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The Influence of Large Prestrains on Dynamic Properties of Sand

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The Influence of Large Prestrains on Dynamic Properties of Sand

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SYNOPSIS: The development of the UMR Resonant Column/Torsional Simple Shear device has provided the means to evaluate high and low amplitude shear moduli on a single sand specimen. Results of cyclic torsional simple shear tests showed that progressive strain increases with the cyclic strain amplitude and the number of cycles and decreases with density of the sand. Large accumulated prestrains were found to decrease the maximum dynamic shear modulus by 30 to 35%.

INTRODUCTION

Recent advances in the analysis of soil-structure interaction problems have developed to the point that they are limited by inadequate knowledge of the dynamic stress-strain soil properties. In particular, more knowledge is needed on the effect of prestrains caused by previous loading and soil creep on soil modulus and damping and how strains progress during cyclic loading of soil. A knowledge of the effects of prestraining on the dynamic properties is useful in determining the residual strength and the dynamic response of soil when the soil has previously undergone strains or is under a static shear stress such as in a soil slope or embankment.

Over the past 25 years, a number of different laboratory tests have been developed to model dynamic loading of soil. Recently, the UMR Resonant Column/Torsional Simple Shear Test device was developed for dynamic soil testing. It consists of a Stokoe Resonant Column Device modified to applying static torsional simple shear stresses to strain levels of 20% or more. The device has three modes of operation: resonant column, cyclic torsional simple shear, and static torsional simple shear. Each of these modes evaluates the soil properties at different levels of shear strain. Hence, the complete strain dependent behavior of the soil can be measured on a single specimen during a single test operation.

This paper describes the effect of large prestrains upon the dynamic shear modulus of an Ottawa sand investigated using the UMR Resonant Column/Torsional Simple Shear Test device. The operation and characteristics of the device are described. Progressive strains due to cyclic loading are also presented. A comparison is made with results found in this study to the results found by other researchers. The parametric effects of average confining stress, void ratio, average shearing strain, and thixotropy upon the dynamic shear modulus and damping are presented elsewhere (Stringer, 1984).

THE UMR RESONANT COLUMN/TORSIONAL SIMPLE SHEAR DEVICE

The Resonant Column/Torsional Simple Shear device developed by the Civil Engineering Department of the University of Missouri -Rolla is similar to those used at the University of Texas-Austin and was designed, in part, by Dr. Kenneth Stokoe. Sutterer (1984), together with Dr. Richard Stephenson, modified this device so that it could be used for static torsional simple shear tests. This modified device makes it possible to study the effects of high prestrains on the low amplitude shear modulus and damping on a single specimen. The use of a single specimen removes the influence of specimen variation and sample preparation and handling on the test results. The device and its modifications have been described by Sutterer (1984) and Isenhower (1979).

Sutterer's modification of the Stokoe Resonant Column Device allows the application of shear strains of 20% and beyond at varying rates of strain on a single specimen. The shearing can be performed slowly enough to be considered static and can be manually reversed to load and unload the specimen in a cyclic manner. This action is made possible by the addition of another drive system consisting of a modified Stokoe base with drive wheel, drive motor, and speed reducer. The details of the modifications are given by Sutterer (1984).

The drive system motor consists of a synchronous stepper motor with an in-line speed reducer. The speed of the motor can be adjusted using the potentiometer controls on the instrument panel. The motor is connected to a function generator which sends an external pulsing signal to the motor. The frequency can be adjusted to obtain a desired strain rate in the specimen.

MEASUREMENT SYSTEM

Several measurements must be made before, during, and after torsional simple shear tests. These are change of height of the specimen, rotation, and torque.

A linear variable differential transformer (LVDT) is used for both the resonant column and torsional simple shear test to measure the change in height of the specimen. It is fastened to the center of the resonant column drive armature. Changes in specimen length due to consolidation and disturbance can then be monitored.

