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SHEAR MODULUS AND DAMPING RATIO OF SANDS AT MEDIUM TO LARGE SHEAR STRAINS WITH CYCLIC SIMPLE SHEAR TESTS

Fardin JAFARZADEH[1], and Mohammad MORIDZADEH[2]

ABSTRACT

Determination of soil dynamic parameters including shear modulus and damping ratio plays a crucial role in prediction of soil behavior in seismic loading. Different devices are often employed to assess theses characteristics in laboratory tests such as Cyclic Simple Shear Device (CSSD) which has been suggested by different researchers. In previous studies, the influence of loading frequency has been investigated rarely and they mainly focused on determination of these parameters at medium strains. In the present study, dynamic properties of Babolsar sand were estimated and compared to those from Toyoura sand. The tests are performed on loose and dense samples. The loading is a sinusoidal shape cyclic loading with various frequencies. The SGI type cyclic simple shear device was used to study the secant shear modulus, *G*, and damping ratio, *D*, of the two above mentioned sands at medium to large shear-strain amplitudes $\gamma_c \approx 0.1\% - 20\%$. The effect of cyclic strain amplitude (γ_c), type of soil, vertical effective consolidation stress (σ_{vc}), and particularly frequency of cyclic loading (*f*) up to 15*Hz* were investigated. The tests were conducted on the constant-volume method equivalent to undrained condition. In addition the results are presented in different ways like hysrteresis curves, effective stress paths.

Keywords: Sandy soil, Shear Modulus, Damping ratio, Cyclic Simple Shear Test, Large Strains

INTRODUCTION

Reliable and accurate shear moduli of soils are necessary for the solution of many soil dynamics problem, such as the vibration of machine foundations, response of soil deposits and earth structures to earthquake loads, the response of offshore soils and supported structures to ocean wave loads, evaluation of traffic vibration, and so forth. In these problems, typically involving cyclic loading, the stress-strain behavior of soils is described by cyclic stress-strain loops, similar to the idealized loop in Fig. 1. In Fig. 1 τ is shear stress, γ is shear strain, τ_c is cyclic shear stress amplitude, γ_c is cyclic shear strain amplitude, G_{max} is maximum shear modulus at small strains, and G_s is secant shear modulus corresponding to τ_c and γ_c.

Various idealized models and analytical techniques may be used to represent a soil deposit and its response, but whatever procedure is followed; it is first necessary to evaluate the appropriate dynamic properties of the materials in the deposit. Precise measurement of dynamic soil properties is somewhat a difficult task in the solution of geotechnical earthquake engineering problems. Several laboratory and field techniques are available to measure the dynamic properties in which many are employed in these measurements at low-strain and many are in the large strain levels. However, the choice of a

[1] Assistant Professor, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran, Email: fardin@sharif.edu
[2] M.Sc., Geotechnical Engineering, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran, Email: moridzadeh@mehr.sharif.edu

particular technique depends on the specific problem to be solved. Figure 2 shows the changes in soil properties with shear strain.

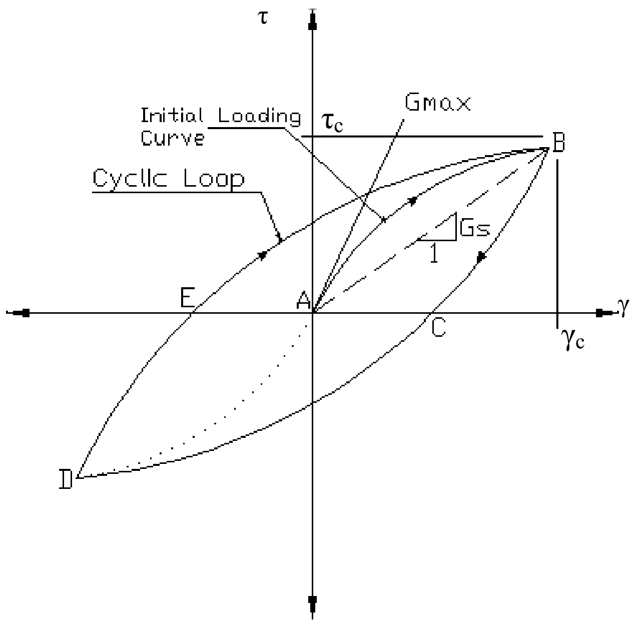

Figure 1. Idealized First-Cycle Stress-Strain Loop

Very few laboratory tests are available to measure the dynamic properties of soils at low strain levels. Resonant Column Test, Ultrasonic Pulse Test and the piezoelectric bender element test are the commonly employed techniques.

