AMPLIFICATION OF EARTHQUAKE MOTIONS RECORDED AT AN ACCELEROGRAPH STATION

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SUMMARY

Forced harmonic vibration tests, using eccentric mass shakers, were conducted at the Jenkinsville, South Carolina accelerograph station to determine the effect of soil-structure interaction on the motions recorded during four nearby earthquakes of small magnitude. The tests showed that the soil-pad-hut system had two strongly coupled translational and rocking modes of vibration in the frequency range 1-60 Hz. The soil-structure interaction model established from test data indicated that the average response spectra of the recorded earthquake motions were amplified by an average of about 30 percent for frequencies greater than 15 Hz.

INTRODUCTION

The construction of accelerograph stations is similar in most seismic countries such as Japan, the United States, China, and Italy (Refs. 3, 4, 5, 6, 8 and 9). A typical accelerograph station permanently located in the field usually consists of a rectangular concrete pad, partially embedded in the ground with a housing structure attached to provide shelter for the accelerograph. The plan dimension of the pad is generally 1-2 m and the thickness varies between about 0.2 and 0.6 m. In some cases the pad will be anchored by means of a small cylindrical concrete pier that may extend as much as 1 m deep into the ground. The accelerograph is bolted directly to the top of the pad or in the case of some stations to the top of a cylindrical pedestal, which protects the instrument from potential flooding. The housing structure is 1-2 m tall and is constructed of plywood, brick, concrete, fiberglass, or aluminum siding.

Permanent accelerograph stations located away from structures are intended to record free-field earthquake ground motions, i.e., motions that are not influenced by the presence of any structure, including the accelerograph station itself. Nearly all accelerograms recorded to date in permanent stations probably have not been influenced appreciably by the interaction between the station and the ground. There have been two primary reasons for this lack of interaction in the frequency band where most of the seismic-wave energy lies: (1) the base dimensions of the

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stations are much smaller than the wavelengths of the seismic waves, and (2) the natural frequencies of the station-ground system are much greater than the frequencies of the seismic waves.

However, more accelerograms are being recorded near the fault ruptures of earthquakes, and improvements in the digitization and processing of these accelerograms have extended their noise-free frequency band to 50 Hz. With a significant amount of energy in the frequency band between 15 and 50 Hz, many of these near-field accelerograms may be influenced by the dynamic interaction of the station with the ground as originally suggested by Bycroft (Ref. 3) and later by McNeil (Ref. 10).

In this paper the influence of soil-structure interaction on the earthquake motions recorded at an accelerograph station located at Jenkinsville, South Carolina is examined in detail. This station recorded four accelerograms in 1978 and 1979 (Refs. 2 and 11) during small, nearby reservoir-induced earthquakes, which had magnitudes (M_L) less than 3 and hypocentral distances less than 2 km. Although the accelerograms were less than 3 sec in duration with the strong shaking portion lasting less than 0.5 sec, the recorded peak motions were as large as 0.36 g. Because the accelerograms contained a significant amount of high frequency energy and because the station rested on relatively soft soil, soil-structure interaction was suspected as one factor accounting for the large peak accelerations. To determine if interaction was important at this station, extensive forced vibration tests were conducted to obtain the dynamic characteristics of the station, i.e., natural frequencies, modal dampings, and mode shapes. These parameters were input into soil-structure interaction models of the station and theoretical free-field accelerograms were computed.

FORCED VIBRATION TESTS AND DATA ANALYSIS

The Jenkinsville accelerograph station is shown in Figure 1a. The station consists of a concrete pad (4'x4'x2') embedded approximately 18 inches into a 58-ft thick Saprolite soil layer overlying granite. A 5-ft-high wooden hut, consisting of 3/4" plywood siding that was nailed to a frame made of 2"x4" pine wood, was attached to the pad with nails. The base of the hut was separated from the concrete pad by a 5/8"-thick foam-rubber pad.

The soil-structure model for both the forced vibration experiments and earthquake response analyses is shown in Figure 1b for horizontal translation and rocking. The interaction in the vertical direction was negligible. The model in Figure 1b has 3 degrees of freedom: horizontal translation (v_0) and rocking (ϕ) of the concrete pad, and rotation (θ) of the wooden hut. A rotational spring was considered sufficient to model the connection between the hut and the pad. During the vibration experiments described below, the hut appeared to rock about the base as evidenced by the compression visible in the front and back ends of the foam rubber.

