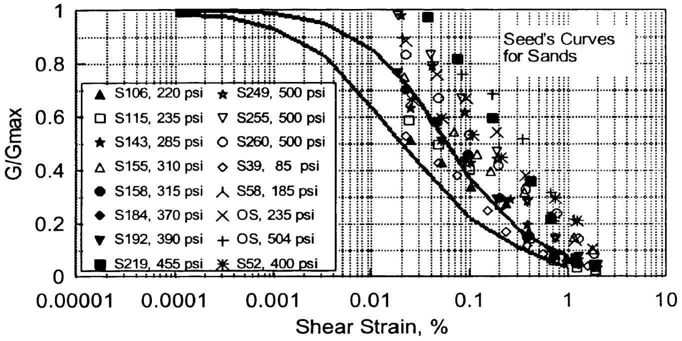

Figure 3. G/G_{max} versus Shear Strain for Fourteen Silty or Clayey Sand and Two Ottawa Sand Samples.

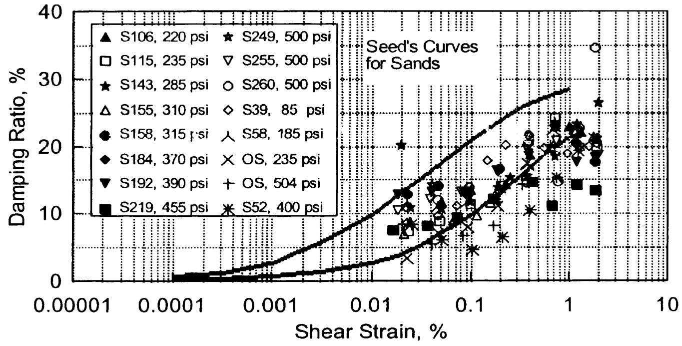

Figure 4. Damping Ratios versus Shear Strain for Fourteen Silty or Clayey Sand and Two Ottawa Sand Samples.

Results of tests from two thin-walled tube samples are also presented in Figures 5 through 8 along with the Hardin-Drnevich model using hyperbolic strain. These samples are a clay from 966 feet and a silty sand from 662 feet. The shear moduli measured in Figures 5 and 7 at high confining pressures are generally in the range predicted by the Hardin-Drnevich model developed for low confining pressure (less than 100 psi). However, measured damping ratios shown in Figures 6 and 8 deviate from the Hardin-Drnevich model, especially at low and high strain levels. In most tests, damping ratios at low strain levels (10^{-2} to 10^{-1} %) are generally erratic indicating difficulties in measuring damping ratio at low strain levels.

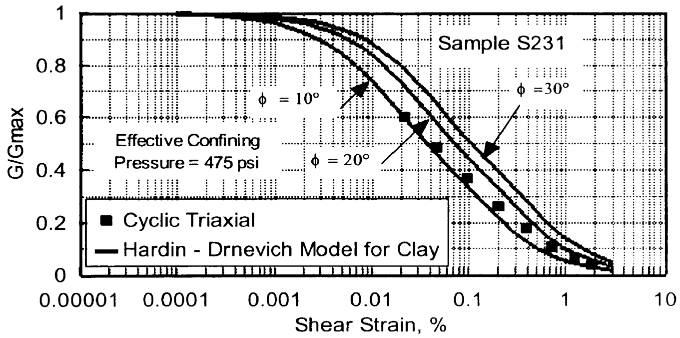

Figure 5. G/G_{max} versus Shear Strain for a Clay.

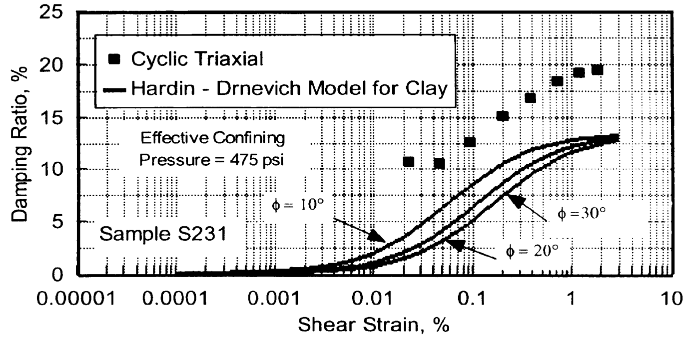

Figure 6. Damping Ratio versus Shear Strain for a Clay.

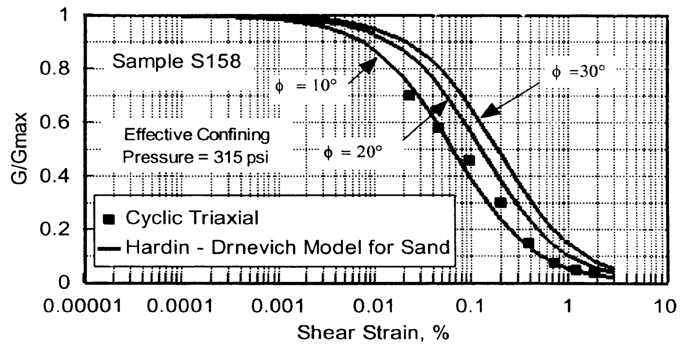

Figure 7. G/G_{max} versus Shear Strain for a Silty Sand.

