4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1274

EFFECT OF VARIOUS PARAMETERS ON DYNAMIC PROPERTIES OF BABOLSAR SAND BY CYCLIC SIMPLE SHEAR DEVICE

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ABSTRACT

In this investigation, dynamic properties especially shear modulus and damping ratio of Babolsar sand that is identified as the standard soil for investigation in Iran was estimated. In order to determine these parameters, a series of cyclic simple shear tests using NGI type cyclic simple shear device under cyclic shear strain between 0.1% and 20.0%, were carried out. The tests were conducted under constant-volume method equivalent to undrained cycle condition. The specimens tested in the device were cylindrical, 7cm in diameter and 2.3cm high. The tests were strain-controlled with an approximately sinusoidal shape of cyclic loading. The effect of cyclic strain amplitude (γ), vertical effective consolidation stress (σ'_{vc}) and relative density (Dr) on the shear modulus (G) and damping ratio (D) were investigated.

Maximum shear modulus (G_{max}) was estimated from current method and normalized shear modulus approximated from the tests were compared to those estimated by Seed (1986). The values of damping ratio estimated from the tests were also compared whit those estimated by Seed (1986).

The results show that, for a given γ, G increases with σ'_{vc} and Dr but it decreases with γ. However, D decreases with σ'_{vc} and Dr but it increases with γ. The effect of γ become smaller if σ'_{vc} and Dr increase.

Keywords: Sandy Soil, Shear Modulus, Cyclic Simple Shear Test, Vertical effective consolidation stress and Relative Density, Cyclic strain amplitude

INTRODUCTION

The dynamic properties of soils are required to analyze their behavior under cyclic loading and solution of many soil dynamics problems such as vibration of machine foundation, response of soil deposits and earth structures to earthquake loads. These dynamic properties are the shear modulus and material damping ratio of the soils. In these problems, typically involving cyclic loading, the stress-strain behavior of soils is described by cyclic loops, similar to the idealized loops in Figure 1.

From such loops, the damping characteristics can be evaluated by the equivalent viscous damping ratio, λ, derived by Jacobsen (1930):

$$\lambda = \frac{1}{4\pi}\,\frac{\Delta w}{\frac{\gamma_c\,\tau_c}{2}} \tag{1}$$

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In Eq. 1 and Figure 1, Δw is area inside the loop, τ is shear stress, γ is shear strain, τ_c is cyclic shear stress amplitude, γ_c is cyclic shear strain amplitude, G_0 is maximum shear modulus at small strain (G_{max}), and G is secant shear modulus corresponding to τ_c and γ_c.
Hardin and Black (1968) have suggested that a large number of factors contribute to the shear modulus and damping of soils. Among these, the major influencing factors are the soil type, void ratio, effective confining pressure, shear strain amplitude and the number of cycles. Degree of saturation has been reported as an important influencing parameter only for modulus of cohesive soils (Hardin and Drnevich 1972). Most of the published literature concentrates on sands and clays. Seed and Idriss (1970, 1986) have summarized the available data on dynamic shear modulus and damping ratios for sands and saturated clays.
The shear modulus and damping ratio of soils at small strains have been investigated in the laboratory with high-frequency resonant column test (Woods, 1991, 1994) and have been developed recently with a new constant-volume equivalent-undrained direct simple shear device called the double specimen direct simple shear device (DSDSS) (Vucetic et al. 1998-2003).

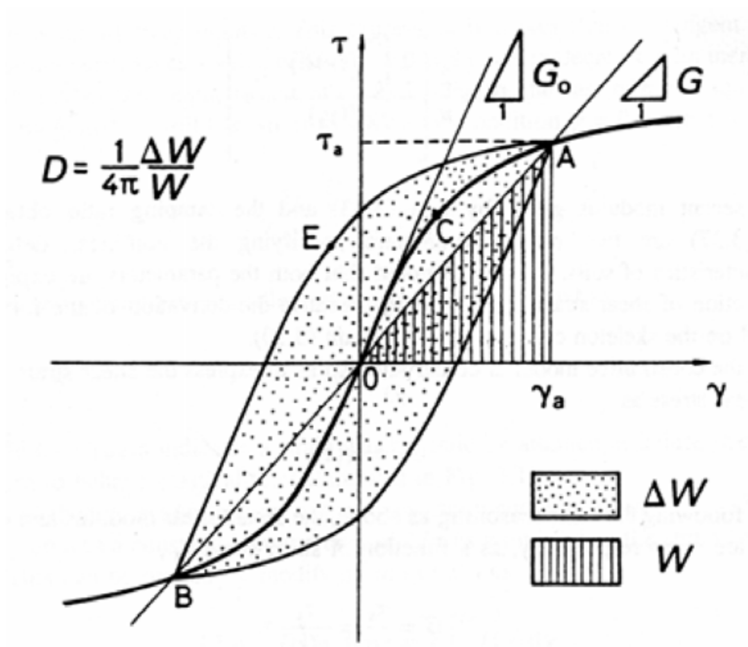

Figure 1. Idealized First-Cycle Symmetric Stress-Strain (Ishihara, 1996)

This paper investigates the dynamic properties of Babolsar sand and presents the result of a series of constant-volume equivalent-undrained simple shear cyclic tests. The dynamic properties of Babolsar sand soils which classified as SP and comparison of these properties with the published data on sands are reported and the influence of cyclic shear strain amplitude, γ_c, effective vertical consolidation stress, σ'_v, relative density, Dr, cyclic frequency, f, and number of loading cycles on the shear modulus and damping ratio were evaluated and are systematically presented.

