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Maximum Moduli of Sands Under Various Loadings

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SYNOPSIS: Maximum moduli are the primary parameter in the determination of wave velocities in soils. They can be evaluated from either laboratory or field testing. In general, the excitation loadings used in laboratory and field testing are different. The resonant column apparatus was used to study the effect of loading type on the maximum moduli of sands. Sinusoidal, random and impulse loading were used. Sand specimens were tested either longitudinally or torsionally with one of the three types of loading at low strain levels, and the low-amplitude moduli were measured. Maximum moduli of the specimens were obtained from the low-amplitude moduli. It was concluded that loading type has no effect on the maximum moduli of soils. Also, the maximum moduli at different confining pressures agreed well with published equations.

INTRODUCTION

Shear modulus, Young's modulus and damping ratio are considered the primary parameters of the dynamic properties of soils. These dynamic properties can be evaluated from either laboratory or field testing (Woods, 1978, 1991). For the determination of dynamic properties, almost all laboratory testing techniques use sinusoidal loading for the excitation force. In field testing, waves are generated by either an impact force or detonation of small charges. Such generating systems transmit energies to the soil, which do not have the same frequency content as in either laboratory or earthquake loading. To determine the dynamic soil properties that can be used in ground motion evaluation under different loading conditions, non periodic loadings should be utilized in laboratory testing. For the case in which no residual strain occurs, the resonant column technique is considered the most effective for the determination of the maximum modulus. Maximum modulus of soils is defined as the modulus of soils at a very low strain level.

The research presented was conducted on Ottawa 20-30 sand to study the effect of loading type on the maximum modulus of soils. Three types of loading: sinusoidal, random, and impulse, were used. Soil specimens were excited either longitudinally or torsionally with one of the three types of loading at very low amplitude strain levels and at different confining pressures. The resonant frequencies and responses of the soil-mass system at low strain levels were measured, and the low-amplitude moduli of soil specimens were determined. The maximum moduli of the soil specimens under various types of loading conditions were calculated from the low-amplitude moduli. The calculated maximum moduli were found to be unaffected by the type of loading, and when compared with previously published equations, good agreement was found.

TEST EQUIPMENT AND PROCEDURES

The resonant column device used was Drnevich's "fixed-free" device. The test system consisted of signal generators, power amplifier, acceleration transducers and charge amplifiers. The excitation and response signals were analyzed either by a voltmeter or an FFT analyzer.

To investigate the effect of loading type on the maximum moduli, air dry Ottawa 20-30 sand specimens were tested after a half hour confinement at each confining pressure of 5, 10 and 40 psi. The specimens were first excited longitudinally with one of sinusoidal, random or impulse loadings at low strain levels, and the resonant frequencies and responses of the soil-mass system in the longitudinal direction under the three types of loading were measured. Similar procedures were then repeated in the torsional direction. The low-amplitude Young's modulus E', shear modulus G', and corresponding strain amplitudes at each condition were evaluated from the resonant frequencies and responses.

The conventional method (Drnevich et al., 1978) was used for testing with sinusoidal loading. The resonant frequency and response of the soil-mass system were measured by adjusting the frequency of the sine-wave generator to the resonance condition. Excitation signals were generated by a white-noise generator and filtered by a variable cut-off frequency filter in testing with random excitation. Random excitation cut-off frequencies were selected at about three times the resonant frequencies of the soil-mass system to cover the whole resonance range and provide high power output from the power amplifier. The random excitation and acceleration response signals were sent to the FFT analyzer, the power spectral density (PSD) functions of the excitation and response, and the transfer function of the soil-mass system were obtained. The frequency and magnitude of the transfer function at the peak were the resonant frequency and response with which the Young's modulus, axial strain amplitude and longitudinal damping ratio could be calculated. A pulse signal generator with variable pulse width was used in the impulse loading testing. Similarly, the excitation and response signals were analyzed by the FFT analyzer. The pulse width was selected to have a relatively flat excitation PSD function at the resonant frequency, and was a requirement for the strain amplitude evaluation.

DETERMINATION OF MAXIMUM MODULI

When the soil specimens were tested at low strain amplitudes, the Young's and shear moduli, E and G, were the low-amplitude moduli E' and G' of the specimens. However, the low strain amplitudes induced in the soil specimens under different types of loading would not be the same because of the differences in the energy levels of the different types of loading even though the same excitation levels were applied. It was necessary to transform the moduli of the specimens at different low strain amplitudes to the moduli at the same strain level to ensure the comparability of the moduli at different conditions since the moduli changed with the strain levels. The simplest way to accomplish this was to transform the low-amplitude moduli to the maximum moduli, which is defined as the moduli at a very low strain level ($<10^{-4}\%$) or at zero strain level.