Field Testing Program

An eccentric mass shaker weighing 35 lb and capable of producing up to 3800 lb of force at 60 Hz was mounted to the top of the concrete pad. Triaxial accelerometer packages consisting of Endevco piezoelectric accelerometers (5241A), with a flat frequency response between 2 and 500 Hz, were placed on each corner of the concrete pad and near the roof of the hut. The accelerometers measured the amplitudes and phases of the horizontal and vertical motions during the forced vibration tests. Signals from the accelerometers were passed through a STI differential amplifier and antialias filter, which removed frequencies greater than 100 Hz. The output was passed through an analog-to-digital converter and stored on a Data General Nova 3 Computer. A Hewlett Packard HP3582A Spectrum Analyzer, and HP7015B x-y plotter, as well as a Houston Instruments plotter were used to monitor the tests.

For one test in the N50^{o}E direction, for example, the eccentric mass shaker was mounted to the top of the pad over the pad's c.g. and the shaker excited the pad with a horizontal harmonic force in this direction at a fixed frequency. The tests were repeated over a range of frequencies from 5 to 60 Hz. The frequencies were incremented such that the frequency of a given test was 1 percent larger than the frequency of the preceding test. The applied force in pounds equaled $1.051\ ef^2$, where e = eccentricity and f = frequency in Hz. To keep the force levels from becoming too large and thereby inducing significant nonlinear response, the eccentricity was lowered at 20 Hz and again at 35 Hz. The eccentricity values selected were: 1.0 (5 to 20 Hz); 0.40 (20 to 35 Hz); and 0.15 (35 to 60 Hz).

The steady-state acceleration amplitudes and phases for the acceleration-time histories recorded by the Endevco accelerometers were determined by Fourier analysis at each frequency of excitation. The modulus was taken as the amplitude of the steady-state acceleration and the phase angle was computed from the real and imaginary parts. The phase angle (p) was defined with respect to the applied force; i.e., if the shaker force was $F = F_o \sin \omega t$, then the response measured by a particular accelerometer was $a = a_o \sin (\omega t + p)$. To time the application of the harmonic force, a sensor was placed on the rotating shaft of the shaker. This sensor recorded the times at which the shaker force reached its maximum positive value during each revolution.

Data Analysis

The steady-state amplitude and phase data obtained from the forced vibration tests were transformed into the 3 translational and 3 rotational accelerations of the c.g. of the concrete pad and the rotation and vertical translation of the wooden hut. This was accomplished by solving the equations that described the rigid body motion of the concrete pad for small displacements. Because the wooden hut was assumed to act as a rigid body attached to the concrete pad by flexible springs, the hut's motions at its c.g. were easily computed from the recorded roof motions and the calculated pad motions.

A plot of the displacement amplitude in the direction of the applied force and phase are shown in Figure 2 for one test. The displacement amplitudes were computed by dividing the corresponding accelerations by ω^2. The displacements shown in Figure 2 have been normalized by the shaker force. The narrow peak at 16 Hz and the broad peak at 47 Hz correspond to the first and second natural frequencies of the soil-pad-hut system. The discontinuities at 20 Hz and 35 Hz reflect the change to lower eccentricities (and hence lower force levels) during the test. Theoretically, if the soil-structure system were completely linear and if the eccentricities were precisely set, then discontinuities would not appear. However, the discontinuities are small and are of no practical consequence.

Determination of Modal Parameters

The natural frequencies (ω_i) and modal dampings (ζ_i) were determined by applying a procedure developed by Beck (Ref. 1). The procedure consists of fitting a theoretical amplification curve for a single-degree-of-freedom system to the observed response data. The method is applicable to modes which are well separated and have low damping, which is the case for the soil-pad-hut system. A computer program for the curve fitting was taken from Appendix A.2 of Lin (Ref. 7). The program was applied to pad displacement data normalized by the applied shaker force such as shown in Figure 2.

The response data that defined each peak near 16 Hz and 47 Hz were used in the curve fitting procedure. This procedure was repeated for the other horizontal direction also. The mode shapes (ψ_i) were obtained by a trial-and-error procedure until the computed responses were reasonably close to those measured during the experiments. The resulting ψ_i, ζ_i and ω_i, are presented in Table 1. The mode shapes clearly show that the first natural frequency in each direction was influenced by the hut, and that the second natural frequency in each horizontal direction represented predominantly the response of the pad.