SOIL TESTED

Owing to lack of a standard soil in the country to conduct various tests, Babolsar sand is described as a standard soil by the researchers of Sharif University of Technology. This soil is classified as SP in the Unified Soil Classifies (USCS). The basic physical properties and classification characteristics of this soil are presented in Table 1.
The grain-size distribution curve of the sand is shown, in Figure 2.

Table 1. Physical properties and classification characteristics of Babolsar sand

G_s	2.724
e_{min}	0.76
e_{max}	0.54
γ_{max}	17.03
γ_{min}	14.80
D_{50}(mm)	0.23

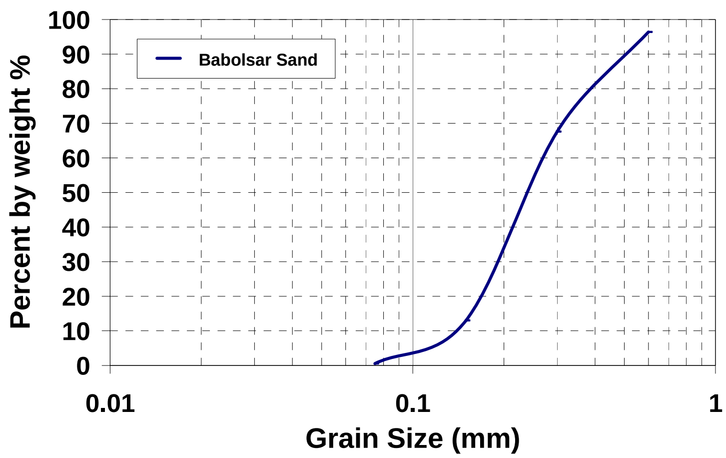

Figure 2. Grain size distribution curve

TESTING APPARATUS AND PROCEDURE

The testing apparatus is cyclic simple shear device of NGI type (Figure 3). As shown in Figure 3, the specimens tested in the device were cylindrical, 0.70 cm in diameter and 2.30 cm high.
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.
At the beginning of any test, the soil specimen was consolidated by applying loads to the loading rod. After consolidating was completed a drained shear test was performed by applying a horizontal shear strain to the specimen at a predetermined rate.

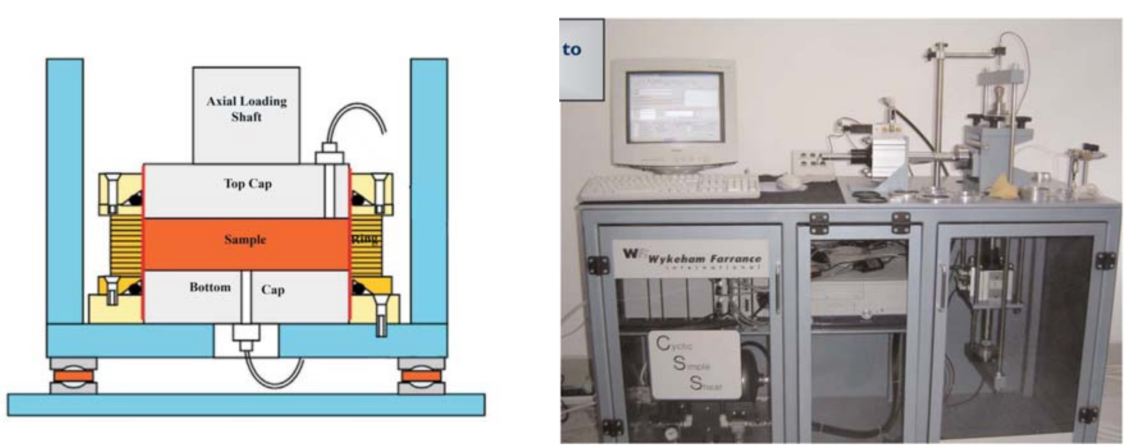

Figure 3- NGI-type direct simple shear device at Soil Dynamics Laboratory of the Sharif University

Owing to the difficulties in the prevention of drainage in a simple shear test the undrained shear tests were carried out as constant-volume tests (Bjerrum et al. 1966). During the shear phase of constant-

volume tests the specimen were drained and test conditions were selected such that the pore pressures in the specimen were zero throughout the tests. The height of the specimen was then kept constant by the vertical actuator in a closed control loop with the vertical displacement transducer. The constant-volume test is equivalent to an undrained test and the change of applied vertical stress on the specimen is equivalent to the change in pore pressure would have occurred in the specimen if the specimen had been prevented from draining for a condition of constant vertical stress application. Therefore, the results presented in this paper are applicable to undrained conditions.
As an example of the capability of the device to measure the dynamic properties, typical records of the several cycles of tests of Babolsar sand in different conditions are presented in Figures 4 through 7.