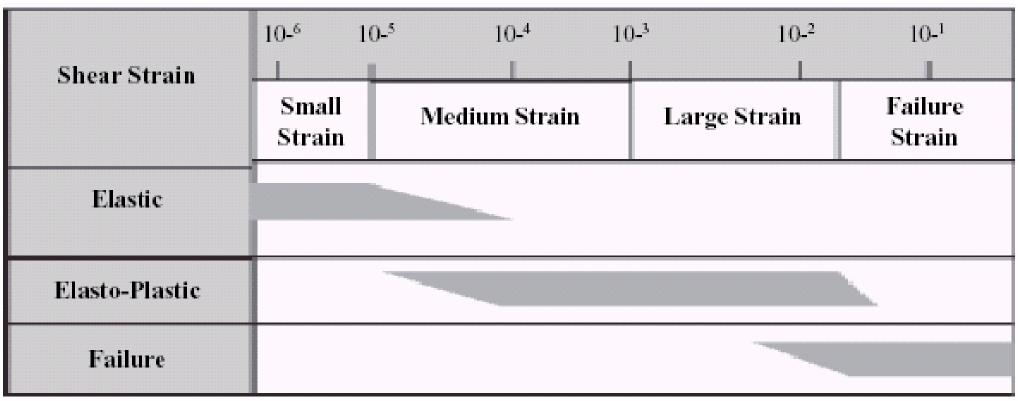

Figure 2. Changes in soil properties with shear strain (Sitharam, T.G., and Govinda Raju, L., 2003)

For the measurement of strain dependent dynamic properties, several devices have been developed. Typical examples are Cyclic Triaxial Test, Cyclic Direct Simple Shear Test and Cyclic Torsional Shear Test devices.

In the past, the shear moduli of soils at small cyclic strains have been investigated in the laboratory mainly with high frequency resonant column tests (Woods 1991, 1994), while the cyclic shear tests, such as cyclic triaxial, cyclic torsional shear, and cyclic simple shear, have been used to investigate the properties at large cyclic strain amplitudes. More recently, however technical improvements in small-strain cyclic testing with triaxial, torsional, and simple shear devices have resulted in more reliable measurements of stiffness characteristics at small γc. Some examples of such complex and often innovative small-strain laboratory experiments are presented in Goto et al. (1991), Kim and Stokoe (1994), Hayashi at al. (1994), Soga (1994), Tatsuoka et al. (1994), Stokoe et al. (1995), and Shibuya et al. (1995). Furthermore, evaluation of dynamic properties of sandy soils at large strain levels is presented in Sitharam and Govinda Raju (2003).

This paper represents the result of a series of large-strain, constant-volume equivalent-undrained direct simple shear cyclic tests. In the cyclic simple shear device, two sands were tested in the approximate range $\gamma_c \approx 0.1\% - 20\%$. The effects of cyclic shear strain amplitude, γ_c, soil type, and particularly frequency of cyclic loading, *f*, up to 15Hz at large strains were investigated and are systematically presented.

SOIL TESTED

This study made an attempt to provide the reference information for the natural sand commonly find in Northern Iran, so called Babolsar Sand and the Japanese Standard Sand, Toyoura. The two soils tested are listed in Table 1 along with their basic physical properties and classification characteristics. They are two sands, Babolsar sand and Toyoura sand. The two sands were tested in the cyclic simple shear device under constant volume conditions, the sands in a wet state. The grain-size distribution curves of the two sands are shown in Fig.3.
In Table 1 C_u is the uniformity coefficient and C_c is the coefficient of curvature.