FREE-FIELD MOTIONS

The modal equations of motion for the earthquake response of the accelerograph station were derived in the frequency domain from the soil-structure interaction model shown in Figure 1b. These equations are easily solved and the transformed free-field acceleration, $\bar{\ddot{v}}_g$, can be expressed in terms of the transformed recorded acceleration, $\bar{\ddot{v}}_r$, the modal parameters, and the height, $h_o + h_3$, of the accelerograph transducers above the bottom of the concrete pad as

$$\bar{\ddot{v}}_g = \bar{\ddot{v}}_r \Big/ \left[1 + \sum_{j=1}^{3} \psi_{1j} \bar{A}_j + (h_o + h_3) \sum_{j=1}^{3} \psi_{2j} \bar{A}_j\right] \qquad (1)$$

where ψ_{ij} are the elements of the mode shape matrix, ψ, and $\overline{A}_j$ is the amplification factor for the j^{th} mode. $\overline{A}_j$ is given by

$$\overline{A}_j = \Gamma_j \ / \ \left[1 - (\omega/\omega_j)^2 - i\ 2(\omega/\omega_j)\ \zeta_j\right] \tag{2}$$

where: ω_j, ζ_j and Γ_j are, respectively, the natural frequency, modal damping and participation factor for the j^{th} mode; ω is the circular frequency; and $i = \sqrt{-1}$.

The denominator on the right-hand side of equation (1) is called the transfer function between $\ddot{\overline{v}}_g$ and $\ddot{\overline{v}}_r$. A graph of the moduli of the transfer functions versus frequency are shown in Figure 3 for both the N50°E and N40°W directions. The transfer functions are similar except the first peaks are located at different frequencies (10.6 Hz and 16.7 Hz) and have different amplitudes.

The theoretical free-field accelerograms, corresponding to the four accelerograms recorded by the SMA-1 accelerograph, were computed by taking the inverse Fourier transform of equation (1). A comparison between a recorded and free-field accelerogram is shown in Figure 4. The recorded accelerogram is the 90° component of the 16 October 1979 earthquake (Ref. 11). Because the transducer directions in the SMA-1 are different from the principal axes of the pad, free-field accelerograms were first computed for the two principal axes and then were transformed into the transducer directions. Figure 4 shows that the computed free-field accelerogram is less than the recorded accelerogram, both in amplitude and frequency content. The peak acceleration has been reduced from 0.36 g to 0.27 g.

The 5 percent damped response spectra of the recorded and free-field accelerograms are shown in Figure 5. The response spectrum of the recorded motion is about 1.2 to 1.6 times greater than the free-field response spectrum for frequencies greater than about 15 Hz. An important point to note is that although the transfer functions showed significant amplification beyond 25 Hz, the response spectrum of the recorded motion has been amplified over a broader frequency band beginning at about 5 Hz. This illustrates the contribution higher frequency motions can have on the response spectrum at lower frequencies, especially when the higher frequency motions contain a relatively large amount of energy.

The above calculations were repeated for the other accelerograms recorded at the Jenkinsville station. The average reduction in the response spectra of the computed horizontal free-field accelerograms was 7 percent between 1 and 10 Hz; 22 percent between 10 and 35 Hz; and 38 percent between 35 and 50 Hz.

CONCLUSIONS

As more permanent accelerograph stations are placed in seismic regions, especially at locations close to potentially active faults, the design of these stations becomes important if soil-structure interaction effects at the station are to be minimized. Recommendations to reduce interaction effects have been suggested by the senior author (Ref. 5) and are briefly summarized. The basic recommendation is to make the stations as small as possible. Some minimum size is required to adequately house the instrument and other supporting equipment, but for most stations a 1 m square concrete pad about 0.2 m thick would be sufficient. The pad should be firmly embedded or anchored in the ground to increase the foundation stiffness or impedence. The instrument should be mounted at the center of the pad close to the ground surface. This will minimize the translational components of the pad's rocking and torsional motions that the instrument would record during an earthquake. Thus, pedestals that substantially elevate the instrument should be avoided.

