DYNAMIC SOIL PROPERTIES FROM
SINUSOIDAL AND RANDOM VIBRATION

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SUMMARY

The two primary dynamic soil properties, namely shear modulus and damping, of dry sand were evaluated in a resonant column device using random vibrations in addition to conventional sinusoidal vibrations. In the random excitation test, white noise was used to excite the specimens and the responses of the specimens were analyzed by the random decrement technique.

The results obtained indicated a good agreement between the modulus and damping obtained from the application of sinusoidal or random loading. However in using a band limited white noise to simulate the impulsive type loading used in field testing of soil, it was found that the damping values obtained by the random decrement technique increased as the frequency band width decreased, whereas the shear modulus was not affected by the type of loading used.

INTRODUCTION

The two primary dynamic soil properties for dynamic analysis are shear modulus and damping values. Dynamic shear moduli are presently determined using laboratory techniques and in situ tests. The soil damping properties for use in response calculations are presently determined using only laboratory techniques, as there is as yet no test for determining usable data in situ. Since no field tests are readily available to determine damping, the correlation between in situ and laboratory values is one of the areas in which data are lacking.

For in situ testing, the method consists of a signal generating energy source at the ground surface or at a depth, and at some distance from the energy source the soil deposit is instrumented to detect the motion at various elevations and locations at the site (Ref. 1). In general, the energy for the testing program is generated through a number of relatively simple systems such as a hammer striking a plate or a steel post. This signal generating system imparts a suitable quantity of energy to the soil. However, the impulse energy imparted to the soil does not have the same frequency content in comparison to random loading (white noise).

The objective of this work was twofold; first to determine the dynamic soil properties from both sinusoidal and random vibrations and to compare the

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results. This is important because almost all laboratory testing utilizes the same type of force excitation, namely sinusoidal loading, though loading such as earthquake loading is of a random nature. Thus, for the measured laboratory value of modulus and damping to be consistent with those occurring in the field during earthquakes, random loading should be used in laboratory testing. This objective was accomplished by performing a comprehensive testing program covering a wide range of variables. The damping and modulus were calculated for both sinusoidal and random vibrations over a wide range of strains. Variables considered were the confining pressure, density state, grain size and strain history. The data from the experimental program showed a good agreement between the modulus and damping obtained from the application of sinusoidal or random loading. That is, the dynamic properties of dry cohesionless soil were not influenced by the type of loading applied (Ref. 2, 3) within the range of variables tested.

The second objective was to assure that extrapolation techniques of different field test data are correct, and to determine the relationship the laboratory determined properties bear to the field values the effect of the frequency content of the exciting random force on the dynamic soil properties was studied. The results of this study are presented in this paper. To analyze the random response of a soil sample subjected to random loading the Random Decrement Technique was used. The effect of the variation of the frequency content of the random loading to simulate the impulsive type loading used in field testing of soil was considered by passing the random signal through a filter before connecting it to the drive system. By varying the cut-off frequency of the bandpass filter; it was found that the damping values obtained by the random decrement technique increased as the cut-off frequency decreased. However the shear modulus was not affected.

METHOD OF ANALYSIS

The random decrement technique was utilized in the analysis of the random response of the soil samples. In this technique the random vibration responses are ensemble averaged to form a signature that is representative of the free vibration decay curve from which damping and frequency can be identified. That is, damping values for random loading are calculated by the logarithmic decrement method as in the case of sinusoidal loading. The random decrement technique was developed by Henry Cole for the measurement of damping and for the detection of structural deterioration of airplane wings subjected to wind flutter excitation (Ref. 4,5). It assumes that the random response of a damped structure is composed of two parts: a deterministic part (impulse and/or step function), and a random part. By averaging enough samples of the same random response, the random part will average out, leaving the deterministic part. It can be shown that by proper digital processing the deterministic part that remains is the free decay response from which the damping can be measured. Hence, the random decrement technique uses the free decay responses of a system under random loading to identify its vibration parameters, namely frequencies and damping. A mathmatical derivation was later developed (Ref. 6,7).

In general, linear systems have many degrees of freedom and the signature is a combination of modes, thus in multi-mode problems, the response records are bandpass filtered to isolate different frequency bandwidths and damping values are then calculated for each mode. To set the low and high

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pass frequencies of the filter, the power spectral density was determined to define the system's resonant frequency, knowledge of which enabled one to choose the low and high pass frequencies.