Table 1. Index Properties of Soils

Granular Material	G_s	e_{max}	e_{min}	D_{10} (mm)	D_{50} (mm)	C_u	C_c
Babolsar Sand	2.777	0.815	0.578	0.13	0.21	1.77	0.97
Toyoura Sand	2.660	0.914	0.673	0.15	0.21	1.47	0.98

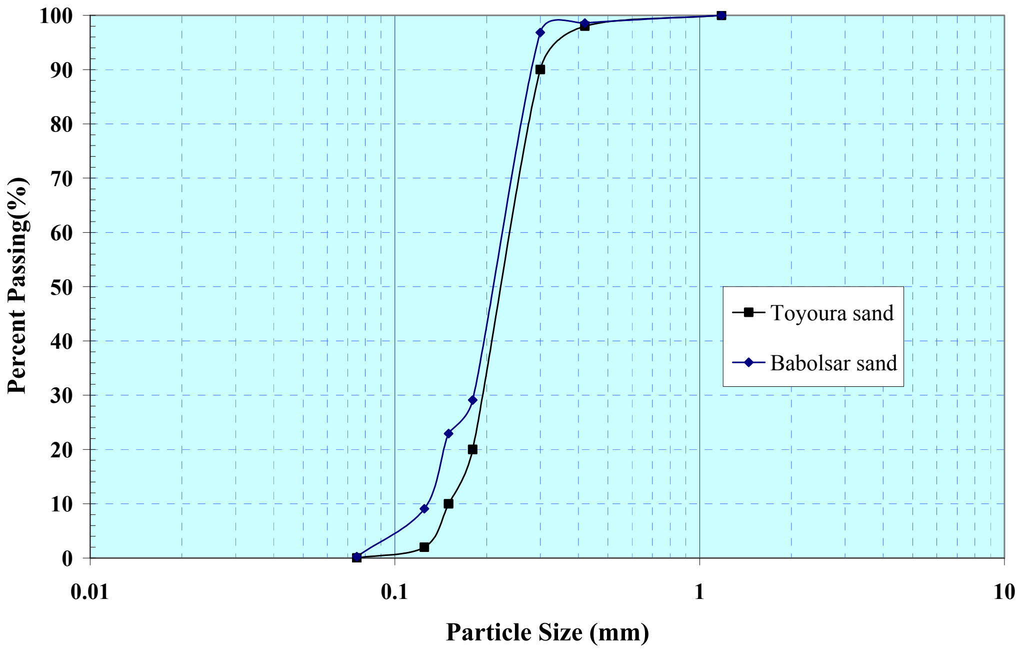

Figure 3. Grain size distribution of Soils

TESTING APPARATUS

The SGI-type concept of Cyclic Simple Shear Device (CSSD) with circular specimen confined in a rubber membrane supported by a series of slip rings has been used. The Cyclic Simple Shear System is a plane strain device. The shear strain is induced by horizontal displacement at the bottom of the sample relative to the top. The horizontal diameter of the sample remains constant. Therefore, any change in volume shall be as a result of vertical movement of the top platen. Constant-volume equivalent to undrained SGI-type CSS tests were conducted. During the shearing stage of the test the vertical height of the sample is maintained at a constant height by the vertical actuator in a closed control loop with the vertical displacement transducer. The rings maintain a constant sample diameter. During shear only the length of the sample side changes. The test is undrained so we maintain a constant volume. The height stays constant which gives us the required test conditions for simple shear. Typical cyclic simple shear device and SGI-type cyclic simple shear device at the Advanced Soil Mechanics Laboratory of Sharif University of Technology are shown in Fig, 4 and Fig. 5 respectively.

The sample is 70 mm in diameter and 23 mm high. It is positioned on a pedestal with a top cap the same as a triaxial sample. The sample has a rubber membrane placed and secured with "o" rings. To maintain a constant diameter throughout the test the sample is supported by a series of rings. During shear the rings slide across each other.