A rotary variable differential transformer (RVDT) measures the rotation of the base of the specimen during torsional shearing from which the shear strain can be determined. It is fastened to the underside of the drive wheel.

The torque load cell serves two separate purposes. It measures torque applied to the top of the specimen and it acts as a stop to prevent any significant rotation of the top of the specimen while the bottom of the specimen is rotated. The stops are designed so that the armature and magnets do not rotate into the drive coils during the test.

Before the beginning of the test, the torque load cell is adjusted so that the stops are separated just enough to prevent contact of the two opposing arms of the armature assembly during the resonant column test. When the torsional simple shear test is begun, the entire specimen and armature assembly are rotated against the stops which applies a torque to the specimen.

This torque is measured by strain gages mounted on the load cell. The strain gages are mounted such that two are in tension and two in compression and that the magnitudes of the strain on all four gages are the same.

Proximity Probes

The accelerometer used in the resonant column test is not sensitive enough to be used for the cyclic torsional simple shear test because of the low accelerations developed. A pair of proximity probes are used instead. The two probes are located to measure angular displacement. The proximity probes operate by measuring the width of the gap between the stationary probe tip and the moving target. Angular displacement can be found by separately adding and subtracting the signals from these probes. They are limited by their narrow linear range. Thus only a limited range of strain amplitudes can be measured. The output from the proximity probes is plotted against the driving current to give torque versus rotation. This plot appears as a hysteresis loop from which shear modulus and damping are found.

TESTING PROGRAM AND PROCEDURE

The testing program was intended to meet seven objectives: (1) demonstrate that the modified resonant column device measures shear modulus and damping values comparable to previously reported results on the same soil; (2) demonstrate that the torsional simple shear adaptation to the resonant column device provides results that may be expected from a torsional shear test; (3) measure the parametric effects of confining pressure, void ratio, and time on the maximum shear modulus and minimum damping ratio; (4) define the entire normalized shear modulus, G/G_{max}, relationship with shearing strain ranging from 10^{-4}% to 10%; (5) define the strain dependency relationship of damping; (6) measure the influence of large prestraining on the shear modulus, and (7) measure the amount of progressive strain during cyclic shear.

Thirteen tests were performed in all. One staged resonant column test was performed on the sand used by Sutterer (1984) to check calibration. Twelve tests were performed using Ottawa No. 20-30 sand. Eight samples were 2.8 in. (7.1 cm) in diameter and four samples were 1.4 in. (3.6 cm.) in diameter. Four staged resonant column tests were performed while the rest were fresh tests under one confining pressure. The 1.4 inch samples were tested using vacuum to give an effective confining pressure. Six torsional simple shear tests were performed. Two cyclic torsional simple shear tests were performed on medium dense and dense 2.8 in. (7.1 cm) diameter sand samples.

PROCEDURE

The testing procedure in this study is discussed in detail by Stringer (1984). The specimens were formed using a dry raining technique. The height of drop was adjusted to control the density of the specimen.

After a resonant column test was performed on a specimen, a torsional simple shear test was performed on the same specimen. Throughout the static torsional simple shear test, torque and rotation readings were taken at small increments below 1% strain and then increased to larger increments up to 20% strain. Upon reaching 20% strain, the rotation was reversed and readings were taken as the specimen was unloaded. At this point, the specimen was rotated further back to about the original proximity probes reading and another resonant column test was performed on the permanently strained specimen.

The rate of strain was adjusted during cyclic load and unload tests such that the period of a cycle was about two minutes. Torque and strain readings were taken at the start, end of loading, and end of unloading. The rate of strain was further decreased on the last cycle of each series of cyclic strain in order to take intermediate readings of torque and strain. After one cyclic strain test was performed, the strain amplitude was increased and the procedure repeated.

