7th Canadian Conference on Earthquake Engineering / Montreal / 1995
7ième Conférence canadienne sur le génie paraséismique / Montréal / 1995

Shear Moduli of Sands under Different Types of Loading

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ABSTRACT

A series of tests were conducted on Ottawa 20-30 air dry sand using the resonant column technique to study the shear modulus of sands under different types of loading: sinusoidal, random and impulse. Each specimen was tested with one of the loadings from low to high excitation amplitudes under confining pressures of 5, 10 and 40 psi, and the shear modulus and shear strain amplitude were determined. The shear modulus under different types of loading was then compared. It was found that the loading type indeed had some effect on the shear modulus, and the reference shear strain was a very important and useful parameter for unifying the shear modulus results at different confining pressures.

INTRODUCTION

Shear modulus, Young's modulus and damping ratio of soils are considered to be the primary parameters of the dynamic properties of soils. These dynamic properties can be evaluated from either laboratory or field testing (Woods 1991). Even though research on the dynamic characteristics of soils under shear deformations were very extensive, sinusoidal loading was almost the only type of loading used in the past. Earthquakes, wind, ocean waves, and certain man-made forces, however, do not provide a sinusoidal pattern of excitation. To establish meaningful results that represent field conditions, a nonperiodic loading should be used in laboratory testing.

A series of tests was conducted to determine the shear modulus of sands under various types of dynamic loading using the resonant column technique. Soil specimens constructed of air-dry Ottawa 20-30 sand were excited torsionally with one of three types of loading: sinusoidal, random and impulse, under confining pressures of 5, 10 and 40 psi. At each amplitude of excitation, the resonant frequency and response were measured and the shear modulus was determined. The shear moduli obtained from these different types of loading were then compared.

TEST APPARATUS AND TEST PROCEDURES

The resonant column device used in this research was the Drnevich "fixed-free" type with solid cylindrical specimens. The specimens were fixed at the base with excitation forces applied to the top. The resonant column device has capabilities of applying both longitudinal and torsional excitations. The solid

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cylindrical specimens were 7.5 cm in length and 3.6 cm in diameter. Air-dried Ottawa 20-30 sand was used in the specimen preparation, and all specimens were prepared to a relative density of approximately 78% using a dry tapping method in four layers.

Each test sequence was composed of several test stages from low strain level to high strain level. The sinusoidal signals were generated by a sine-wave oscillator with variable frequency and amplified by a power amplifier. Then the amplified sinusoidal signals were sent to the torsional coil for excitations. The acceleration responses of the soil-mass system in the torsional direction were picked up by a transducer mounted in the top platen sitting on top of the soil column. Then the response signals were amplified by a charger amplifier. Both the excitation and response signal were connected to an X-Y oscilloscope. The resonant conditions were established by changing the excitation frequency to a situation at which a vertical ellipse on the X-Y oscilloscope was observed. The amplitudes of the excitation and response at the resonance were read on a voltmeter in root-mean-square (rms) values, and the resonant frequency was read from a digital frequency meter.

A white-noise generator was used in the tests with random excitations. The signals from the white-noise generator were first filtered through a two-channel variable cut-off frequency filter, and then amplified and sent to the torsional exciting coil. The signals of the excitation and response were recorded on a tape recorder. After the tests were finished, the signals were analyzed by replaying the recorded signals to a digital analyzer (FFT analyzer). As random signals are nondeterministic, a large amount of data was necessary to establish the statistical characteristics of the random signals. Therefore, it was necessary to perform many averages on the FFT analyzer to eliminate the noise in the random signals and to get smooth power spectral density functions (PSD) of the response, and to determine the magnitude of the transfer function (MTF). The impulse signals were generated by a pulse signal generator, and amplified by the power amplifier and then sent to the exciting coil. The excitation and response signals were directly sent to the FFT analyzer for the determination of the MTF of the soil-mass system.