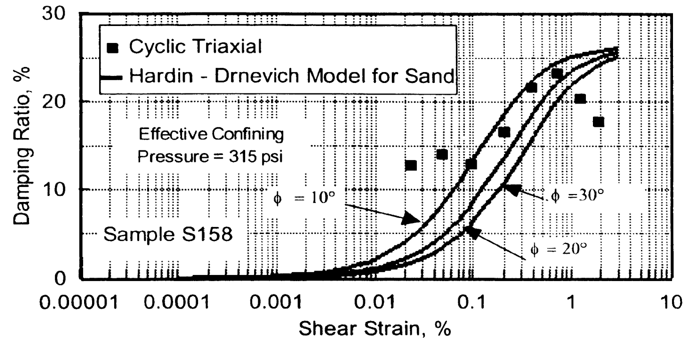

Figure 8. Damping Ratio versus Shear Strain for a Silty Sand.

To determine the effect of loading frequency on shear modulus and damping, three different frequencies: 0.1, 1 and 10 Hz were used in one test on a silty sand sample. Shear moduli and damping ratios measured at three different loading frequencies are shown in Figures 9 and 10. Shear moduli are virtually the same for all three different loading frequencies. Damping ratios at loading frequencies of 0.1 and 1 Hz are found to be the same; however, damping ratios at loading frequency of 10 Hz are approximately 3 to 5 % higher than those at lower frequencies.

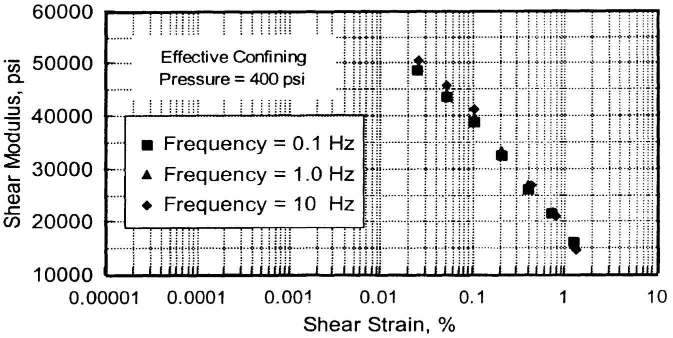

Figure 9. Shear Modulus versus Shear Strain at Three Different Loading Frequencies for a Silty Sand (Sample S52).

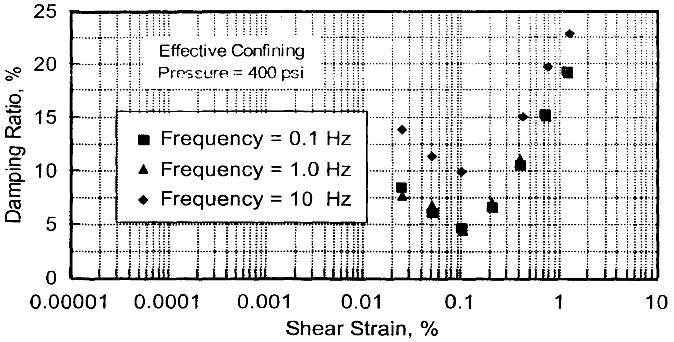

Figure 10. Damping Ratio versus Shear Strain at Three Different Loading Frequencies for a Silty Sand (Sample S52).

CONCLUSIONS

Cyclic triaxial tests at confining pressures ranging from 185 to 504 psi were performed and the results are presented in the paper. This pressure range is two to five times higher than the pressures used in conventional cyclic triaxial tests. Based on the high pressure test results, the following tentative conclusions can be drawn:

1. High pressure cyclic triaxial tests require a special metal triaxial chamber and multiple membranes. More research is needed to determine the effect of multiple membranes on both shear modulus and damping.
2. Two high pressure cyclic triaxial tests on Ottawa sand indicate good correlation with resonant column tests on the same batch of samples under the same conditions. The Hardin-Drnevich hyperbolic model appears to fit the Ottawa sand test data fairly well despite that the model was developed for confining pressures less than 100 psi.
3. Comparisons of measured shear moduli and damping ratios with the Seed, et. al. (1984) empirical curves indicate that the shear moduli measured at high confining pressure are generally above the range defined by Seed's curves, whereas damping ratios measured at high confining pressure generally fall into the range.
4. Results on two undisturbed samples indicate that shear moduli measured at high confining pressure are generally in the range predicted by the Hardin-Drnevich model; however, damping ratios at the low and high ends of range in strain deviate from the Hardin-Drnevich model.
5. Limited test results show no effect of loading frequency on shear modulus and damping at high confining pressure.

This paper provides useful information on dynamic properties of soils subjected to high confining pressures which were not available before. More studies are needed to better understand how soils behave under high pressures.

REFERENCES

D3999- 91 (1994), "Standard Test Methods for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus." Annual Book of ASTM Standards, Volume 04.08, Soil and Rock (I).

Hardin, B. O. and Drnevich, V. P. (1972), "Shear Modulus and Damping in Soils: Design Equations and Curves," Journal of Soil Mechanics and Foundations Division, ASCE, Vol. 98, No. SM7, July.

Hardin, B. O., and Blanford, G. E. (1989), "Elasticity of Particulate Materials," Journal of Geotechnical Engineering, ASCE, Vol. 115, No. 6, June.

Hardin, K. O., Drnevich, V. P., Wang, J., and Sams, C. E. (1994), "Resonant Column Testing at Pressures up to 3.5 MPa (500 psi)," Dynamic Geotechnical Testing: Second Volume, ASTM STP 1213.

Seed, H. B., Wong, R. T., Idriss, I. M., and Tokimatsu, K. (1984), "Moduli and Damping Factors for Dynamic Analysis of Cohesionless Soils," Report No. UCB/EERC-84/14, University of California, Berkeley, California.