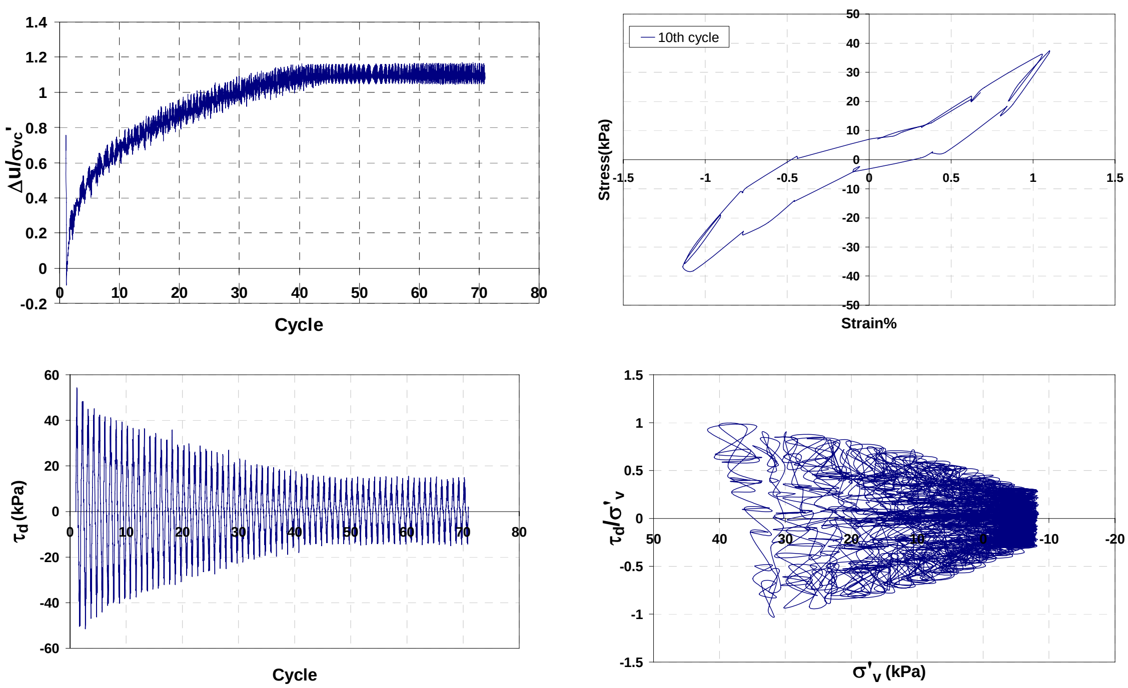

Figure 4- Typical records of CSS test (Dr=30%, f = 0.1 Hz, σ'_v=50 kPa) (Test No.1)

TESTING PROGRAM

Babolsar sand soil samples were collected from different site in the North of Iran. The samples were distributed and prepared by moist placement method (wet tamping) in which three or four equal preweighed oven-dried portions of sands are mixed with de-aired water at a water content of about 5% and then each portion of the slightly moist sand is strewn by hand to a predetermined height in three to four lifts and tamped down lightly with a small flat bottom tamper. A total of 18 specimens of this soil were tested. As mentioned before, this soil is classified as SP.
The influencing parameters that were investigated in the consecutive cyclic strain-controlled tests, were the effective vertical consolidate stress, σ'_v, the level of constant cyclic shear-strain amplitude, γ_c, relative densely, Dr, and the number of cycles, N. Specimens were tested at two effective vertical consolidate stress, 50 and 150 kPa.
These pressures corresponded with those at the depth which is determined in definition of main object of this investigation. Shear strain amplitudes γ_c were 1% and 1.5% and relative density were 30% and 70%. During shear tests, the frequencies used were 0.1, 0.5 and 1.0 Hz. The number of cycles was varied from 50 to 1000 cycles based on specimen specifications. The details of various parameters in each test are summarized in Table 2.