RESULTS

The results of the testing program are in the following paragraphs. The parametric effects on dynamic shear modulus and damping from resonant column tests have been reported by Stringer (1984). The torsional simple shear tests yield stress-strain plots from which an average shear modulus for different strain levels could be found. The combined results from resonant column and cyclic torsional simple shear tests define the strain dependency of shear modulus for the range of 10^{-4}% to 10% and are compared to the empirical relationship suggested by Hardin and Drnevich (1972). The influence of prestraining to beyond failure of the sample on the resonant column shear modulus and damping is presented below.

CYCLIC TORSIONAL SIMPLE SHEAR TEST RESULTS

Two strain controlled, cyclic torsional shear tests have been performed for this study. Up to 12 cycles of one directional loading and unloading were applied to the specimen using a period of cycle of about two minutes. Progressive strains were measured during testing.

Figure 1 shows a typical cyclic, stress-strain curve upon achieving shear failure. The amount of progressive strain was determined from the offset in rotation between cycles. The rebound shear modulus, G_r, was computed and the recovery strain, γ_r, was considered to be the average dynamic shear strain. The rebound shear modulus for sand is almost totally an elastic modulus.

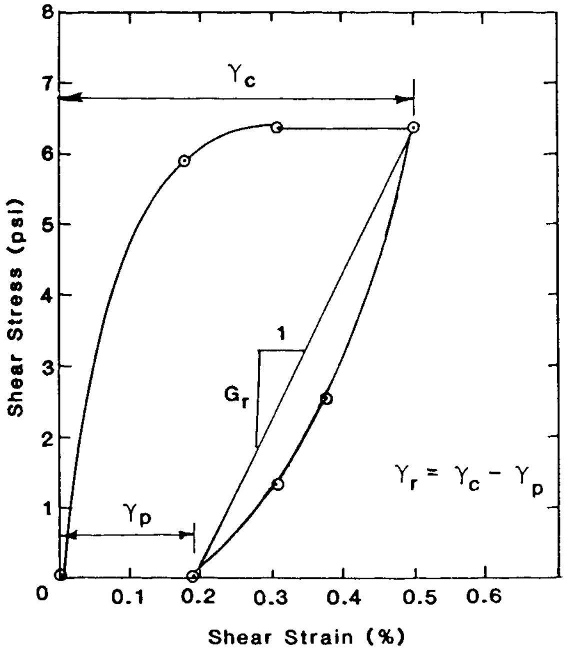

Figure 1. Typical Cyclic Stress-Strain Curve

Figure 2 shows the amount of progressive shear strain, γ_p, versus number of cycles of loading and unloading at each cyclic strain level. After about four cycles of loading, the increase of progressive strain per cycle seems to remain constant through 12 cycles. Whether this relationship becomes logarithmic as predicted by Timmerman and Leelanitkul (1981) for higher number of cycles is not shown from the results of this study. The influence of frequency of loading was not considered for this study.

Figure 3 shows the amount of progressive strain, γ_p, after four cycles of loading versus the cyclic strain level. On a log-log plot, this relationship becomes nearly linear. Two series of cyclic shear strain were applied on the specimens in Test No. 11. During the first series of cyclic shear strain, the amount of progressive strain is greater than the second series of cyclic shear strain, but the amount of progressive strain during the second series approaches the first series at high levels of cyclic shear strain. This behavior may be due to the fact that a failure plane was developed during the first series and subsequent progressive strain during the second series was due to rotation alone the failure plane. In addition, some strain hardening may have occurred at low cyclic strain.

COMBINED RESULTS

Figure 4 shows the combined results from the resonant column, static torsional simple shear,