TEST RESULTS

With the measured resonant frequencies and magnitude of the transfer function of the soil-mass system under different conditions, the shear modulus and the corresponding shear strain amplitude were determined. Wave propagation theory was used for the calculation of the shear modulus of the sand specimens in the resonant column testing (Hardin and Drnevich 1972). Under sinusoidal loading, the shear strain amplitude induced in a sand specimen was directly evaluated from the acceleration responses of the soil-mass system at resonant frequency. Under random and impulse loadings, the rms values of shear strain amplitude were evaluated using random vibration theory (Zhang 1994).

Figure 1 shows the result of theshear modulus G of a sand specimen under sinusoidal loading at different shear strain levels and at different confining pressures. It can be seen that at each confining pressure the shear modulus G decreased with the increase of shear strain amplitude γ. At higher γ, G decreased more significantly with the increase of γ. The confining pressure effect on the decreasing rate of shear modulus can be seen as in Fig. 2 as a result of normalizing the shear modulus G at each strain level by dividing the G at each γ by the initial maximum shear modulus G_{max} of each test sequence, as G/G_{max}. Under a higher confining pressure, the decreasing rate of normalized shear modulus G/G_{max} was slower with the increase of shear strain amplitude γ. In the figures, the maximum shear modulus G_{max}

was defined as the shear modulus of a soil specimen at very low strain levels (< 10^{-3}%). The initial maximum shear modulus G_{max} of each test sequence was evaluated from the low-amplitude shear modulus G' at low shear strain γ' obtained at the first test stage in each test sequence from the following equation (Hardin and Drnevich 1972):

$$G_{max} = G'\left(1 + \frac{\gamma'}{\gamma_r}\right) \tag{1}$$

in which G' and γ' are the low-amplitude shear modulus and shear strain at the first test stage of each test sequence; γ_r is defined as a reference shear strain and calculated from:

$$\gamma_r = \frac{\sigma_o \sin \phi_{triax}}{G_{max}} \tag{2}$$

where σ_0 is the effective mean stress in the soil specimen, and ϕ_{triax} is the internal friction angle of the sand from triaxial tests. As can be seen, reference shear strain γ_r is a parameter that includes the properties and conditions of soils and was first introduced by Hardin and Drnevich (1972). The reference shear strain γ_r was found to be very useful in unifying the test results of dynamic properties of soils with strain amplitudes and confining pressures. As shown in Fig. 3, when the shear strain γ at each test stage was normalized as γ/γ_r, and the normalized shear modulus G/G_{max} was plotted with γ/γ_r, the test results of shear modulus at different confining pressures were unified. Figures 4 and 5 show the results of shear modulus in the space of G/G_{max} vs. γ/γ_r, as in the case of sinusoidal loading, for the random and impulse excitations. The figures show the unified results of shear modulus under random and impulse loadings, respectively. Therefore, it can be concluded that under all three types of loading the normalized shear strain amplitude γ/γ_r is the primary controlling factor of the normalized shear modulus, G/G_{max}, of sands under different confining pressures.

Since the sand specimens used in all the tests were almost identical, and under the same test procedures, the test results of shear modulus under all three types of loading could be compared by plotting all the unified shear moduli together to study the loading type effect on the shear modulus of sands, as shown in Fig. 6. From the figure, it can be seen that the loading type indeed had some effect on the shear modulus. At strains γ/γ_r below 0.1, the loading type effect was not significant and G/G_{max} slightly decreased with the increase of γ/γ_r. When the strains γ/γ_r became higher (>0.1), G/G_{max} was more significantly affected by the loading type. Comparing the three types of loading at a strain γ/γ_r level above 0.1, the G/G_{max} under impulse loading was the lowest, under sinusoidal loading was the highest, and under random loading was between the impulse and sinusoidal loading. Considering the fact that loading type has no effect on the maximum or low-amplitude modulus of sands (Zhang and Aggour 1995), therefore, at a high strain level, the shear modulus of cohesionless soils under random loadings would be lower than that under sinusoidal loadings, and under impulse type of loadings would be lower than random loading.

