Deformational Characteristics of Soils From Laboratory Dynamic / Cyclic Tests

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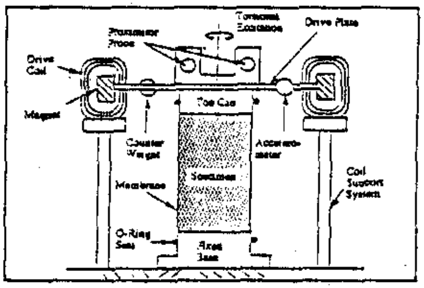


INTRODUCTION

Deformational characteristics of soils, expressed in terms of shear and Young's moduli and material damping, are important parameters in the design of soil-structure and soil pavement systems subjected to cyclic and dynamic loadings. In the past, much of the concern has been focused on the behavior of soils during earthquake loading. However, in recent years, much interest has developed in the area of low-amplitude problems associated with human-made vibrations such as those caused by vehicular traffic, machine vibrations, pile driving, and blasting. Furthermore, as the accuracy of static measurements improves, the perceived difference between static and dynamic moduli continues to decrease, and an understanding is glowing that strain amplitude is a key variable in predicting soil behavior whether the strain comes from static or dynamic phenomena (Bolton and Wilson, 1989; Woods, 1991; Tatsuoka and Shibuya, 1991; Kim, 1991; Kim and Stokoe, 1992). Therefore, measurement of deformational characteristics at small (10^{-5}% to 10^{-3}%) to intermediate (10^{-3}% to 10^{-1}%) strains has become important in both dynamic and static analyses.

Soil-structure systems are frequently subjected to cyclic loads exceeding the elastic range of the soil while soil-pavement systems are often loaded beyond the elastic range. In these cases, the effect of cyclic loading beyond the elastic range is an important factor influencing deformational characteristics of soils. Each source externally loading a soil-pavement or a soil-structure system has a different pattern which results in loading frequencies ranging from very low frequencies about 0.05 Hz and above (such as ocean storm waves) to high frequencies above 100 Hz (created by machine vibrations). Laboratory and field testing techniques also have different frequency characteristics in their measurements. If the deformational characteristics of soils are affected by the number of loading cycles and loading frequency, then the values obtained from various testing techniques will be different. Therefore, in the design of soil-structure and soil-pavement systems, the effect of loading cycle beyond elastic range and the effect of loading frequency on deformational characteristics should be considered, and the measured values should be adjusted to the values at the same condition where the actual system is working.

In 1986, the American Association of State Highway and Transportation Officials (AASHTO) adopted use of resilient modulus to represent the deformational characteristics of subgrade soils in the design of pavement structures. However, experience gained in applying the cyclic triaxial test in geotechnical earthquake engineering has shown that great care must be exercised in evaluating the deformational characteristics of geotechnical materials at small to intermediate strains, where resilient modulus testing is performed, or significant inaccuracies can occur (Stokoe et al., 1990; Pezo et al., 1991).

The purpose of this research is to study the deformational characteristics of soils, particularly the effects of number of loading cycles and loading frequency, at small to intermediate shearing strains using resonant column / torsional shear (RCTS) equipment. Test equipment and measurement techniques of cyclic tests are discussed. Deformational characteristics of dry sand and cohesive soil are investigated separately. Furthermore, procedures assessing a reliable resilient modulus testing system are also investigated.

TEST EQUIPMENT AND MEASUREMENT TECHNIQUES

Torsional Resonant Column Test

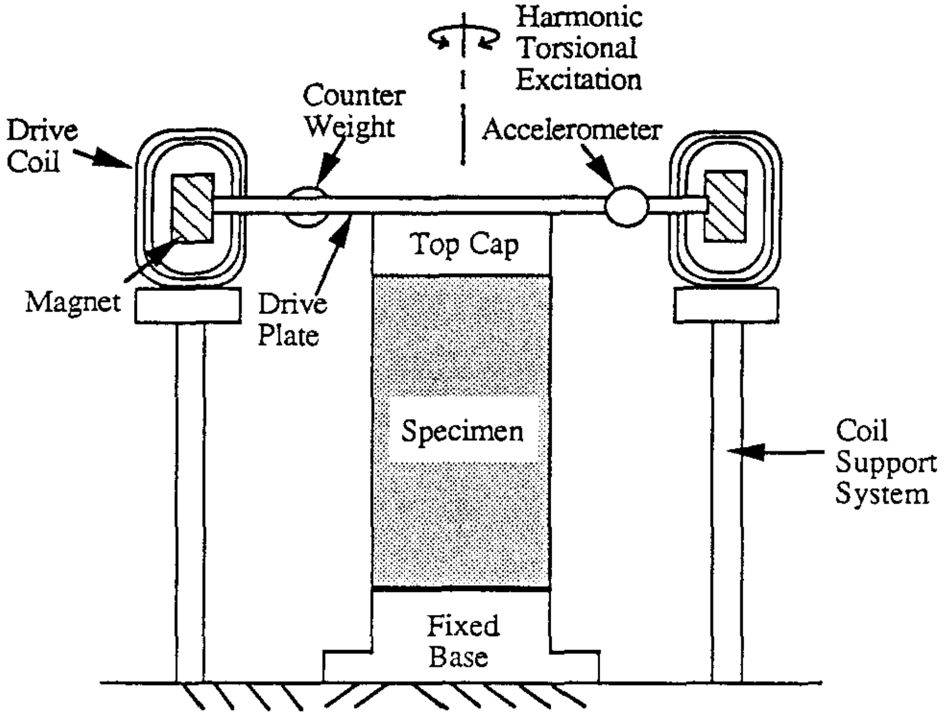
Resonant column (RC) equipment of the torsional fixed-free type was used. In the fixed-free resonant column test, the bottom end of the specimen is rigidly fixed against rotation at the base pedestal while the top (free end) is connected to a drive system that is used to excite and monitor torsional motion as illustrated in Fig. 1.

The basic operational principle is to vibrate the cylindrical specimen in the first-mode torsional motion. Harmonic torsional excitation is applied to the top of the specimen over a range in frequencies, and the variation of the acceleration amplitude of the specimen with frequency is obtained. Once first-mode resonance is established, measurements of the resonant frequency and amplitude of vibration are made. These measurements are then combined with equipment characteristics and specimen size to calculate shear wave velocity and shear modulus based on elastic wave propagation (Kim, 1991).