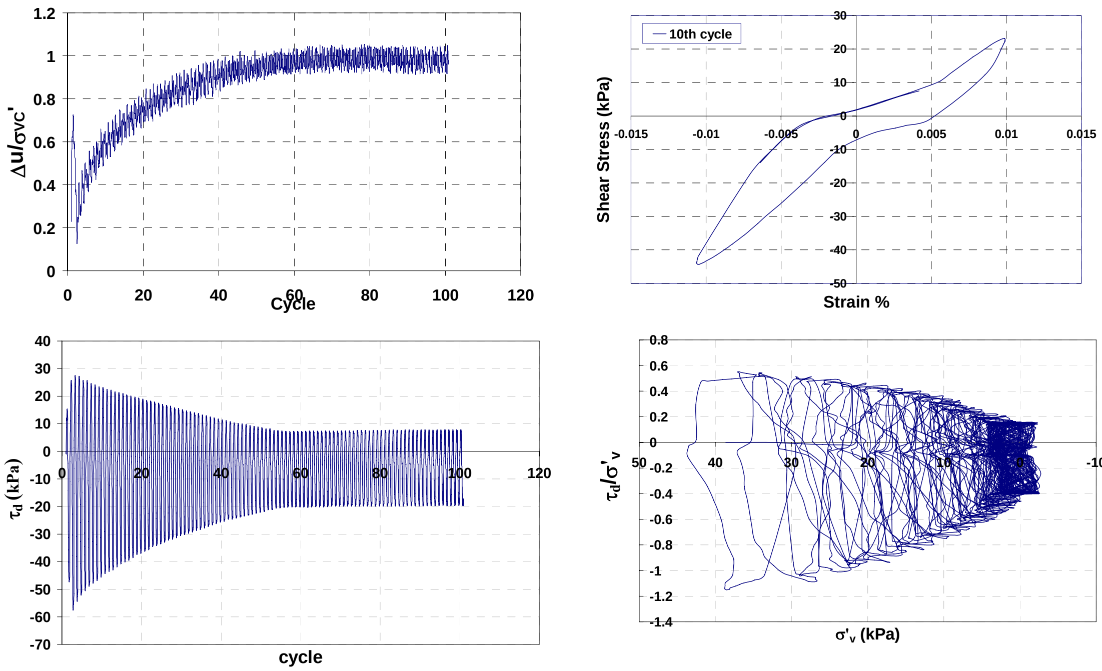

Figure 5- Typical records of CSS test on (Dr=30%, f = 1 Hz, σ'$_v$=50 kPa) (Test No.3)

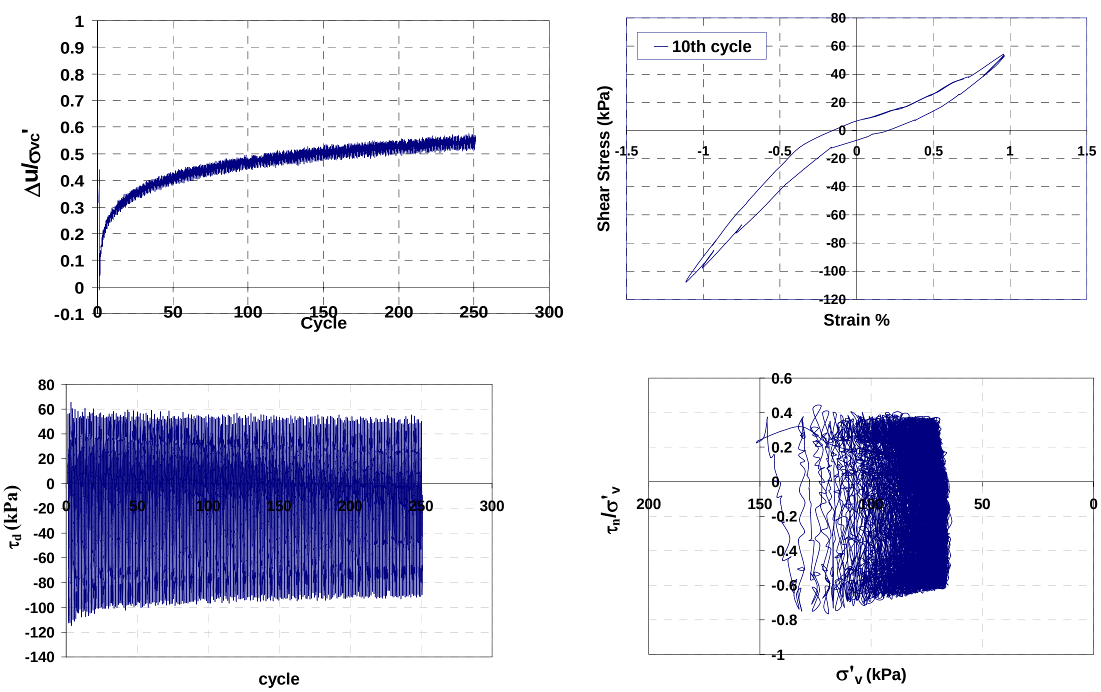

Figure 6- Typical records of CSS test (Dr=70%, f = 0.1 Hz, σ'$_v$ =150 kPa) (Test No.16)