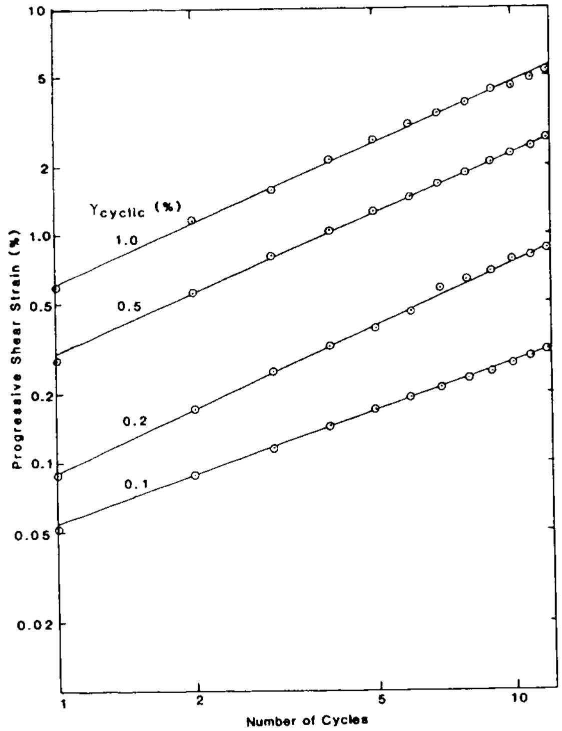

Figure 2. Progressive Strain versus Number of Cycles

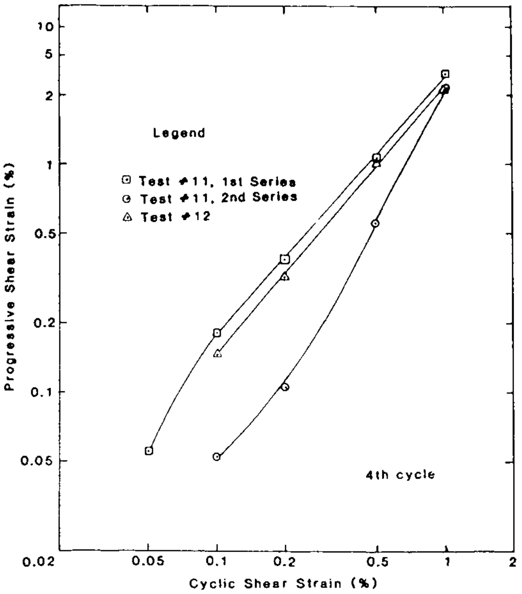

Figure 3. Progressive Strain versus Cyclic Shear Strain

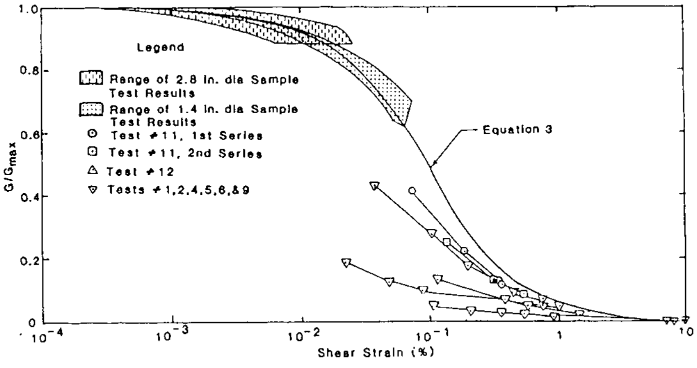

Figure 4. Normalized Shear Modulus versus Shear Strain

and cyclic torsional simple shear tests when plotted as G/G$_{max}$ versus average shear strain. The shear modulus was observed to have a hyperbolic dependency with shear strain. The suggested Hardin and Drnevich empirical curve (1972) is drawn for comparison.

The resonant column test results show excellent agreement with the empirical relationship. The shear modulus did not decrease substantially until about 5 x 10^{-3}% shear strain. The scatter of the data is greater for the 2.8 in. (7.1 cm.) diameter specimens than from the 1.4 in. (3.6 cm.) diameter specimens. This greater scatter probably reflects the greater variation of density and confining pressures used in the testing program for the larger specimens. The maximum shear strain amplitude reached for the 2.8 in. (7.1 cm.) diameter specimens was about 2.5 x 10^3%, while the maximum shear strain level reached for the 1.4 in. (3.6 cm.) diameter specimens was about 7 x 10^3% due to less specimen stiffness. Consequently, the lowest G/G$_{max}$ ratio measured was 0.62 from the resonant column test. The frequency of resonance was not considered to be an important factor for the analysis of the results. The resonant frequency of the 2.8 in. (7.1 cm.) diameter specimens varied from 98 to 167 Hz and varied from 25 to 47 Hz. for the 1.4 in. (3.6 cm.) diameter specimens.