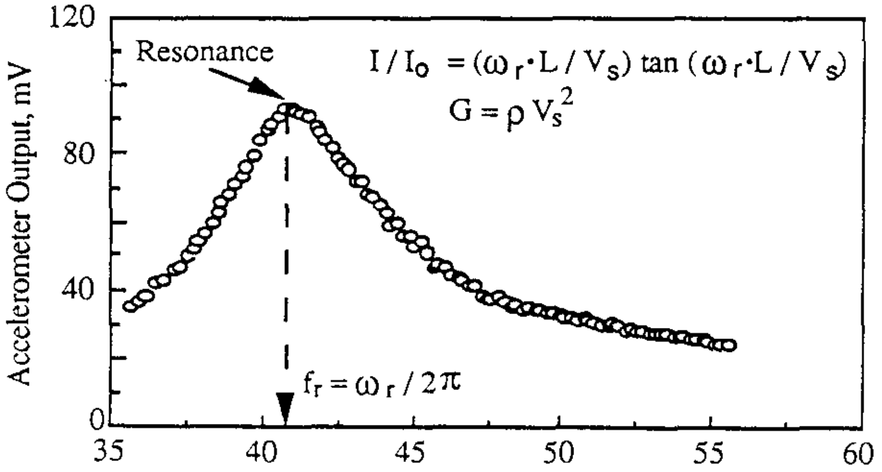
In the RC test material damping is evaluated from the dynamic response using either the free-vibration decay curve or the half-power bandwidth (Kim et al., 1991). The free-vibration decay curve is recorded by shutting off the driving force after the specimen has been vibrating for a large number of cycles in steady-state motion at the resonant frequency. The half-power bandwidth method is based on measurement of the width of the frequency response (amplification) curve near resonance. For small strains below about 0.001%, both methods were used, but only the free-vibration decay method was applied for larger strains because of nonlinear distortion of the frequency response curve.

Torsional Shear Test

The torsional shear (TS) test is another method of determining shear modulus and material damping using the same RCTS equipment but operating it in a different manner. The



a) Specimen in the Resonant Column Apparatus



b) Typical Frequency Response Curve

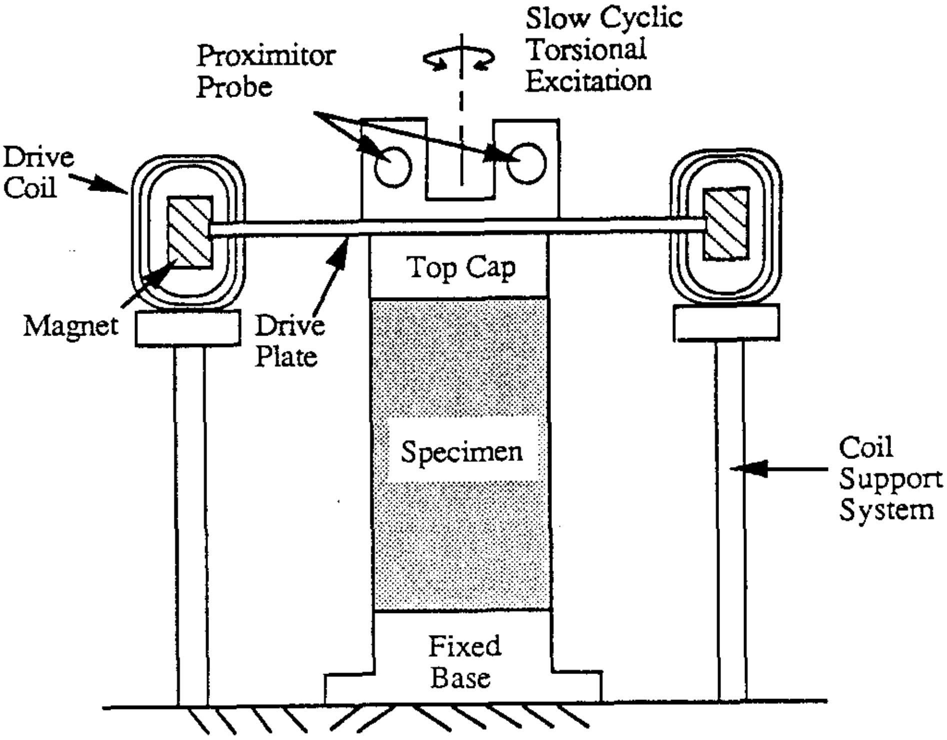
Figure 1 Simplified Diagram of a Fixed Free Resonant Column Test and an Associated Frequency Response Curve simplified configuration of the torsional shear test is shown in Fig. 2. A cyclic torsional force with a given frequency, generally below 10 Hz, is applied at the top of the specimen. Instead of determining the resonant frequency, the stress-strain hysteresis loop is determined from measurements of the torque-twist response of the specimen. Proximitors are used to measure the angle of twist while the voltage applied to the coil is calibrated to yield torque. Shear modulus is calculated from the slope of a line through the end points of the hysteresis loop, and material damping is obtained from the area of the hysteresis loop as shown in Fig. 2.

Advantages of RCTS Equipment

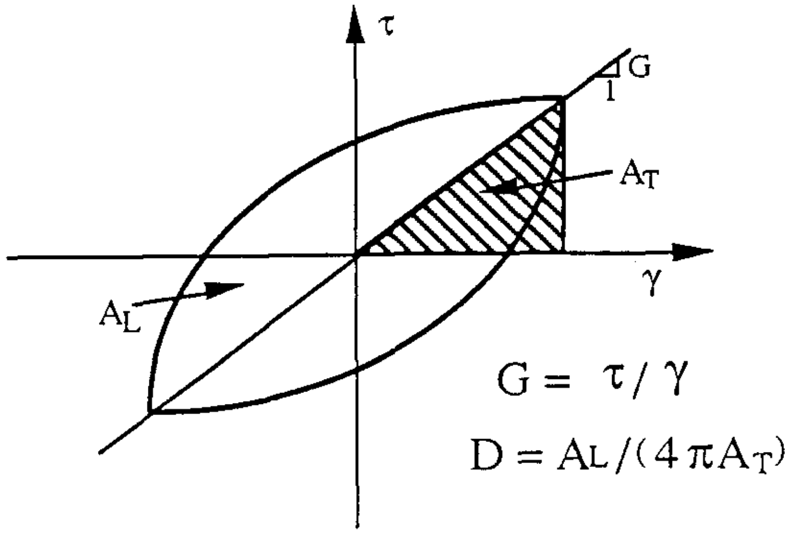
The RCTS apparatus developed at UT-Austin has three advantages. First, both RC and TS tests can be performed with the same set-up simply by changing (outside the apparatus) the frequency of the forcing function. Variability due to preparing "identical" samples is eliminated so that both test results can be compared effectively. Second, the torsional shear test can be performed over a shearing strain range between 10^{-5}% and 10^{-1}%. Common types of torsional shear tests, which generate torque by mechanical motors outside of a confining chamber, are usually performed at strains above 0.01% because of system compliance. However, the RCTS apparatus generates torque with an electrical coil-magnet system inside the confining chamber, thus eliminating the problem with an external motor. The torsional shear test can be performed at the same low-strain amplitudes as the resonant column test, and results between TS and RC tests can be easily compared over a wide range of strains. Third, the loading frequency in the torsional shear test can be changed easily from 0.01 Hz to 10 Hz or more. The effect of frequency on deformational characteristics can be investigated effectively using this apparatus.