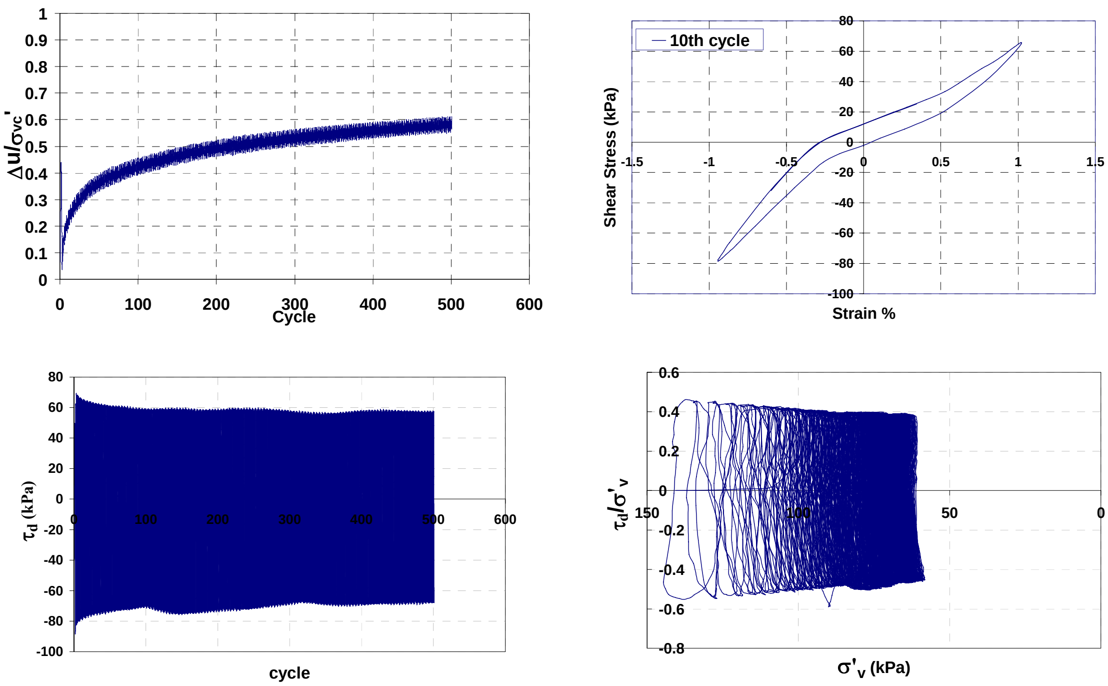

Figure 7- Typical records of CSS test (Dr=70%, f =1 Hz, σ'_v =150 kPa) (Test No.18)

Table 2. Summary of Testing Program

Test No	λ_c %	Dr %	e	f Hz	σ'_v (kPa)
1	1.0	29.0	0. 6964	0.1	50
2	1.0	31.0	0.6918	0.5	50
3	1.0	31.1	0.6916	1.0	50
4	1.0	42.0	0.6676	0.1	150
5	1.0	37.0	0.6786	0.5	150
6	1.0	34.5	0.6841	1.0	150
7	1.5	29.0	0.6962	0.1	50
8	1.5	30.4	0.6931	0.5	50
9	1.5	28.9	0.6964	1.0	50
10	1.5	28.3	0.6977	0.1	150
11	1.5	34.0	0.6852	0.5	150
12	1.5	32.0	0.6896	1.0	150
13	1.0	69.0	0.6082	0.1	50
14	1.0	72.2	0.6012	0.5	50
15	1.0	72.8	0.5998	1.0	50
16	1.0	73.0	0.5994	0.1	150
17	1.0	77.5	0.5895	0.5	150
18	1.0	71.7	0.6022	1.0	150

TEST RESULTS

The value of shear modulus, G, and damping ratio, D, at different cycles, of all the specimens tested are presented in Table 3.

Table 3. The value of shear modulus and damping ratio of Babolsar sand

Test No	γ_c %	Dr %	σ'_v (kPa)	f Hz	G (kPa) Cycle			D Cycle		
					4	10	20	4	10	20
1	1.0	29.0	50	0.1	3995.0	3313.4	2607.2	0.10064	0.10502	0.10549
2	1.0	31.0	50	0.5	3712.5	3294.9	2898.6	0.10068	0.10534	0.10658
3	1.0	31.1	50	1.0	3851.4	3313.7	2653.2	0.10052	0.10402	0.10522
4	1.0	42.0	150	0.1	7249.4	6976.7	6779.1	0.0575	0.06257	0.07180
5	1.0	37.0	150	0.5	7063.8	6839.0	6516.3	0.0614	0.05902	0.06711
6	1.0	34.5	150	1.0	6915.6	6732.3	6501.2	0.05448	0.05743	0.06940
7	1.5	29.0	50	0.1	2383.9	1823.7	1258.0	0.1529	0.23592	0.19303
8	1.5	30.4	50	0.5	2911.0	2074.9	1099.5	0.1823	0.15061	0.14040
9	1.5	28.9	50	1.0	2560.6	1748.0	1031.9	0.1743	0.18248	0.17870
10	1.5	28.3	150	0.1	N.A.	5752.9	N.A.	0.13495	0.13659	0.13656
11	1.5	34.0	150	0.5	N.A.	6612.8	N.A.	0.0767	0.08408	0.08592
12	1.5	32.0	150	1.0	N.A.	6430.6	N.A.	0.10083	0.10361	0.10442
13	1.0	69.0	50	0.1	4024.1	3751.9	3193.1	0.09419	0.09514	0.10077
14	1.0	72.2	50	0.5	3700.1	3422.7	3083.5	0.14115	0.14148	0.14523
15	1.0	72.8	50	1.0	3716.5	3314.4	2855.9	0.04722	0.08725	0.06599
16	1.0	73.0	150	0.1	7946.8	7829.1	7538.0	0.04024	0.05363	0.05371
17	1.0	77.5	150	0.5	7847.7	7665.0	7412.9	0.04453	0.05503	0.05879
18	1.0	71.7	150	1.0	7588.0	7340.6	7133.7	0.04722	0.04770	0.06500

To emphasize the behavior at large strains, the data are plotted in a semilogarithimic coordinate system, as originally suggested by Seed et al. (1986). In this way, the low-amplitude or maximum shear modulus, G_{max}, was estimated by available equation. Then the values of normalized shear modulus were approximated from the test and the data points are compared with curve proposed by Seed (1986).
The values of shear modulus and damping ratio are plotted versus the cycle number, N, and frequency, f, at different Dr, and γ_c. It can be seen, as expected (i.g. Stokoe et al. 1995) that the secant shear modulus, G, decreases and damping ratio increases with the cycle number, N, and cyclic shear-strain amplitude and for a given soil and given γ_c, Gs increases and D decreases with σ'_v and Dr.