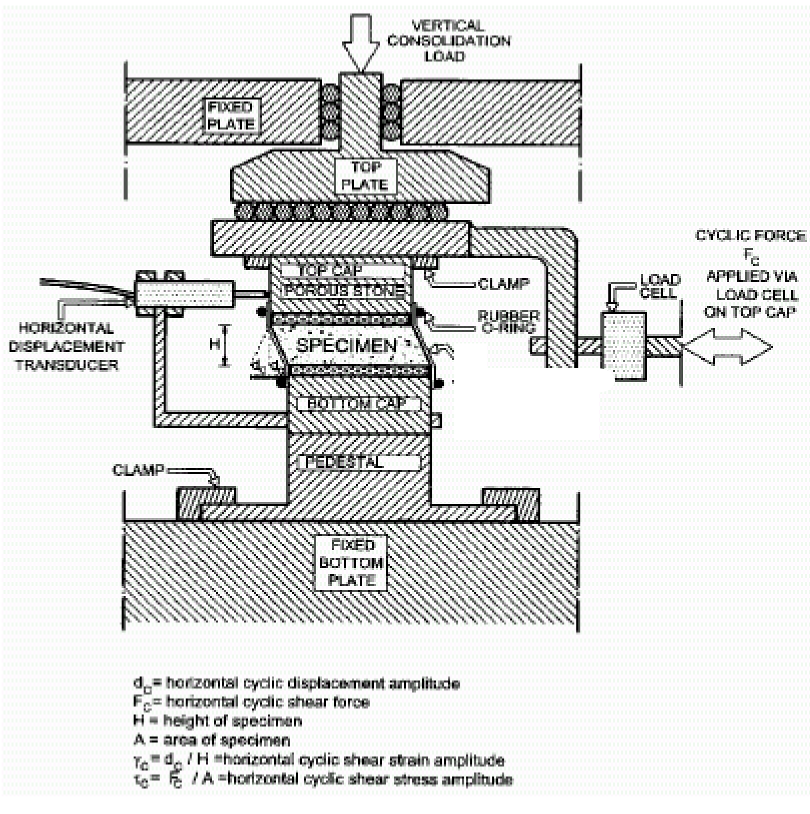

Figure 4. Typical cyclic simple shear device (Lanzo, Vucetic, and Doroudian, 1997)

TESTING PROGRAM

The testing program is shown in Table 2. For each test, a specimen was prepared and subjected to vertical stress σ_v' listed in Table 2 until the completion of primary consolidation; they were then under the same σ_v' subjected to several cycle strain-controlled tests.

Figure 5. SGI-type cyclic simple shear device at the Advanced Soil Mechanics Laboratory of Sharif University of Technology

In the consecutive cyclic strain-controlled tests, the level of constant cyclic shear-strain amplitude, γ_c, relative density, *Dr*, and frequency, *f*, varied from test to test. The amplitude γ_c varied between 0.1% and 20% and was applies in each test for more than 100 cycles. The tests were conducted for relative densities, *Dr*, 30% and 70%. Frequency, *f*, varied within a range between 1 and 20 *Hz*. The shape of the cyclic straining was similar to sinusoidal.

EXPRIMENTAL INVESTIGATION

Sample Preparation

Soil specimens of size 70 mm diameter and 23 mm in height were prepared using wet tamping technique. The sand was poured and then densified to the required density. The specimens were prepared at two different target relative densities (*Dr*), including 30 and 70%.

Cyclic Loading Procedure

Strain–controlled cyclic simple shear tests were carried out on the soil samples under constant-volume equivalent-undrained conditions to simulate essentially undrained field conditions during earthquake. During the shearing stage of the test the vertical height of the sample is maintained at a constant height by the vertical actuator in a closed control loop with the vertical displacement transducer. The rings maintain a constant sample diameter. The test is undrained so we maintain a constant volume. The height stays constant which gives us the required test conditions for sample shear. Cyclic loading was applied on the soil specimens using pneumatic actuator. In the strain-controlled method, the sample was subjected to cyclic loading with a constant lateral deformation till the soil liquefied. Pore water pressure may be evaluated by measuring the vertical load changes.