Resilient Modulus Test

The equipment used in resilient modulus (M_R) test is similar to most cyclic triaxial equipment except that the cell is somewhat larger to facilitate the internally mounted load and deformation transducers. Because transducers are located inside the triaxial chamber, air is generally used as a cell fluid to provide confinement to the specimen. The external loading source, in most cases, is a closed-loop electrohydraulic system capable of providing a variable load of fixed cycle and load duration (usually 0.1 second). The final setup of triaxial chamber developed at UT-Austin is shown in Fig. 3. It should be mentioned that this M_R testing equipment cannot measure accurately axial strains smaller than about 0.01% because of the limitation in the resolution of the transducers installed and compliance of the system itself.



a) Specimen in the Torsional Shear Test Apparatus



b) Measurement of Shear Modulus and Damping Ratio

Figure 2 Configuration of a Torsional Shear Test and Evaluation of Shear Modulus and Material Damping Ratio

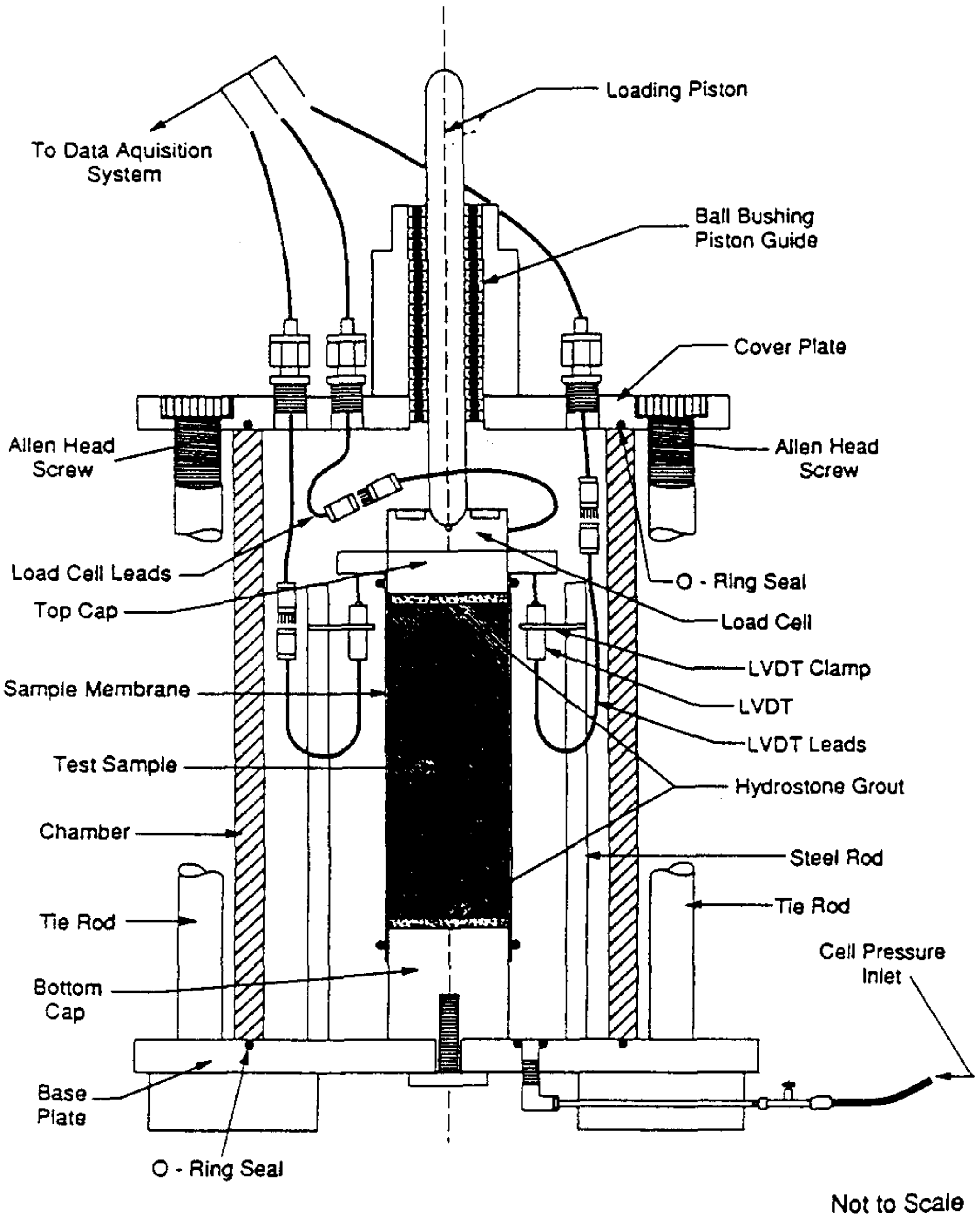


Figure 3 Final Configuration of the Triaxial Cell in the Resilient Modulus Test

During the M_R test, specimens are subjected to testing sequences that consist of the application of different repeated axial deviator stresses under different confining pressures. The recoverable axial strain is also determined by measuring the resilient deformation of the specimen, and then resilient modulus is determined from the ratio between axial deviator stress and recoverable axial strain. The standard testing procedure was specified in 1982 by AASHTO T-274. However, in recent years this test method has increasingly criticized and new testing procedures are suggested.

RCTS RESULTS ON DRY SAND

Typical variations in shear modulus of dry sand with shearing strain amplitude and number of loading cycles are shown in Fig. 4. Shear moduli determined from the first and tenth cycles in the TS test, the RC test, and the first cycle in the TS test after RC testing are plotted together. It is very interesting to note that, both TS (pseudo-static) and RC (dynamic) tests result in almost identical shear moduli at shearing strains below about 0.001%. In this strain level, the behavior of dry sand is elastic, and shear modulus is independent of strain amplitude and type of test. In the past, static and dynamic stiffnesses were considered as different material properties and dynamic stiffness measured by RC test was considered to be much higher than the static stiffness. This work shows that dynamic and static stiffnesses of dry sand are the same material property at small strains, if accurate stress-strain measurements are achieved in the static tests.

However, above the cyclic threshold strain, shear modulus is affected by the number of loading cycles; the shear modulus from the tenth cycle is greater than from the first cycle, and the difference between the two moduli increases as shearing strain increases. Moduli obtained from the RC test during which at least 1000 loading cycles were applied before measuring the shear modulus, are greater than first-cycle moduli and are close to (or greater than) the tenth-cycle moduli. The difference in shear moduli determined at different loading cycles is caused by cyclic hardening when strain amplitude exceeds the cyclic threshold. However, after many load repetitions shear modulus is again independent of loading cycles and shear modulus measured by TS and RC tests result in equivalent values.

Typical variations in damping ratio with strain amplitude determined at different numbers of loading cycles are shown in Fig. 5. At strains below about 0.002%, damping ratios measured for different number of loading cycles are almost identical. At this small-strain level, the damping ratio of dry sand is also independent of measurement technique; in other words, both TS and RC tests give the same damping value. However, at higher strains, material damping is affected by the number of loading cycles. Damping ratio measured for the