Evaluations of Maximum Shear Modulus, G_{max}

The value of G_{max} was estimated by the relation developed by Seed and Idriss (1970):

$$G_{\max} = 1000\, K_{2\max}\, (\sigma'_m)^{0.5} \tag{2}$$

In Eq. (2), σ'_m is mean effective consolidation stress and equal to $(\sigma'_v + 2\sigma'_h)/3$, where σ'_v is vertical effective consolidation stress and σ'_h is horizontal effective consolidation stress and K_{2max} is an empirical factor.
In this equation, the units of G_{max} and σ'_m are pounds per square feet. The mean effective stress, σ'_m, was estimated by assuming that $\sigma'_v = \sigma'_{vc}$ and $\sigma'_h = K_0\, \sigma'_v$, where K_0 is the coefficient of earth pressure at rest. The values of K_{2max} vary according to void ratio as presented in Table 4.

Table 4. Values of K_{2max} (Seed and Idriss 1970)

e	K_{2max}
0.4	70
0.5	60
0.6	51
0.7	44
0.8	39

Then the values of normalized shear modulus approximated from the test and the data points are compared with the curve proposed by Seed (1986). It can be seen in Figure 8 that the data points are in a relatively good agreement with these curves. The values of damping ratio are also compared with the curve proposed by seed et al (1986). As can be seen in Figure 9 there is a significant difference between data points and this curve.

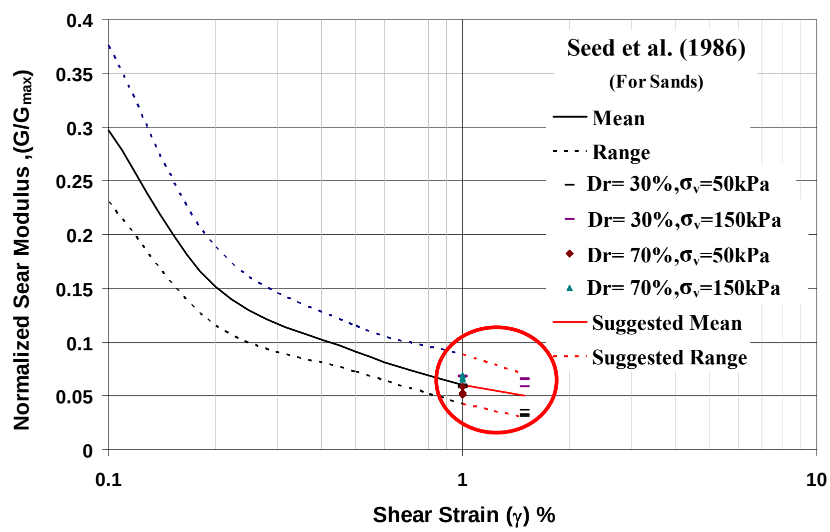

Figure 8. Comparison between values estimated from test results and values computed from Seed (1986)

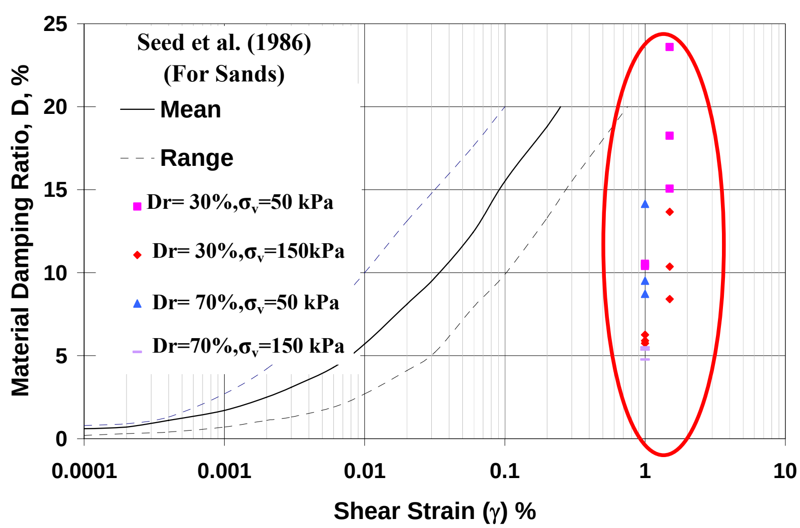

Figure 9. Comparison between values estimated from test results and values computed from Seed (1986)

Effect of the number of cycles on damping ratio and shear modulus

Effect of the number of cycles on the dynamic behavior of the Babolsar sand was investigated.

When a soil is subjected to cyclic loads under undrained strain-controlled conditions, the shear stress amplitude decreases with the number of cycles due to structural changes and building pore water pressure. As can be clearly seen in Figures 4 through 7, the maximum shear stress reduces with an increase in the number of cycles in such a way that the rate of reduction is higher within the first few cycles. The variations of the stress ratio, τ/σ'_v, exhibits the same trend.