Table 2. Testing program

Test No.	Soil	Vertical consoilidation stress σ_v (kPa)	Relative density Dr (%)	Shear strain amplitude γ	Frequency f (Hz)
1	Babolsar	150	30	0.044	1
2	Babolsar	150	30	0.044	5
3	Babolsar	150	30	0.044	8
4	Babolsar	150	30	0.044	10
5	Babolsar	150	30	0.044	15
6	Babolsar	150	30	0.001	1
7	Babolsar	150	30	0.22	1
8	Babolsar	150	30	0.22	5
9	Babolsar	150	30	0.22	8
10	Babolsar	150	70	0.044	1
11	Babolsar	150	70	0.044	5
12	Babolsar	150	70	0.044	8
13	Babolsar	150	70	0.044	10
14	Babolsar	150	70	0.22	1
15	Babolsar	150	70	0.22	5
16	Babolsar	150	70	0.22	8
17	Babolsar	150	70	0.22	10
18	Toyoura	150	30	0.001	1
19	Toyoura	150	30	0.044	1
20	Toyoura	150	30	0.044	5
21	Toyoura	150	30	0.044	8
22	Toyoura	150	30	0.044	10
23	Toyoura	150	30	0.22	1
24	Toyoura	150	30	0.22	5
25	Toyoura	150	30	0.22	8

TEST RESULTS

As shown in Fig. 6, cyclic loops can be recorded clearly at $\gamma_c = 4.4\%$. Other CSS results confirm that cyclic loops can be recorded comfortably at $\gamma_c = 0.1\% - 22\%$. However, when frequency or relative density increase, the shear strain amplitude range is limited to $\gamma_c = 4.4\% - 22\%$.

As shown in Fig. 6, shear stress amplitude decreases with number of cycles at strain-controlled condition. Therefore, shear modulus decreases and damping ratio increases with number of cycles. However, their dependency on number of cycles decreases when strain amplitude decreases.