CONCLUSION

Three types of loading, sinusoidal, random and impulse, were used, and the shear moduli of sand specimens under different types of loading at different shear strain amplitudes and at different confining pressures were obtained, and compared. The following conclusions can be drawn from the results of this research:

1. Confining pressure had an effect not only on the shear modulus values but also on the decreasing rate with strain amplitude; at a higher confining pressure, the normalized shear modulus G/G_{max} had a slower decreasing rate.
2. Reference shear strain γ_r is a very important soil parameter that represents soil conditions including soil density, mean effective stress, and soil type, etc. By normalizing shear strain amplitude with the reference shear strain γ_r, the normalized shear modulus G/G_{max} under each type of loading at different confining pressures was unified. Therefore, the shear modulus under each type of loadings was primarily controlled by the normalized shear strain γ/γ_r.
3. When normalized shear strain γ/γ_r was below 0.1, shear modulus did not significantly decrease with strain amplitude, and loading type had no effect on the shear modulus. When γ/γ_r was higher than 0.1, however, shear modulus started decreasing with the increase of strain amplitude, and was thus affected by loading type. At a shear strain amplitude above $0.1\gamma_r$, the shear modulus obtained from random loading tests was smaller than that obtained from sinusoidal loading tests, and the shear modulus obtained from impulse loading tests was even smaller than that obtained from random loading tests. Therefore, for shear strain amplitudes higher than $0.1\gamma_r$, a different shear modulus should be used for the analyses of soils under different types of loading.

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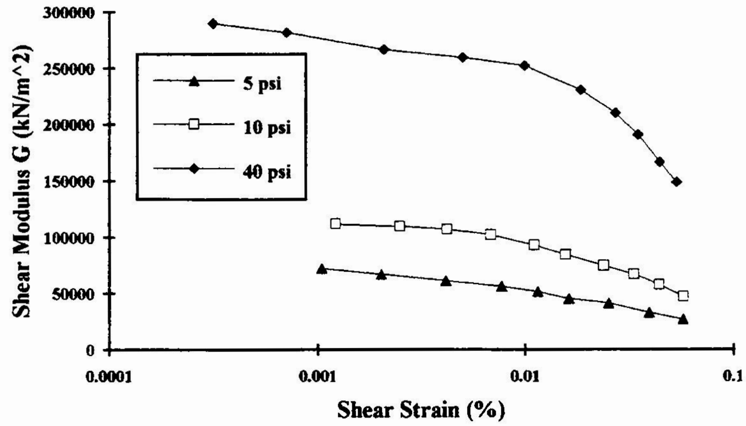

Fig. 1 Shear Modulus, G, vs. Shear Strain, γ, Under Sinusoidal Loading for Different Confining Pressures

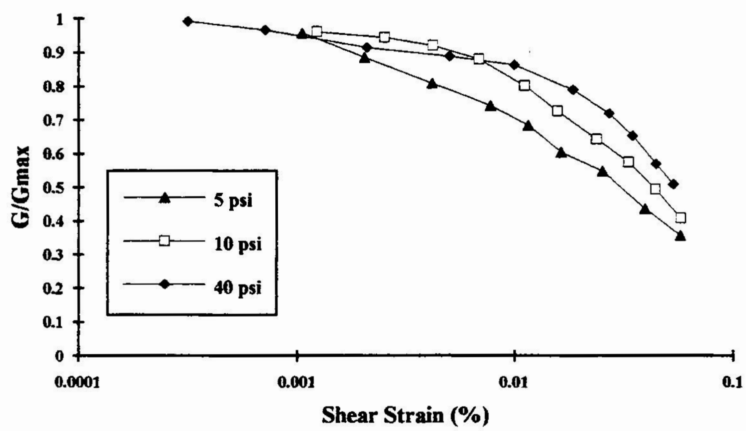

Fig. 2 Normalized Shear Modulus, G/G_{max}, vs. Shear Strain, γ, Under Sinusoidal Loading