Therefore, shear modulus identified as the slope of a line through the end points of the hystresis loop decreases with the number of cycles. It can be clearly seen in Figure 10.

The effect of the number of cycles on damping ratio is also investigated. As shown in Figure 11, damping ratio increases with the number of cycles.

It can also be seen in these figures that the effect of the number of cycles on both parameters, is dependent on cyclic shear strain amplitude and σ'_v (Figures 10 through 13).

Effect of σ'_v and Dr on damping ratio and shear modulus

Influences of vertical consolidation stress on the dynamic properties of Babolsar sand were also investigated. Figures 10 and 11 show a summary of the result of the tests in which samples were consolidated to vertical stresses varying from 50 to 150 kPa and subjected undrained to cyclic shear stress. These Figures indicate that for sand, the shear modulus and damping ratio are significantly affected by σ'_v and Dr especially σ'_v as previously reported by other researchers.

It can be seen that as σ'_v and Dr increase, the ordinates of the G-N curve increase and the ordinates of the D-N curve decrease. According to the result of the tests, the effect of σ'_v on damping ratio is more than that on shear modulus.

This effect can be also illustrated with Figures 4 through 7. As shown in these figures, reduction in shear stress amplitude at vertical consolidation stress 150 kPa is significantly smaller than this reduction at vertical consolidation stress 50 kPa. Therefore, the rate of reduction in shear modulus identified as the slope of a line through the end points of the hystresis loop at the higher stress is smaller.

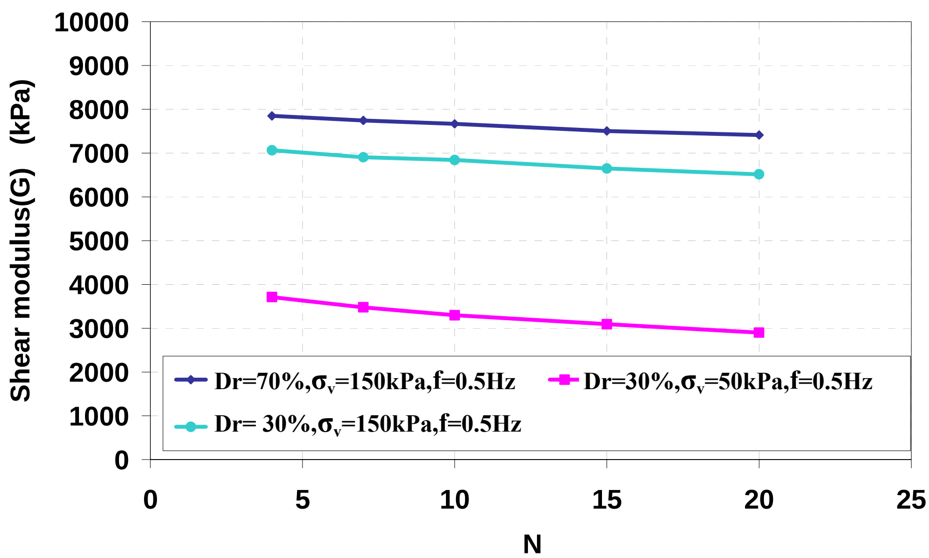

Figure 10. Effect of number of cycles, σ'_v and Dr on shear modulus

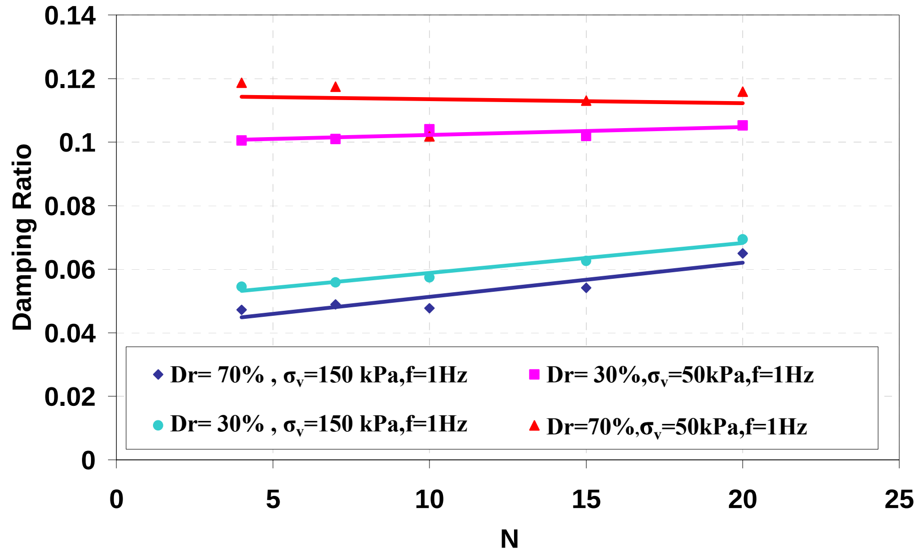

Figure 11. Effect of number of cycles, σ'_v and Dr on damping ratio

Effect of cyclic shear strain amplitude

Shear modulus decreases and damping ratio increases with γ_c. The effect of the cyclic shear strain amplitude depends upon several factors such as effective vertical stress and number of cycles. It is apparent from Figures 12 and 13. As shown in Figure 12, the effect of γ_c on shear modulus decreases if σ'_v increases. It has the same trend for damping ratio.