To determine the maximum modulus, G_{max}, from the low-amplitude modulus G', the following hyperbolic equation was used:

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

in which γ' is the low shear strain amplitude (%); and γ_r is the reference shear strain (%) defined as:

$$\gamma_r = \frac{\sigma_o \sin \phi_{triax}}{G_{max}} \times 100 \qquad (2)$$

and σ_o is the effective confining pressure or the effective mean principal stress (kN/m^2); ϕ_{triax} is the internal friction angle of the sand from triaxial tests, for Ottawa 20-30 sand, $\phi_{triax} = 30^\circ$ (Ray and Woods, 1988). Similar equations were used for maximum Young's modulus, E_{max}:

$$E_{max} = E'(1 + \frac{\varepsilon'}{\varepsilon_r}) \qquad (3)$$

where ε' and ε_r are the low axial strain amplitude and reference axial strain, respectively, and ε_r is defined as:

$$\varepsilon_r = \frac{\sigma_o}{E_{max}} \times 100 \qquad (4)$$

Before using the maximum modulus equations, the low amplitude strains and reference strains should be determined. The corresponding maximum moduli were needed for the reference strains. However, the maximum moduli were unknown. Since G' and E' were the moduli at low strain amplitude, and very close to the maximum moduli, satisfactory results of maximum moduli could be obtained by using the low-amplitude moduli for maximum moduli in the reference strain calculations.

For the determination of low amplitude strains γ' and ε', different methods were used for different types of loading. Under sinusoidal loading, excitation and response are single frequency and constant in amplitude, so the strain amplitude was calculated from the acceleration responses (Drnevich et al., 1978). Under random and impulse loading, vibrations are nondeterministic in frequency and amplitude. A frequency spectrum method for determining the root-mean-square (rms) strain amplitude was developed from random vibration theory and was used in this study (Zhang, 1994).

RESULTS AND DISCUSSIONS

Figure 1 shows the measured low-amplitude shear moduli G' under the three types of loading with the low-amplitude shear strain. Although the lowest possible amplitude excitations were used with all three types of loading, different low-amplitude shear strains were induced in the specimen. The low-amplitude shear strains were much higher under sinusoidal loading than under random and impulse loadings, because all the energy

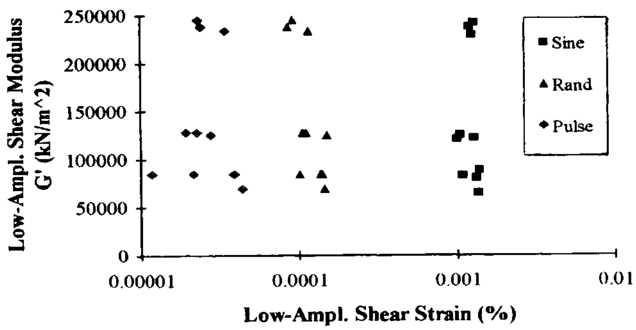

Fig. 1 Low-Amplitude Shear Modulus G' and Sheai Strain γ' (%) with Different Types of Loading

under sinusoidal loading concentrated at one frequency, while the energy under random or impulse loading distributed in a frequency range, i.e., sinusoidal loading has a much higher energy concentration. The low-amplitude moduli under different types of loading were then transformed to the corresponding maximum moduli. Figure 2 shows the comparison of the G_{max} of a sand specimen under the three types of loading, plotted with the results of sinusoidal (S) loading as the horizontal axis, and the random (R) and impulse (P) loading as the vertical axis. Similarly, the E_{max} of the specimen under different types of loading is shown in Fig. 3. The figures indicate that loading type has no effect on the maximum moduli of soils.

Maximum moduli of soils are affected by many factors, such as voids ratio e, effective mean principal stress σ'_o, and overconsolidation ratio OCR, etc., of which, e and σ'_o are the most significant factors for cohesionless soils. The relationships of maximum shear modulus, voids ratio, and confining pressure have been extensively studied (Hardin and Drnevich, 1972; Chung et al., 1984). Hardin (1978) suggested the following equation for the G_{max}.

$$G_{max} = S\frac{1}{0.3 + 0.7e^2}(OCR)^k P_a^{1-n}(\sigma'_o)^n \qquad (5)$$

in which, S is a nondimensional stiffness coefficient; e is the voids ratio; OCR is the overconsolidation ratio; k is a coefficient depending on the plasticity index of soils; P_a is the atmospheric pressure; n is a power of stress; and σ'_o is the effective mean principal stress, or effective confining pressure. Normally a value of 625 for S, 0.5 for n, and 1.0 for OCR can be used for cohesionless soils. The average voids ratio of the specimens in this research was 0.54. Figure 4 compares the G_{max} under the three types of loading with the results from the above equation at different confining pressures. It can be seen in this figure that the G_{max} under different types of loading obtained from different specimens are close to each other at each confining pressure and agree well with the equation.