EXPERIMENTAL PROCEDURE

The determination of dynamic characteristics of soils can be obtained by a variety of laboratory testing equipment. The most widely used equipment are cyclic triaxial shear, cyclic simple shear, cyclic torsional shear, and the resonant column device. The resonant column method is a relatively nondestructive test, and was used in this study. The resonant column test procedure, apparatus description, and damping measurements can be found in Hardin (Ref. 8) and Drnevich, et al. (Ref. 9). In this study, the logarithmic decrement method was used in evaluating damping for sinusoidal loading because it utilizes the free vibration decay curve from which damping can be measured. The reason for using this method is that the random decrement method results in a signature that is the free decay curve from which damping is also calculated using the logarithmic decrement method.

For the sinusoidal loading test, the input signal was generated by a variable frequency sine wave oscillator. For the random vibration test, the excitation was provided by a random wave generator. The output of the random wave generator (white noise generator) was passed through a bandpass filter, then connected to the drive coils via a power amplifier. Response was recorded on a magnetic tape with an FM tape recorder. A schematic of the Drnevich-type resonant column device used in this test program is shown in Fig. 1.

Random Loading Test

After construction of the sample and assembly of the apparatus, the random vibration was first applied by connecting the white noise generator to the driving coils. The amplitude of the response vibration was adjusted to a predetermined value of acceleration that was read on the multimeter. At each response level, the exciting force was also measured on the multimeter in terms of millivolts. The response signals at each level were recorded on the magnetic tapes. The recorded response signal was passed through a bandpass filter, then through a signal amplifier before it was fed into a micro-computer for discretization and digitization. The computer analysis was continued until 1000 segments or more had been ensemble averaged resulting in a random decrement signature.

Random Loading with a Band Limited Frequency Content

The effect of the frequency content (band limited white noise) of the exciting force was studied by passing the exciting random noise from the white noise generator through a low pass filter eliminating all frequencies above a certain limit. This limit is referred to as the cut-off frequency. The cut-off frequencies used in this study were 50, 200, 1000 and 2000 Hz and the high pass frequency was set at zero. The power spectral density of such exciting forces when an ideal filter is used is uniform from zero to the cut-off frequency, and zero afterward. Fig. 2 shows the time history and power spectral density of one of the exciting forces, and shows that the filter did not have a sharp cut-off frequency like an ideal filter. During testing it

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was found that to obtain the same root mean square (RMS) of the output for all loading types required the input RMS to be modified slightly depending on the cut-off frequency used. The band limited white noise signal was then connected to the driving coils of the apparatus and the testing followed the same procedure as for the random loading test.

Sinusoidal Loading Test

By disconnecting the random wave generator and connecting the sine wave oscillator, sinusoidal torques were applied to the soil sample. To accomplish response at the predetermined response levels, the following procedures were followed. The output level on the sine wave generator was increased until a response was read on the multimeter. Then the frequency on the sine wave generator was adjusted until the first mode natural frequency was obtained by observing the Lissajous figure formed on the oscilloscope. To accomplish resonance at the predetermined response levels, it was necessary to adjust the output level and frequency simultaneously. Both excitation input and response output were read on the voltmeter and the resonant frequency was read on the frequency meter. Damping was determined by turning off the driving power at resonance and recording the decaying vibrations. The decayed wave was recorded on a magnetic tape, then fed into a microcomputer for discretization and digitization.

EXPERIMENTAL PROGRAM

Monterey #0 sands were used in the resonant column device in this investigation. This sand was chosen because its dynamic properties have been studied by other researchers (used in the Round Robin Testing Program, ASTM) thus the results can be verified and compared. The test samples were 3.53 cm in diameter and 8.0 cm long. Two methods were used for sample preparation. For a dense condition the specimen was constructed by pouring the sand in layers and tamping. For a loose condition the specimen was obtained by pouring the sand through a funnel. The minimum and maximum void ratios obtained in this study were 0.59 and 0.69, respectively.

Several series of dynamic tests were performed. The confining pressure varied from 103 to 241 kPa and the void ratio corresponded to both the dense and loose condition. In all of the test series, the magnitude of shear strain was varied from approximately 1.5×10^{-3} percent to 4×10^{-2} percent to study the effect of shear strain amplitude on the dynamic properties of the soil. Details of the testing program are presented in Ref. 2 .