According to results of the tests, the effect of γ_c on damping ratio is more than this effect on shear modulus especially under higher vertical consolidation stress.

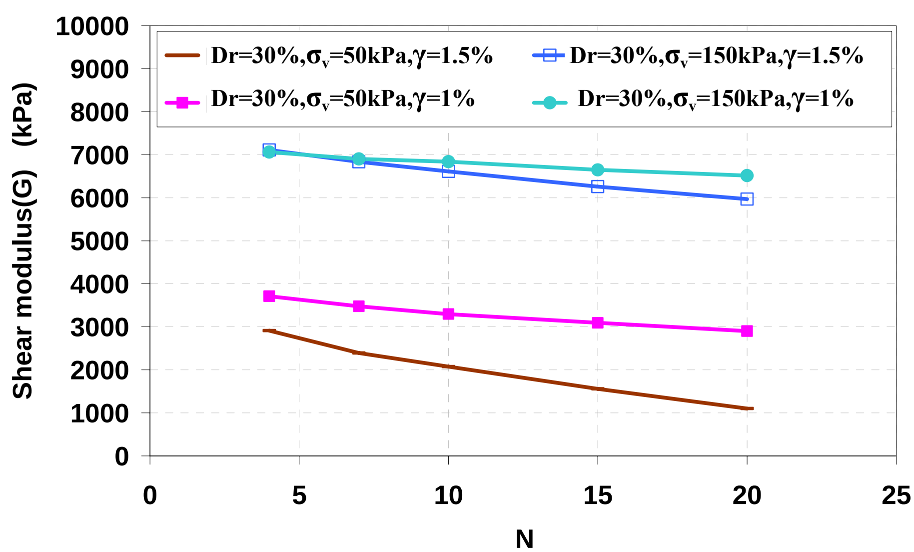

Figure 12. Effect of shear strain γ on shear modulus

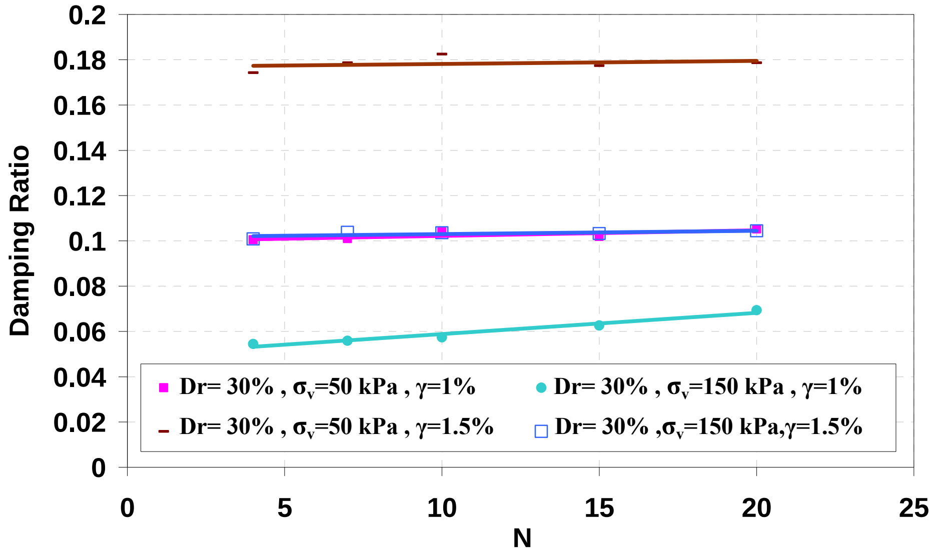

Figure 13. Effect of shear strain γ on damping ratio

CONCLUSION

A series of cyclic strain – controlled tests on Babolsar sand was conducted using a constant-volume equivalent-undrained cyclic simple shear device of NGI type, aimed at measuring the shear modulus and damping ratio at various environmental conditions.

The values of γc were 1.0 and 1.5% .The samples had two different relative density, Dr = 30 and 50%.

The test were conducted at two different vertical effective consolidation stresses, σ'_v = 50 and 150 kPa, and three different frequencies, f, between 0.1 and 1.0 Hz.

The values of maximum shear modulus, G_{max}, were estimated from current methods and then normalized shear modulus approximated from the tests were compared to those estimated by Seed (1986). The result of this comparison shows a good agreement between them.

The values of damping ratio were also compared with the curve proposed by Seed et al. (1986). Result of this comparison shows a significant difference between achieved data points and the curve proposed by Seed.

The values of shear modulus and damping ratio were plotted versus the cycle number, N, at different σ'_v, Dr, and γ_c. It can be seen, as expected, the shear modulus, G, decreases and damping ratio increases with growing the cycle number, N, and cyclic shear-strain amplitude. For a given γ_c, Gs increases and D decreases with σ'_v and Dr.

It also shown that the effect of the number of cycles on both parameters is dependent on various parameters including vertical consolidation stress and shear strain.

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