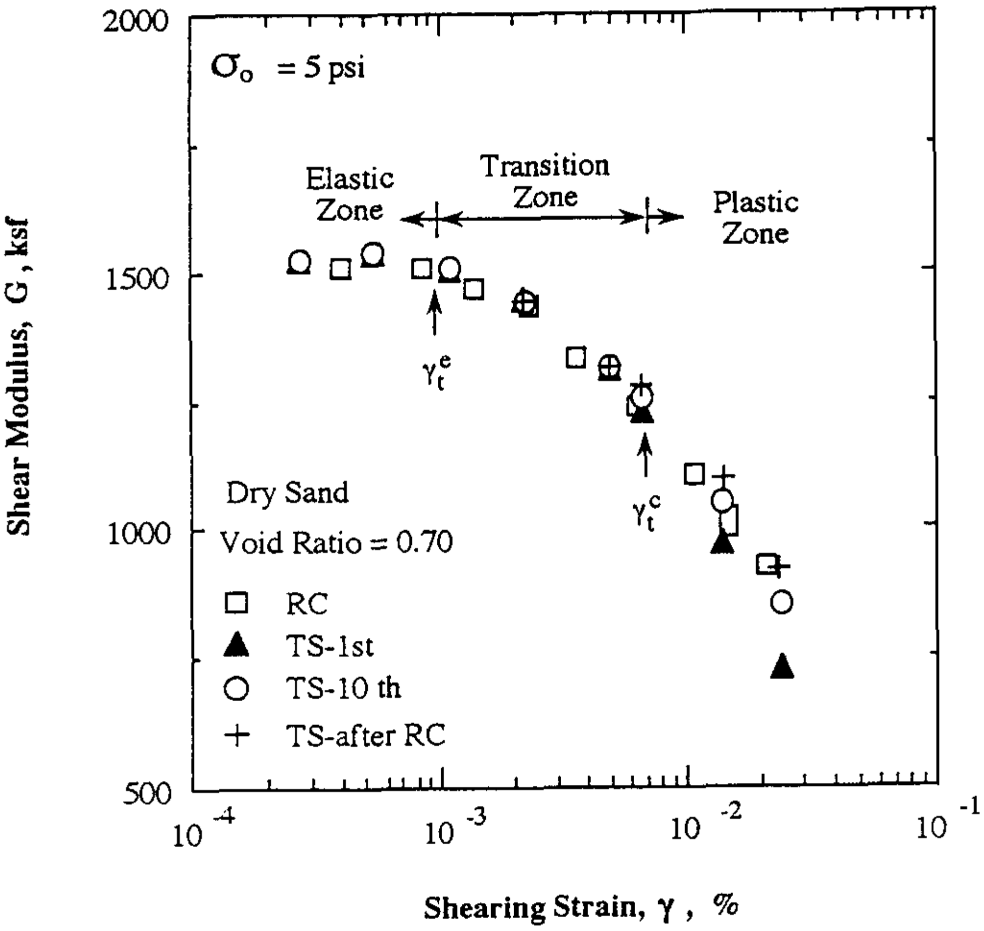
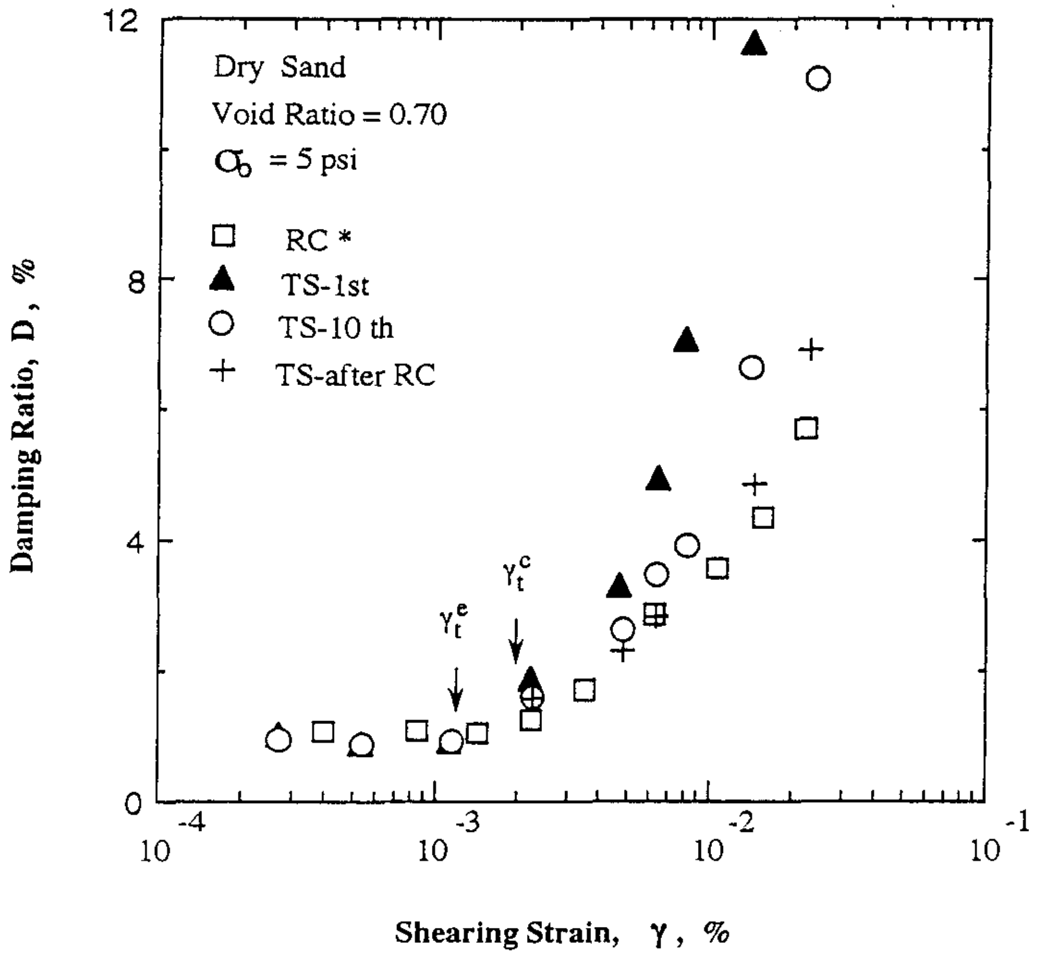


Figure 4 Variation in Shear Modulus of Dry Sand with Strain Amplitude Determined from 1st Cycle, 10th Cycle, RC test, and after RC test at a Confining Pressure of 5 psi (34 kPa)



* Damping ratios in RC tests were corrected for equipment damping by subtracting a damping value of 0.4 %.

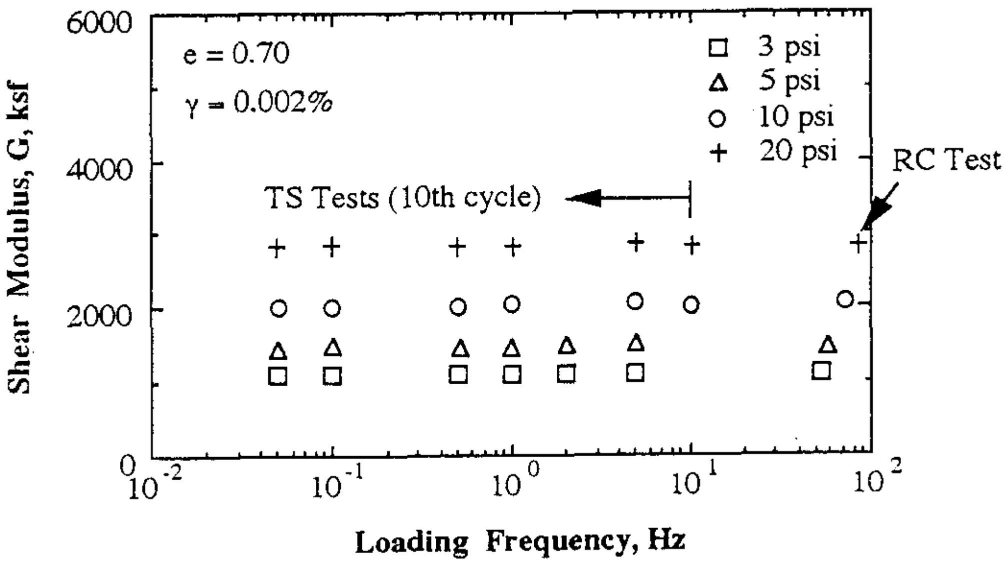
Figure 5 Variation in Damping Ratio of Dry Sand with Strain Amplitude Determined by 1st Cycle, 10th Cycle, RC test, and After RC testing at a Confining Pressure of 5 psi (34 kPa) first cycle of loading is larger than the tenth cycle of damping ratio and the difference between the two damping ratios increases as shearing strain increases. Damping ratio determined by the RC test, in which at least 1000 loading cycles were applied before measuring damping, is even smaller than the tenth -cycle hysteretic damping ratio at high strain amplitudes. However, it is interesting to note that first cycle damping ratio determined by TS test after the RC test is nearly the same as the viscous damping ratio determined by the RC test.