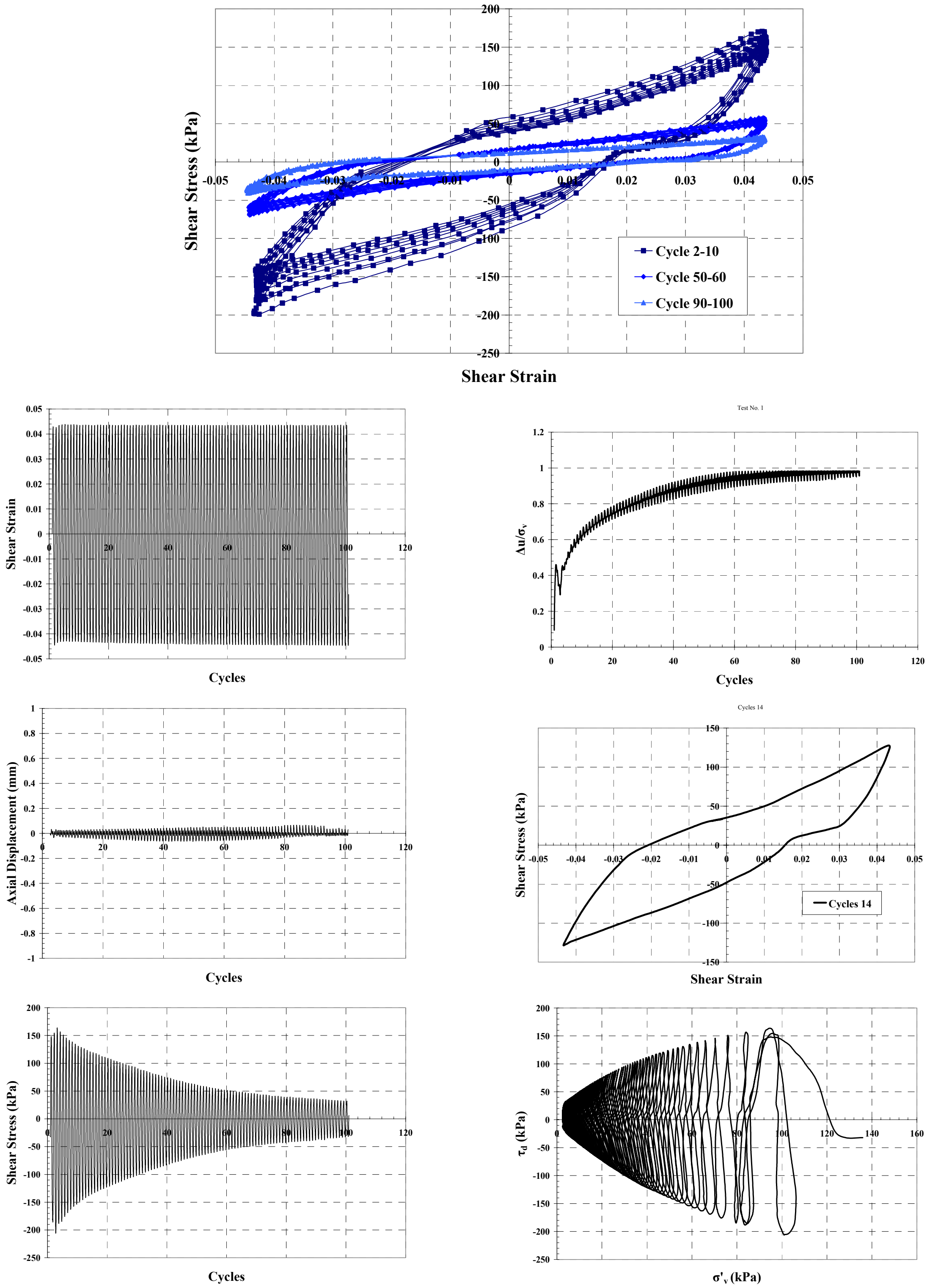

Figure 6. Typical CSS test results (Test No. 10, Babolsar sand, γ=0.044, Dr=70%,fr=1 Hz, σv=150KPa)

The effect of relative density or void ratio on the dynamic properties of sand is examined with two different relative densities for the same confining pressure of 150 kPa. Figures 7 and 8 show the variation of shear modulus and damping as a function of shear strain for Babolsar sand. In Fig. 7, G_{max} has been calculated by Seed (1970). It is clear that, the reduction in shear modulus and increase in damping vary significantly over a range of shear strain tested (0.1% to 20%). The soil, which is initially stiff, looses its stiffness due to the increase in pore water pressure as number of the loading cycles increase. The progression of loading cycles induces higher magnitudes of pore water pressures resulting in drastic reduction of shear modulus. The soil samples with higher relative densities exhibit slightly higher shear modulus and lower damping. The scatter in the values of shear modulus and damping of soil for the relative densities of 30% and 70% fall in the narrow band in the range of shear strain tested. The results indicate that the relative density has almost no significant influence on the dynamic properties of soil such as shear modulus and specially damping; however, the strain has a greater influence.

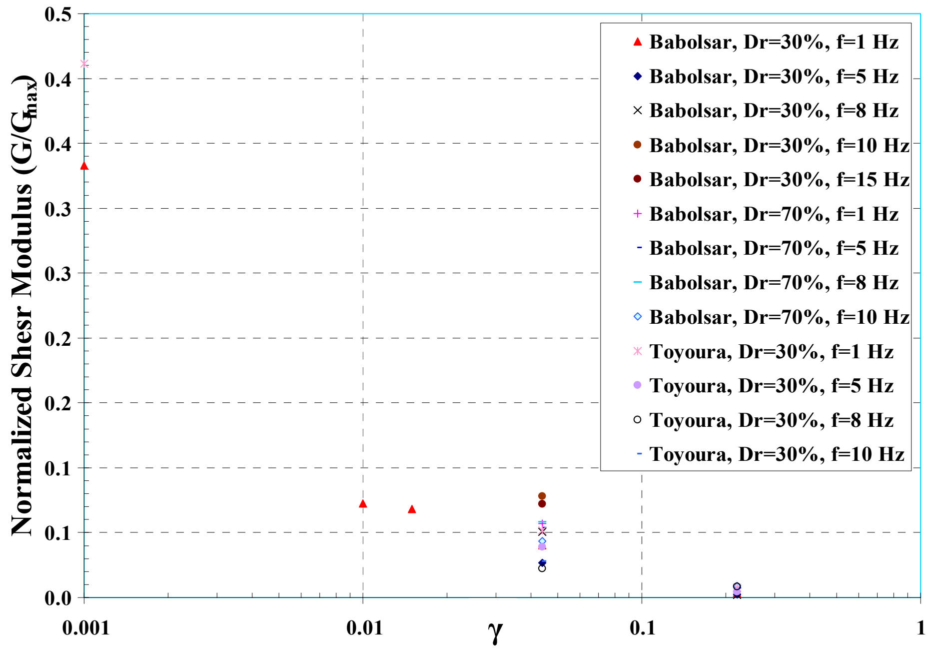

Figure 7. Variation of shear modulus with shear strain for Babolsar and Toyoura sand