The strain calculations for samples subjected to sinusoidal loading followed the same procedure presented by Drnevich et al. (Ref. 9), which utilized the root mean square (RMS) of the specimen response in the calculation of the strain. To compare the results obtained from the sinusoidal excitation with those from the random excitation test it was necessary to first determine the strain induced in a soil specimen due to applied random loading so that the dynamic properties could be compared at the same strain level. Since the random decrement technique transforms the random response of a system into the system free vibration response, and since the RMS of the response of both vibration types were forced to be the same, we used the same technique used in the calculation of the sinusoidal loading to approximately calculate the strain for the random loading. This strain was termed the equivalent strain.

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The justification of the use of the equivalent strain is presented in Ref. 3 . At each strain level damping was calculated by the random decrement method when the random excitation was applied and by the logarithmic decrement method when the sinusoidal excitation was applied.

For the purpose of limiting the size of the paper only an example of the data obtained is presented. Detailed results are presented by Al-Sanad (Ref. 2). To study the effect of the frequency content of the exciting force on the dynamic soil properties Figs. 3 and 4 are presented. Fig. 3 shows that as the cut-off frequency increased the damping values of random vibrations approached the damping values of the sinusoidal loadings. The cut-off frequency did not show an effect on the shear modulus values. This is shown in Fig. 4 where the values from random loading did not differ significantly from the values from the sinusoidal loadings.

EVALUATION AND DISCUSSION

The dynamic properties of Monterey #0 sand were studied using random loading in the resonant column device and the results were compared with those properties obtained using sinusoidal loading. The damping of the sinusoidal loading was calculated from the free vibration decay using the logarithmic decrement method. Similarly the damping of the random loading was calculated from the random decrement signature using the logarithmic decrement method. The shear modulus was calculated using the resonant frequency from the resonance condition when a sinusoidal vibration was applied and from the power spectral density or random decrement signature when a random vibration was applied. These frequencies along with response (RMS) were used in computing strain for sinusoidal loading and equivalent strain for random loading.

The values of the resonant frequency, damping ratio and shear modulus calculated for the random loading showed good agreement with those values of the sinusoidal loading over a range of strains from 1.5×10^{-3} to 4×10^{-2} percent. The good agreement obtained led to the conclusion that the dynamic properties of sand are not influenced by the type of loading used.

When the effect of different cut-off frequencies was investigated, the results showed that the higher the frequency content of the exciting load the closer was the agreement of the damping ratios from both the sinusoidal and random loading. Thus, the exciting forces currently in use in field testing of soils will indicate higher damping values than if sinusoidal loading is used. Aggour, et al. (Ref. 10) showed values of damping obtained from field testing that were higher than would have been expected. That is, field testing should be corrected to obtain damping for white noise excitation unless the field loading used itself is a white noise. The cut-off frequencies meanwhile, showed a slight influence on the shear modulus.

CONCLUSION

The experimental program showed a good agreement between the modulus and damping obtained from the application of either sinusoidal or random loading. That is, the dynamic properties of dry cohesionless soil were not influenced by the type of loading applied within the range of variables tested. However the use of a band limited white noise influenced the

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damping values calculated by the random decrement technique but not the shear modulus.