To investigate the effect of loading frequency, the loading frequency in the TS test was varied between 0.05 and 10 Hz. The variation in shear modulus and material damping with loading frequency at different confining pressures are shown in Figs. 6a and 6b, respectively. It is clearly noted that both shear modulus and material damping of dry sand are independent of loading frequency at a given confining pressure even though shear modulus increases and material damping decreases as confining pressure increases. Therefore, it can be concluded that deformational characteristics of dry sand are frequency independent, and both stiffness and material damping obtained from dynamic tests such as the RC test are identical with the values from the quasi-static tests such as the TS test, provided the effect of number of loading cycles is considered in the comparison.

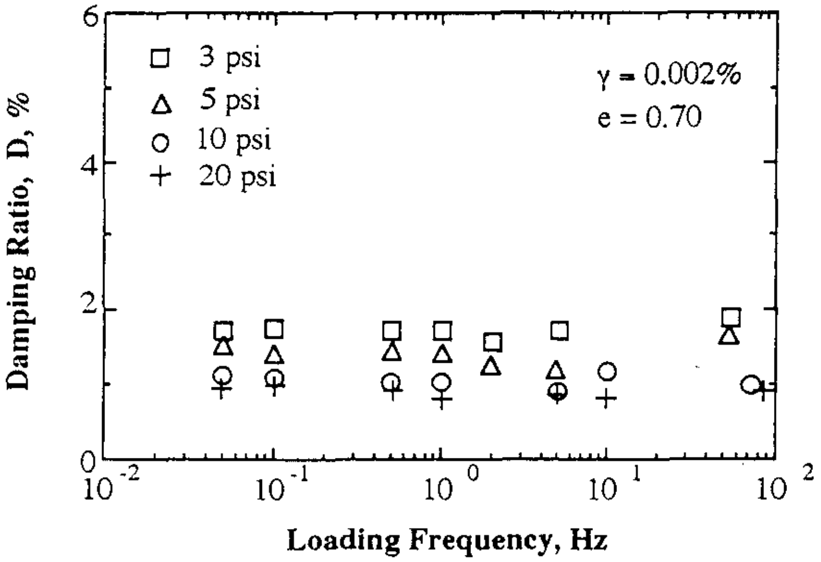
RCTS RESULTS ON COHESIVE SOILS

Typical variations in shear modulus of cohesive soil with strain amplitude determined for different numbers of loading cycles are shown in Fig. 7. At strains below about 0.006%, moduli determined from the first and tenth cycles are identical and independent of strain amplitude. In this strain range, cohesive soil shows elastic behavior and the elastic range of cohesive soil is a rather larger, almost an order of magnitude larger, than that of dry sand. At higher strains, however, the tenth-cycle modulus is smaller than the first-cycle one due to cyclic degradation, with the difference between moduli increasing as strain amplitude increases.

Moduli determined by the RC test are different from those obtained by the TS test over the whole strain range. Below the elastic threshold strain of about 0.006%, moduli from the RC test are larger than the corresponding ones measured by TS tests at the same strain amplitude. However, the difference between moduli from both tests does not vary with strain. In the RC test, moduli at small strains were measured at a loading frequency of 43 Hz while corresponding values in the TS test were obtained at 0.5 Hz. Generally, the stiffness of cohesive soil increases with increasing loading frequency. Therefore, the moduli differences between the two types of tests at small strains can be explained by the difference in loading frequency. At shearing strains above the cyclic threshold, the difference in shear moduli between RC and TS tests decreases as shearing strain increases. At large strains, moduli



a) Variation of Shear Modulus



b) Variation of Damping Ratio

Figure 6 Variations in Shear Modulus and Damping Ratio of Dry Sand with Loading Frequency

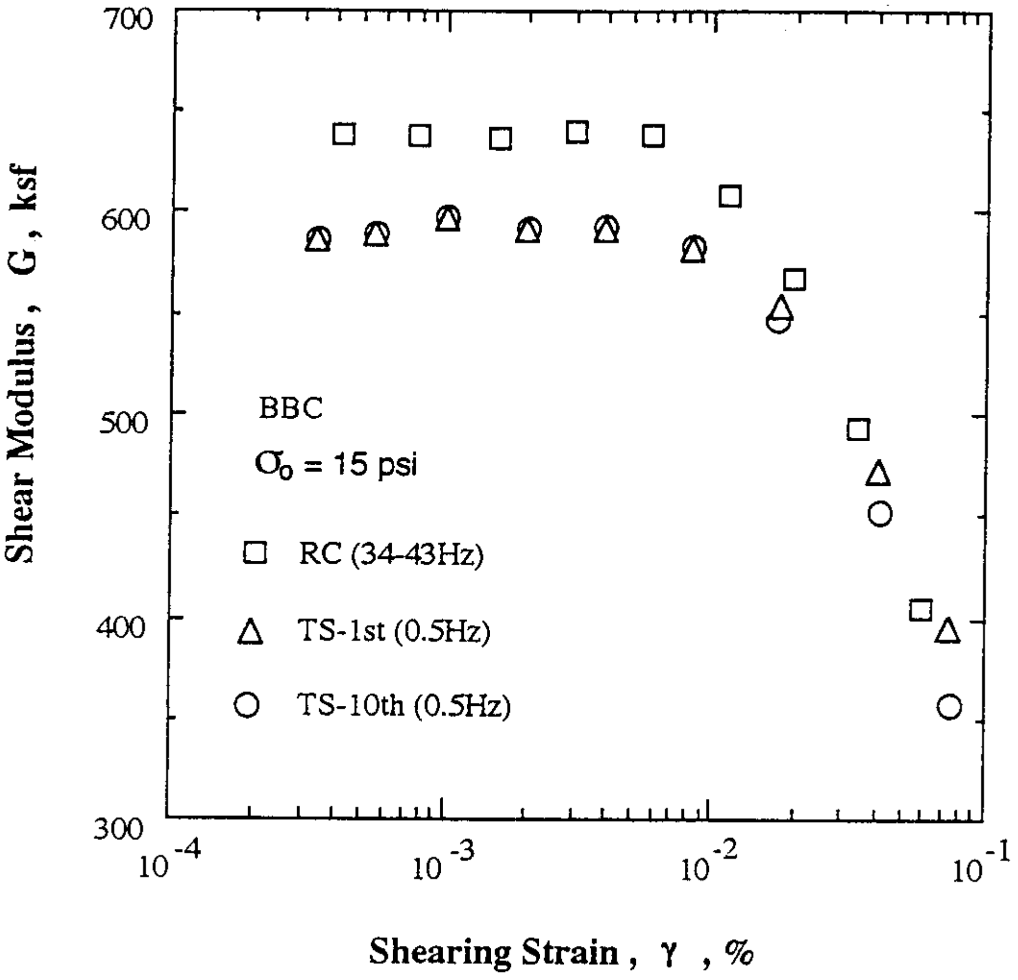


Figure 7 Typical Variation in Shear Modulus of Cohesive Soil with Strain Amplitude Determined for the 1st and 10th Cycles of Torsional Shear Loading and in the Resonant Column Test