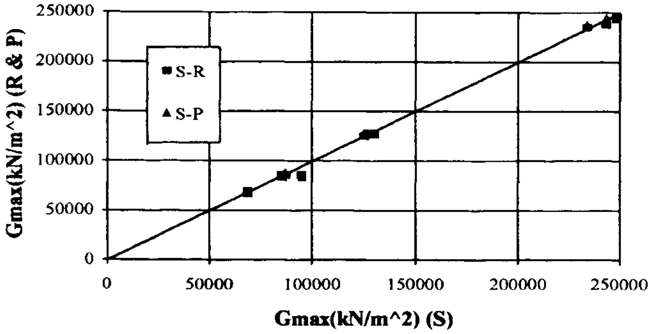

Fig. 2 Comparison of Maximum Shear Modulus G_{max} under Different Types of Loading

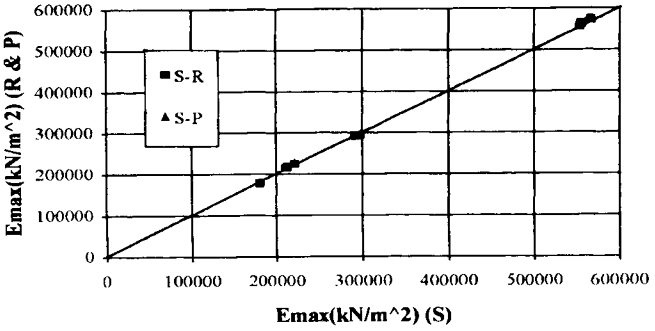

Fig. 3 Comparison of Maximum Young's Modulus E_{max} under Different Types of Loading

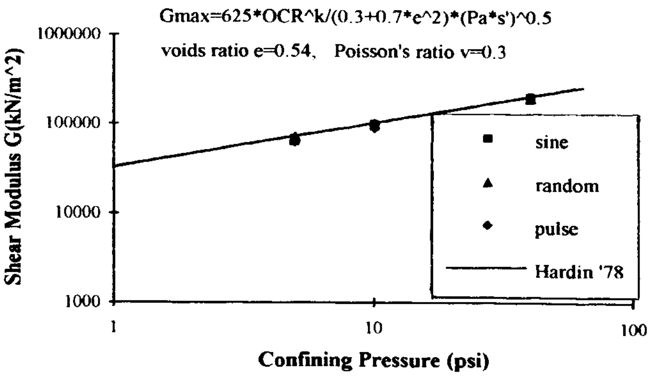

Fig. 4 Comparison of Measured G_{max} with Hardin's Equation

The equation of E_{max} was derived from the G_{max} equation above. Since soils behave like elastic materials at very low strain levels, the following relationship exists between E_{max} and G_{max}:

$$E = 2(1 + \nu)G \tag{6}$$

where ν is the Poisson's ratio of soils. For the sand used in this research, a value of 0.3 was used for the Poisson's ratio ν. The measured E_{max} was compared with the calculated results and is shown in Fig. 5 at different confining pressures. There is good agreement between the measured and calculated results.

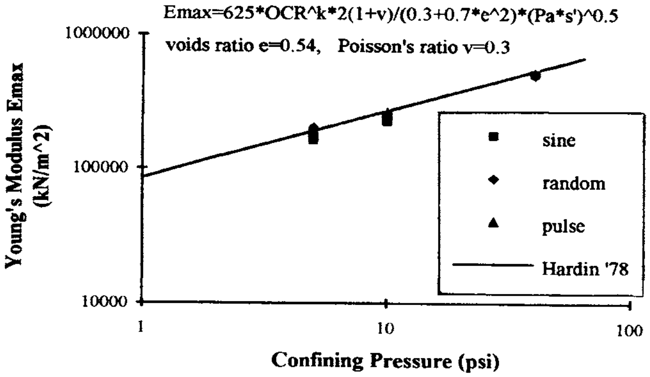

Fig. 5 Comparison of Measured E_{max} with Hardin's Equation

CONCLUSION

Tests were conducted on Ottawa 20-30 sand using a resonant column device to study the effect of loading type on the maximum moduli of soils. Sinusoidal, random and impulse loading were used. The low-amplitude Young's and shear moduli, E' and G', were measured, and then transformed to the maximum moduli, E_{max} and G_{max}.

It was found that the loading type has little effect on the maximum moduli of soils. The maximum moduli measured from different types of loading tests were almost the same. The maximum Young's and shear moduli of sand specimens were very consistent, and had very good agreement with the published equations.

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