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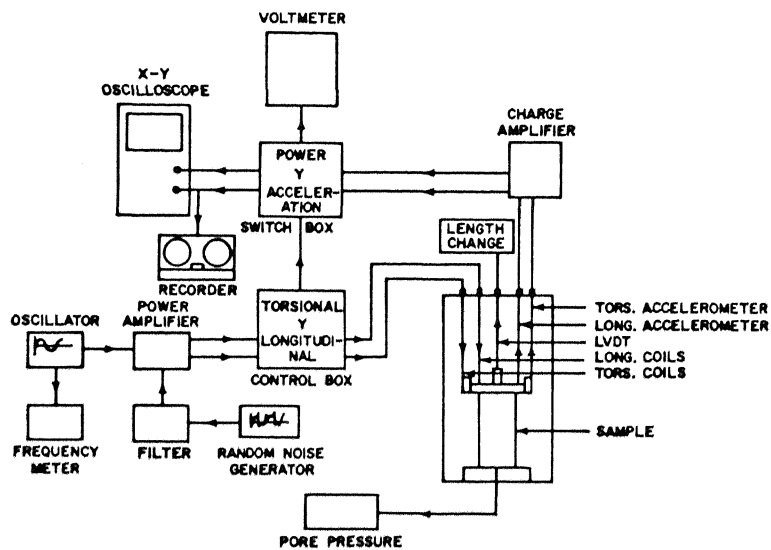
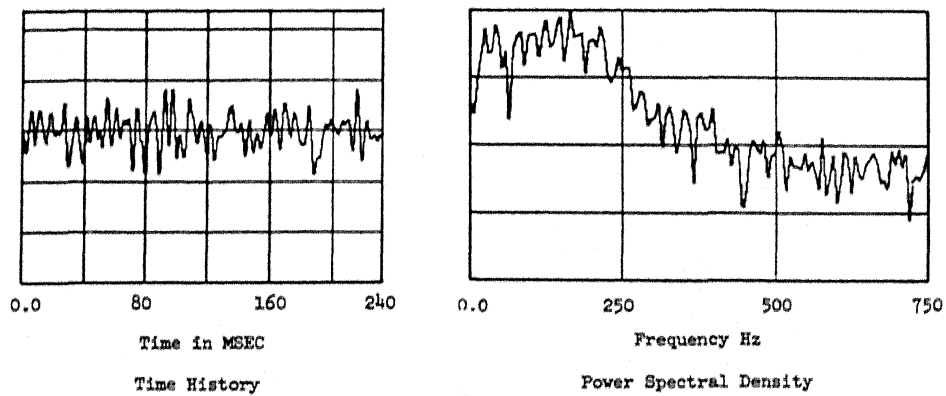Fig. 1.   Schematic Diagram of the Resonant Column Electronics

Time in MSEC

Time History

Frequency Hz

Power Spectral Density

Fig. 2.   Excitation Time History and Power Spectral Density with
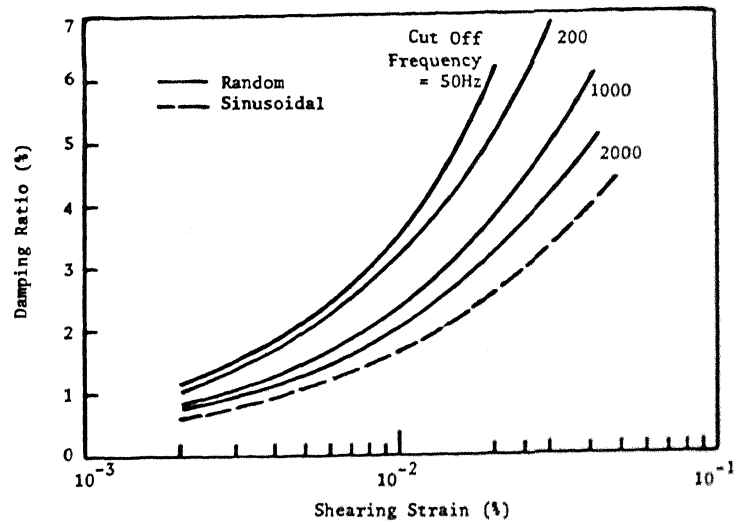Cut-Off Frequency of 200 Hz

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Fig. 3. Effect of Shear Strain on Damping for
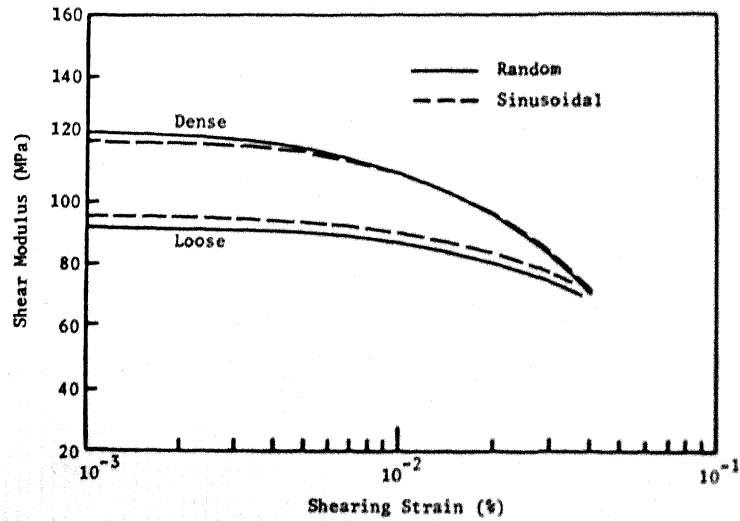Different Cut-off Frequency (Confining
Pressure 103 kPa)

Fig. 4. Effect of Shear Strain on Shear Modulus
(Confining Pressure 103 kPa)

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