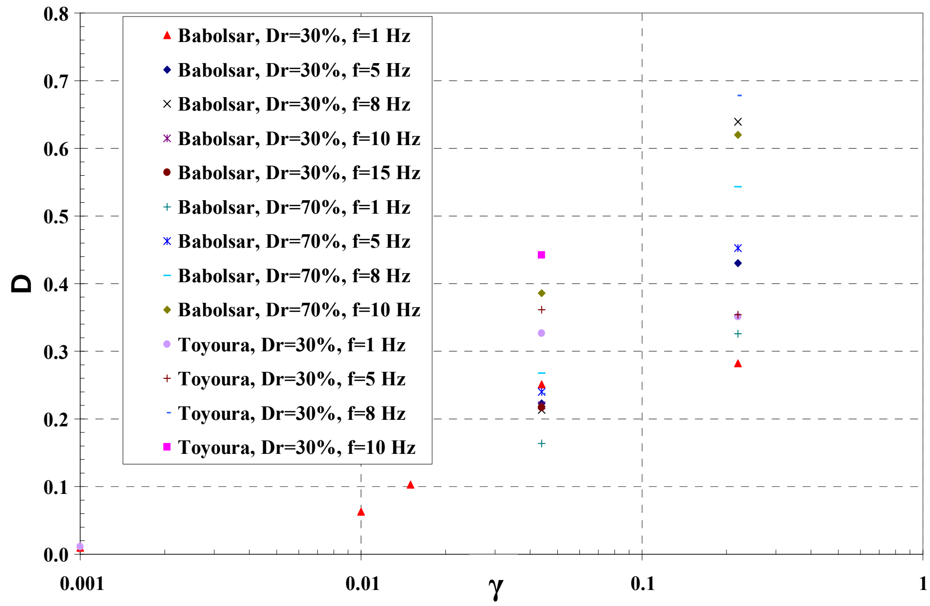

Figure 8. Variation of damping ratio with shear strain for Babolsar and Toyoura sand

Figures 7 and 8 show the strain dependent shear modulus and damping values of Toyoura sand for the relative density 30% tested at an effective confining pressure of 150 kPa in the range of shear strain 0.1% to 20%. Similar behavior has been observed as reflected in the Babolsar sand.