The results from the cyclic torsional simple shear tests (Tests #11 and #12) show the rebound shear modulus (Figure 4) decreases sharply for shearing strains from 0.1% to 1%. The rebound G/G$_{max}$ plot is parallel but below the empirical curve. Additional cycles for loading may further stiffen the sand such the G/G$_{max}$ plot would follow the empirical curve more closely. The shear modulus of the denser specimen (Test #11) appears to agree better than the less dense specimen (Test #12).

The static torsional test results show the secant shear modulus to be substantially less than the cyclic rebound modulus in all but one test (Test #6). This lower shear modulus is due to that there is a substantial plastic component of total strain during the first cycle of loading. The average secant shear modulus includes both an elastic and plastic component. Once a hysteretic loop is established during cyclic torsional shear, the rebound modulus becomes nearly an elastic modulus and is greater than the static, secant shear modulus as shown on Figure 4.

INFLUENCE OF PRESTRAINING

Five resonant column tests have been performed to determine the influence of large prestrains (20% shear strain in four of the samples) on the dynamic shear modulus (Figure 5). A marked decrease in shear modulus was measured after specimen failure. The G/G$_{max}$ ratio varied from 0.71 to 0.80 and averaged about 0.73. Two resonant column tests were performed during Test #12 after the 0.5% and 1.0% cyclic torsional shear strain intervals, resulting in a G/G$_{max}$ ratio of 0.78 and 0.73, respectively.

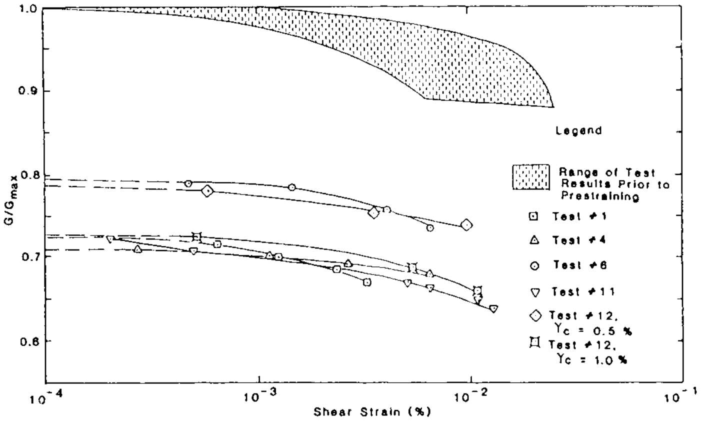

Figure 5. Influence of Prestraining to Failure on Shear Modulus

The decrease may be the result of interference of the failure plane to the transmitted shear waves. A definite failure plane was observed after torsional shearing. This plane was generally horizontal and located at about midheight of the specimen. This failure plane appears to be where the permanent, plastic strain occurs upon reaching failure stress. The failure plane apparently creates a zone of weakness in the specimen which causes about a 20 to 30% reduction in the measured shear modulus.

Cyclic shearing resulting in progressive strains will also reduce the stiffness as seen in Test #12. The amount of progressive strain that occurs in the specimen appears to decrease the shear modulus until shear failure occurs. Shear failure of the specimen occurred sometime during the 1.0% cyclic torsional shearing. Upon shear failure the decrease in the shear modulus appears to be the same as for static shearing the specimen to failure.

COMPARISON WITH OTHER RESEARCHER'S RESULTS.