obtained from the RC test can even be less than those obtained from the TS test because of cyclic degradation during RC testing where at least 1000 cycles are applied in measuring the modulus. In this case, cyclic degradation can have a more significant effect than the effect of loading frequency.

To investigate the effect of loading frequency on stiffness, the variation in shear modulus with loading frequency is plotted at strain amplitudes of 0.001% and 0.01% in Fig. 8. Moduli from RC tests are also included. It is interesting to note that the modulus of cohesive soil increases linearly as a function of the logarithm of loading frequency. The effect of loading frequency on stiffness was investigated for various undisturbed soils and compacted subgrade soils. The effect of frequency ranges between 2.2% and 5.7% per log cycle of frequency for undisturbed soils and between 4.5% and 8.4% per log cycle of frequency for compacted subgrade soils (Kim, 1991).

Typical variations in damping ratio with strain amplitude determined at different number of loading cycles are shown in Fig. 9. Damping ratios determined for the first- and tenth-cycles of TS loading are almost identical and it can be concluded that material damping of these undisturbed cohesive soils was not affected by cyclic loading over the complete strain range tested. However, damping measured in the RC test is much larger than corresponding measurements in the TS test, with the difference between the two methods being almost constant over the whole strain range. This difference can be explained as the effect of loading frequency.

A typical variation in damping ratio of cohesive soil with frequency is plotted in Fig. 10. Damping ratios at frequencies above 1 Hz were corrected by subtracting the values of damping ratio detected in metal specimen (Kim et al. 1991; Stokoe 1992). The damping ratio is almost independent of loading frequency at frequencies below 2 Hz. At 5 Hz, the damping ratio starts to be affected by loading frequency. It can be noted then that on cohesive soils damping ratio increases as loading frequencies increase above 5 Hz.

APPLICATION TO M_R TESTS

One aspect of this research has been to help develop an understanding of moduli measured during M_R testing, especially at small strains, and compare M_R measurements with RCTS measurements. Synthetic (urethane) calibration specimens were developed with stiffnesses ranging from that of very soft subgrade to stiff uncemented base. Stiffness characteristics were evaluated with three independent tests; static compresion, resonant column,

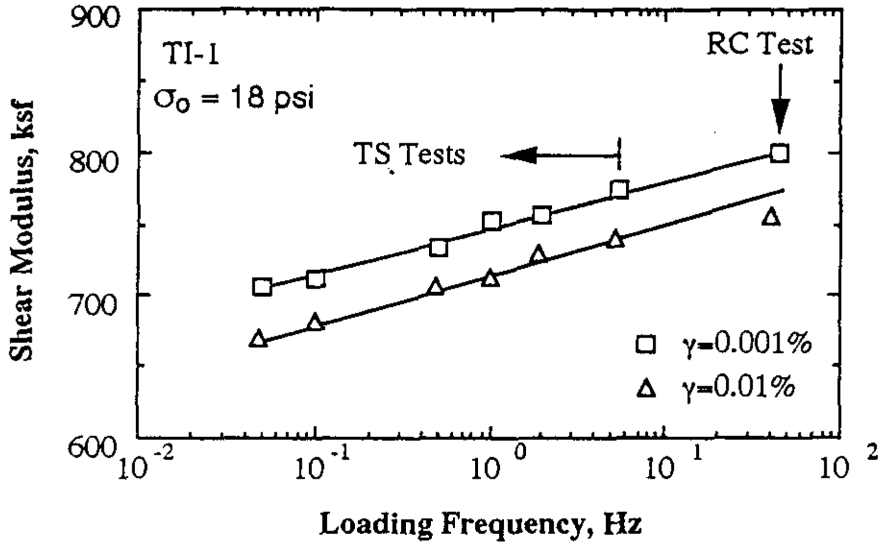
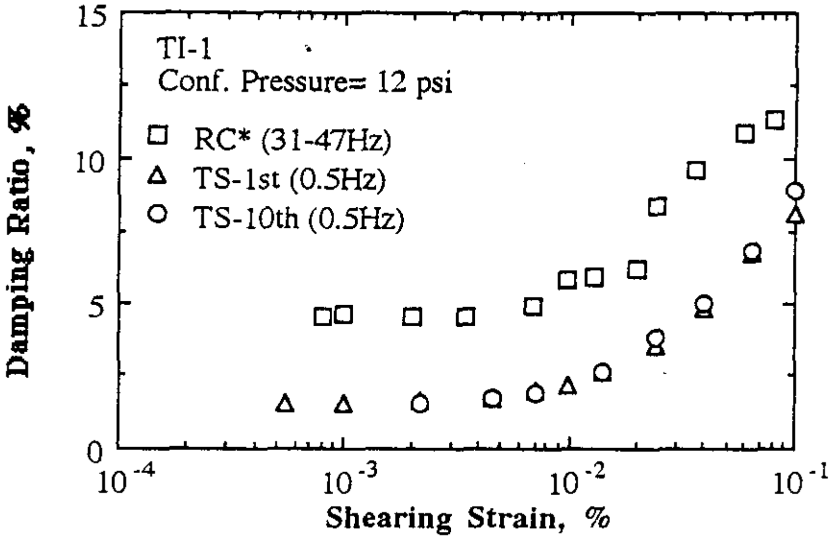


Figure 8 Typical Variation in Shear Modulus of Undisturbed Cohesive Soil with Loading Frequency



* corrected for equipment damping by subtracting a damping value of 0.4%

Figure 9 Typical Variation in Damping Ratio of Cohesive Soil Determined for Different Numbers of Loading Cycles