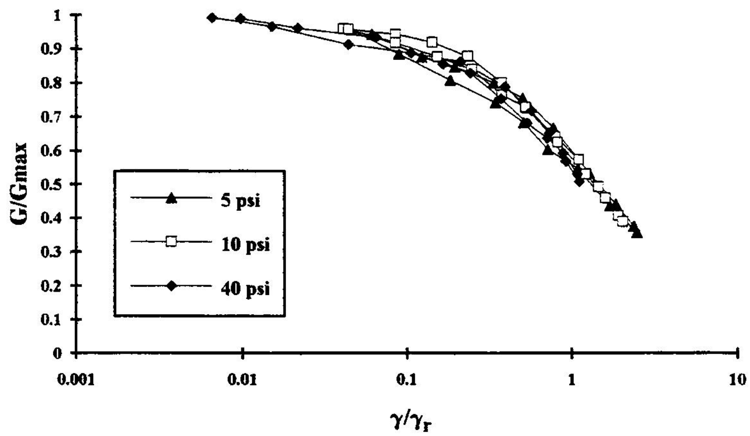

Fig. 3 G/G_{max} vs. γ/γ_r Under Sinusoidal Loading

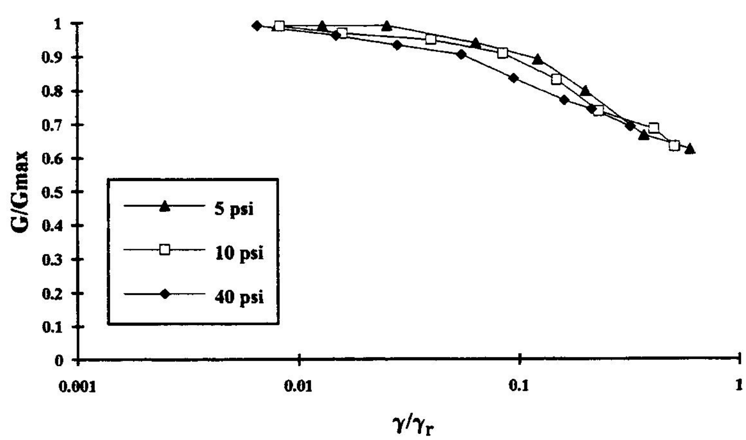

Fig. 4 G/G_{max} vs. γ/γ_r Under Random Loading

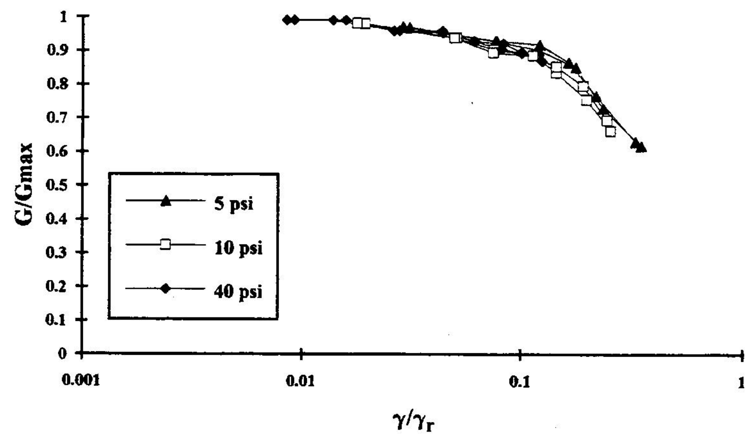

Fig. 5 G/G_{max} vs. γ/γ_r Under Impulse Loading

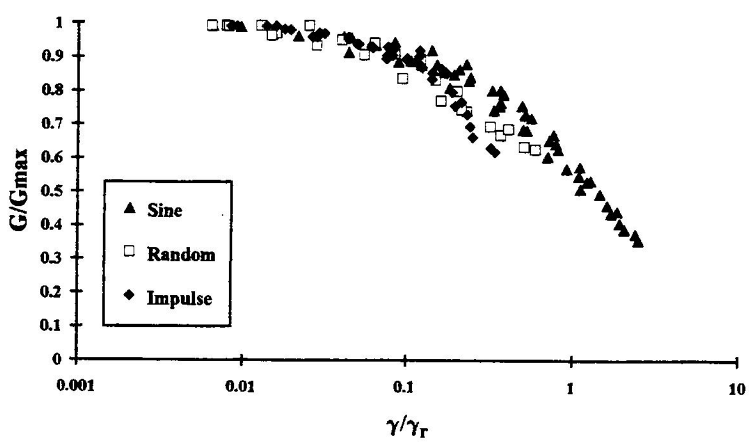

Fig. 6 Comparison of G/G_{max} Under Sinusoidal, Random and Impulse Loadings