Figure 6 shows a comparison of the measured G$_{max}$ to the computed G$_{max}$ as calculated from the empirical relationship suggested by Hardin (1968) and Iwasaki et. Al. (1978). A linear regression analysis was used to determine the correlation between the measured values and values calculated from the empirical relationships. The correlation of the results with Iwasaki et. al. is excellent while the correlation with Hardin and Drnevich is only fair. The Hardin and Drnevich relationship overestimates the measured G$_{max}$. G$_{max}$ appears to increase with confining pressure to the 0.4 power as Iwasaki et. al. suggests. Some scatter of the data is probably due to measurement inaccuracies of confining pressure and density.

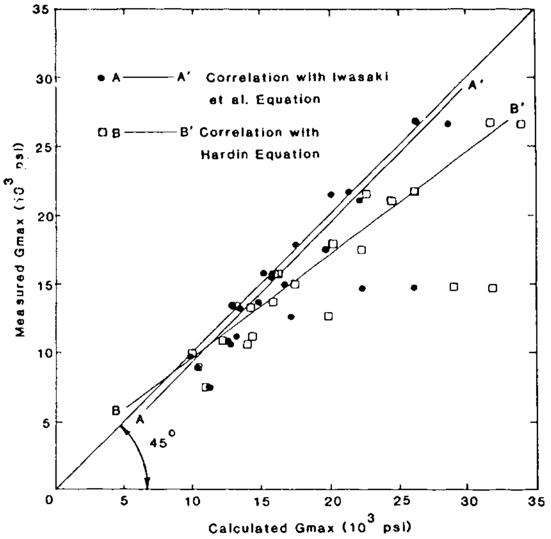

Figure 6. Measured G_{max} versus Calculated G_{max}

Figure 7 shows the measured damping values obtained compared to the calculated damping values as found from the Hardin and Drnevich (1972) relationship. The correlation is fair because of the large scatter of the results. The calculated damping may over or under estimate the damping by a factor of 3. The large scatter of measured damping values is consistent with that found by other researchers (Sherif and Ishibashi, 1976; Sherif and Ishibashi, 1976; Edil and Lub, 1978). The large scatter may be attributed to the sensitivity of damping to measurement and measurement system inaccuracies.

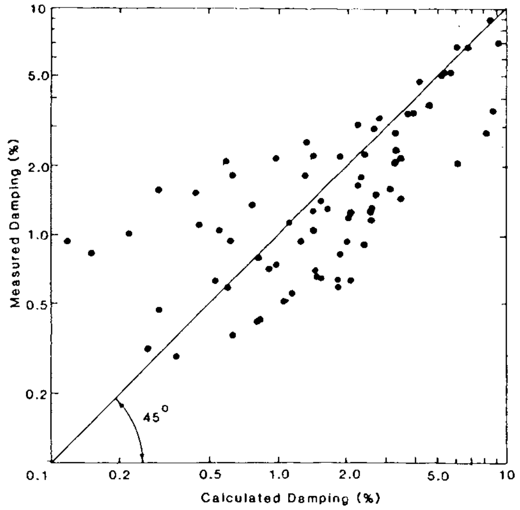

Figure 7. Measured Damping versus Calculated Damping

CONCLUSIONS AND RECOMMENDATIONS

The University of Missouri - Rolla resonant column/torsional simple shear device is capable of measuring shear moduli over a wide range of strain amplitudes (10^{-4}% to 20%). This was achieved without unnecessary disturbance caused by disassembly and reassembly of the device.

The static torsional simple shear adaptation to the device was used to measure shear strengths. The results from the static torsional simple shear tests show general stress-strain characteristics and shear strengths similar to results reported in the literature.

Progressive strain during low frequency, cyclic loading and unloading was found to be a function of the cyclic strain amplitude, number of cycles, and relative density of the soil. Plastic, progressive strain was found to increase with the cyclic strain amplitude and the number of cycles. Plastic strain was found to decrease with increasing relative density.

Large prestraining of the specimen to beyond shear failure was found to decrease the maximum dynamic shear modulus by about 20 to 30%. The decrease in shear modulus appears to be due to the development of shear failure planes.

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