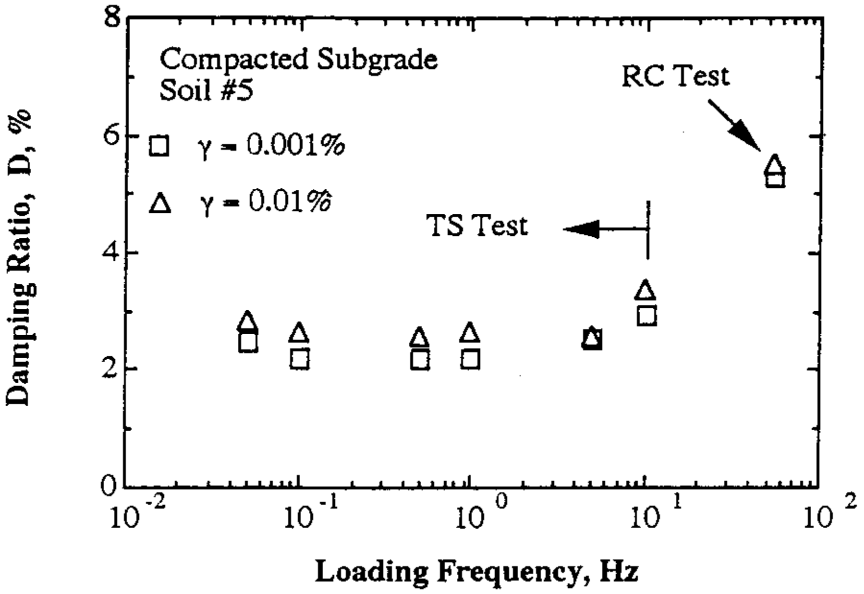


Figure 10 Typical Variation in Damping Ratio of Cohesive Soil with Loading Frequency

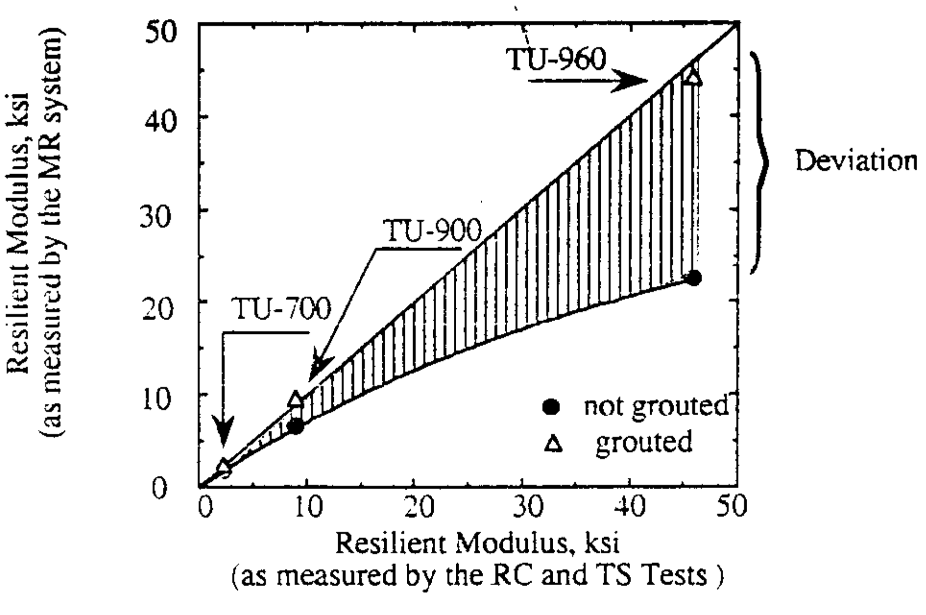


Figure 11 Comparison of Resilient Modulus Determined by M_R and Torsional Testing Systems Showing the Effect of Grouting

and torsional shear tests. Urethane can be considered to be a linear, viscoelastic material with stiffness characteristics that are independent of confining pressure, strain amplitude, and stress history. These properties make urethane a good material to construct calibration specimens which can be used in the evaluation of M_R equipment. Urethane stiffness is, however, dependent on loading frequency and temperature. Therefore values of Young's modulus used to equate to M_R have to be selected at the appropriate frequency and temperature (Stokoe et al., 1990).

Like all other cyclic loading equipment, M_R equipment requires careful calibrations of all transducers (LVDT's and load cell). In addition, calibration of the complete system is advisable to achieve the reliable results for stiff specimens or for small-strain measurements. To calibrate the entire M_R system, the synthetic specimens of known stiffness properties were used. To study the dynamic motions and find the best location for monitoring axial deformations, relative movements of several points in the triaxial chamber were measured while performing M_R tests on synthetic samples and then final set-up of the triaxial cell was achieved as shown in Fig.3 (Pezo et al., 1991).

Once the final arrangement was selected, more testing with synthetic samples was performed. The new results, although closer to the moduli than those previously obtained by Claros et al.(1990), were not close enough as shown in Fig. 11. It was then decided to glue the specimen in the equipment. Hydrostone paste was used as the glue to improve the contact between the specimen and the top and bottom platens. Finally, new values were very close to the values obtained from independent tests as shown in Fig. 11. The deviations in the moduli caused by not grouting the specimens are significant for materials with resilient moduli greater than about 5000psi.

To determine the capability of the testing equipment, resilient moduli of compacted subgrade soils obtained from M_R and RCTS equipments were compared. Companion specimens (two samples with "identical" characteristics) were prepared so that they could be tested at the same time. To make this comparison, shear moduli obtained with the RC and TS tests were converted to equivalent resilient moduli. In addition, the moduli were adjusted to an excitation frequency of 10 Hz, which is the primary loading frequency in the M_R measurements. Figure 12 shows the typical variation in resilient modulus with axial strain as determined by the three different testing methods. Moduli obtained from the M_R test overlap nicely with values from the RC and TS tests. This overlapping of values provides sufficient evidence that a reliable system for measuring the elastic properties of subgrade materials has been developed.