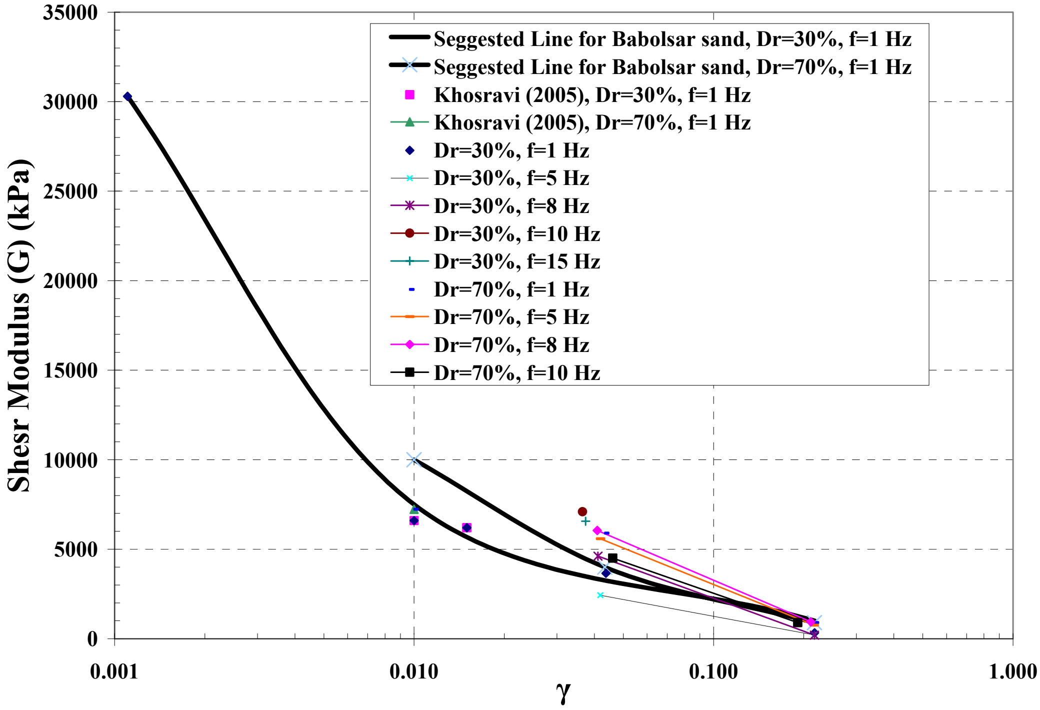

Figure 9. Variation of shear modulus with shear strain for Babolsar sand

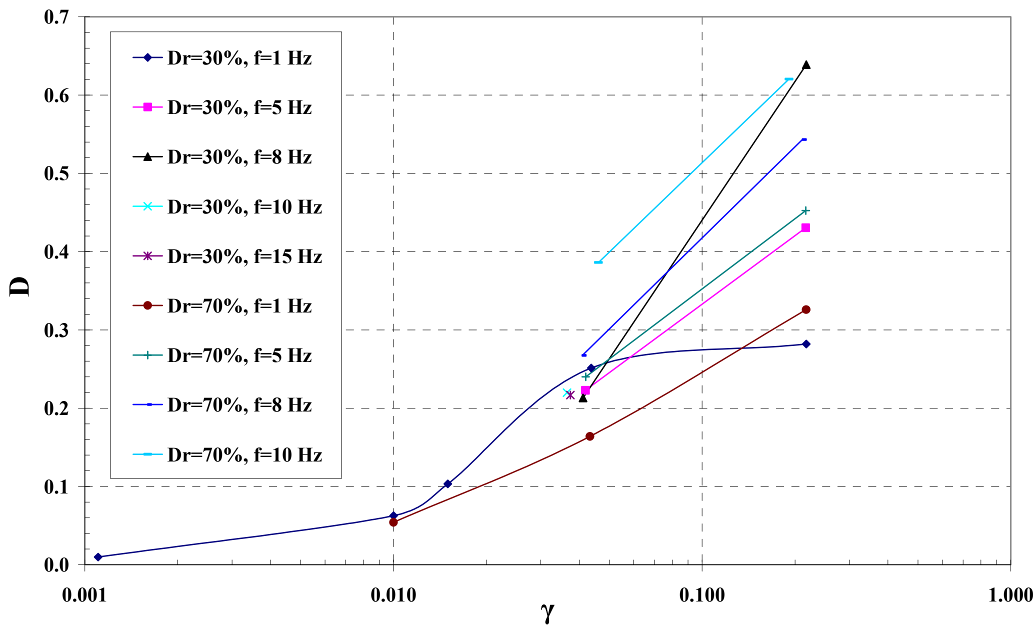

Figure 10. Variation of damping ratio with shear strain for Babolsar sand

The shear modulus increases significantly with shear strain amplitude. However, damping ratio decreases with strain amplitude drastically. These variations are shown in figures 9 and 10 for different conditions.

As seen in figures 9 and 10, the value of shear modulus does not change with frequency in a specific matter. The value of damping ratio, however, increases with frequency.

CONCLUSIONS

An attempt has been made to evaluate the dynamic properties of Babolsar sand and Toyoura sand. Strain-controlled cyclic simple shear tests were conducted on soil samples. A major reduction in the shear modulus and a corresponding increase in the damping of theses soils occur in the large shear strain range exhibiting highly non-linear behavior. Toyoura sand showed higher values of shear modulus compared to Babolsar sand. With respect to damping ratio, Toyoura sand showed a lower damping ratio than Babolsar sand. As the initial densities of Babolsar sand and Toyoura sand increases, the shear modulus shows clearly an increasing trend. The value of shear modulus does not change with frequency in a specific matter. The value of damping ratio, however, increases with frequency.

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