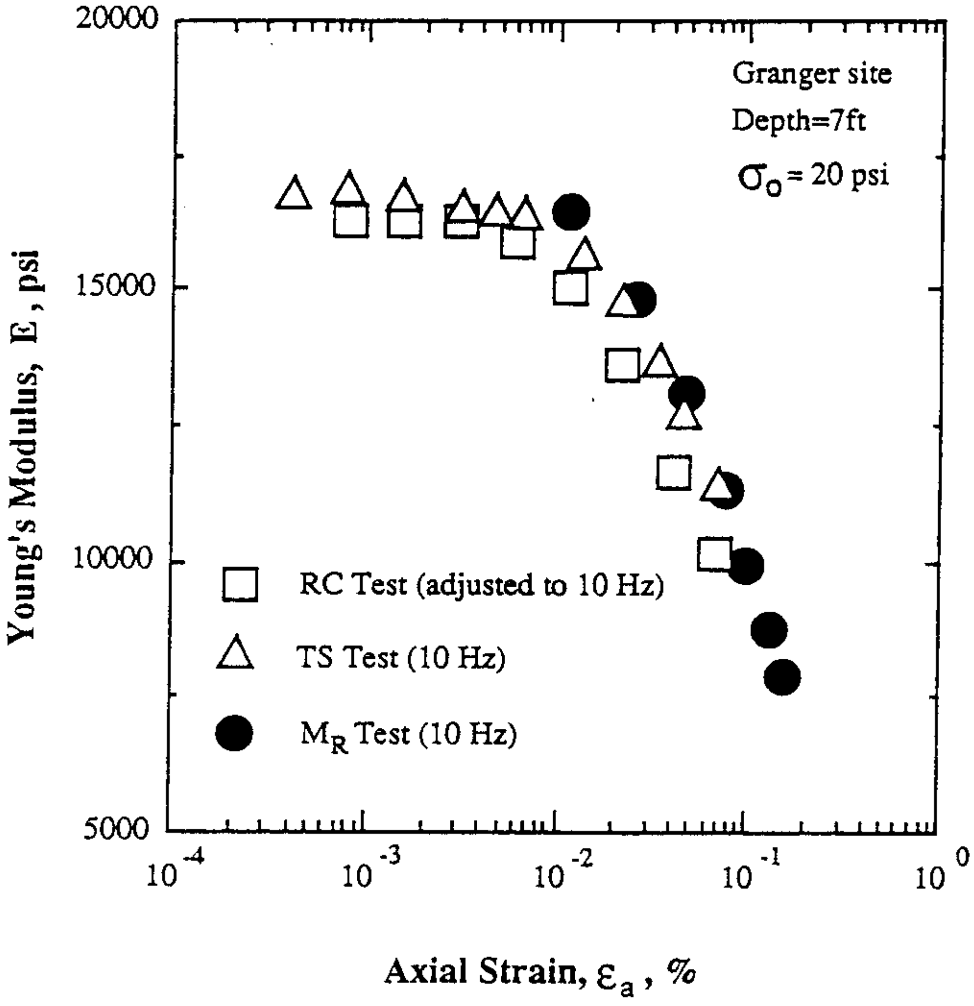


Figure 12 Comparison of M_R Values of Undisturbed Compacted Subgrade Soil Determined by RC, TS, and M_R Tests

Resilient modulus of compacted subgrade soils was also characterized with RCTS equipment (Kim and Stokoe, 1992). The effects of strain amplitude and loading frequency on M_R values were investigated varying the plasticity index (PI). The elastic threshold strain of compacted cohesive soils ranged from 0.0008% to 0.0048% as PI varied from 4% to 52%. Both RC and TS tests accurately measured resilient modulus below the elastic threshold strain. On the other hand, M_R equipment could not measure resilient modulus below the elastic threshold strain because of the lack of resolution. Resilient modulus was found to increase as loading frequency increases, even below the elastic threshold. The variation of the general normalized curves (E / Emax) with plasticity index obtained from Ramberg-Osgood model is plotted in Fig. 13. Using the curves in Fig. 13, once the small-strain modulus (Emax) of compacted subgrade soils is obtained from field seismic methods, it is possible to predict the strain dependent behavior of subgrades using the normalized curve at the given plasticity index.

CONCLUSION

The deformational characteristics of dry sand and cohesive soils were investigated at small to intermediate strains using resonant column and torsional shear tests. Both RC and TS tests were performed on the identical specimen in a sequential series.

An "elastic" zone where deformational characteristics are independent of number of loading cycles and strain amplitude was found at small strains in dry sand. Above the cyclic threshold strain, shear modulus increases and damping ratio decreases with increasing number of loading cycles. Once cyclic hardening is completed for dry sand, which occurred in less than 1000 cycles of loading during RC test, the deformational characteristics become independent of number of loading cycles, and moduli and damping ratios measured by both RC and TS tests result in equivalent values. For dry sand, both stiffness and damping ratio are independent of loading frequency and values obtained from the TS tests are identical with values from the RC test, provided the effect of number of loading cycles is considered in the comparison.

At small strains below the elastic threshold, deformational characteristics of cohesive soils measured in the TS test are independent of number of loading cycles and strain amplitude. Above the cyclic threshold strain, cohesive soil exhibits a decrease in shear modulus with increasing number of loading cycles. However, material damping of cohesive soil is essentially independent of number of loading cycles and exhibited no cyclic threshold over the strain range tested. Both shear modulus and damping ratios obtained from RC and TS tests are different over the complete strain range. The shear modulus of cohesive soil increases linearly as a function of the logarithm of loading frequency. However, the effect of frequency does not

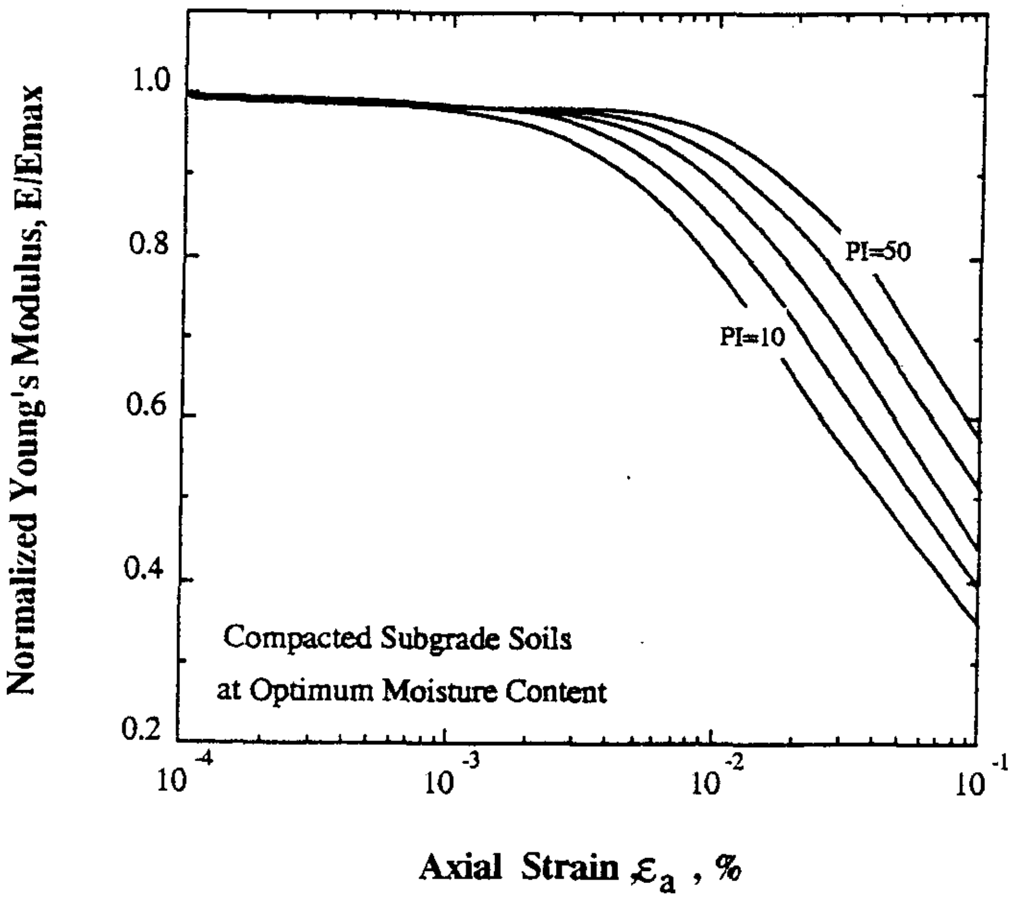


Figure 13 Variation in Normalized Young's Modulus with Plasticity Index for Compacted Subgrade Soils at Optimum Moisture Content

begin to increase material damping until loading frequency exceeds about 2 Hz.

To develop a reliable M_R testing system, synthetic specimens were developed and calibrated by independent tests. With known stiffness specimens, compliance problems in M_R testing equipment were detected, and modifications to the equipment were undertaken. After calibrating the M_R equipment with synthetic specimens, compacted subgrade soils were tested using M_R and RCTS equipment. Moduli obtained from both tests agreed well at strains above about 0.01% once frequency is accounted for. The effect of plasticity index on the normalized behavior (E / Emax) of compacted subgrade soils was investigated.

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