The shelter design should not be overlooked either. Lightweight fiberglass or aluminum construction is ideal. Tall and heavy shelters, such as those made of thick plywood, brick, or concrete, could affect the response of the pad. The connection between the larger shelters and the pad is also important. For example, if the shelter is extremely stiff and is rigidly attached to the pad, the fundamental natural frequency of the system would decrease and the rocking response of the pad would tend to increase, which in turn could amplify the recorded motions. On the other hand, if the connection is flexible, an extra degree of freedom and, hence, natural frequency will be introduced to the system, which could result in significant amplification in one more frequency band.

As the stiffness or shear-wave velocity of the ground medium supporting the pad decreases, the natural frequency of the station decreases. Thus, if motions on relatively soft alluvial deposits are not the motivating factor in site selection for a particular accelerograph station, then the station should be located on the stiffest material in the region of interest to minimize any potential amplification in the lower frequencies.

ACKNOWLEDGMENTS

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Table 1. Modal Parameters for Soil-Pad-Hut-Models

	1st Mode			2nd Mode		
Direction	ω	ζ	ψ	ω	ζ	ψ
N50°E	16.7 Hz	.04	2.34×10^{-3}	49.8 Hz	.20	-6.14×10^{-2}
			3.39×10^{-3}			-1.95×10^{-2}
			6.56×10^{-2}			4.54×10^{-2}
N40°W	10.6 Hz	.06	9.13×10^{-4}	47.9 Hz	.21	-6.21×10^{-2}
			1.33×10^{-3}			-1.91×10^{-2}
			6.90×10^{-2}			4.16×10^{-2}

Note: The units on ψ are $\{\text{in., rad., rad.}\}^T$

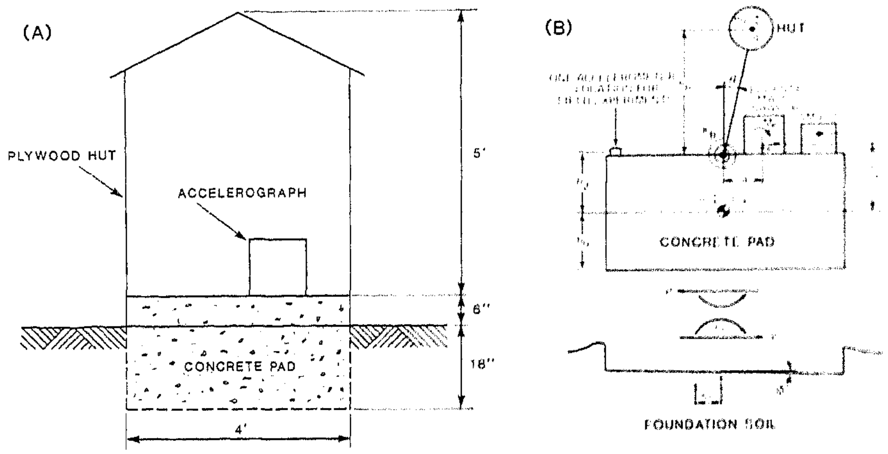

FIGURE 1. (A) JENKINSVILLE ACCELEROGRAPH STATION (B) INTERACTION MODEL

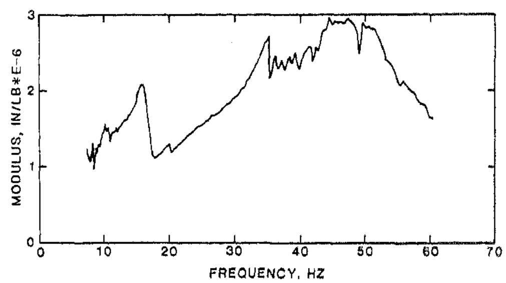

FIGURE 2. DISPLACEMENT AMPLITUDE OF PAD DURING FORCED VIBRATION TEST

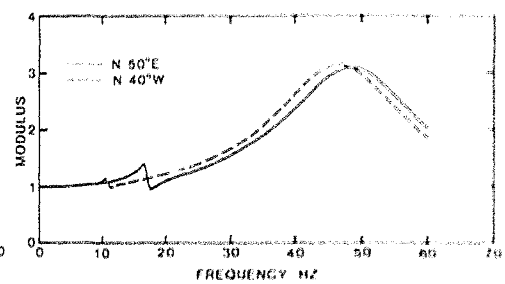

FIGURE 3. TRANSFER FUNCTION, $|\hat{v}_r/\hat{v}_g|$.

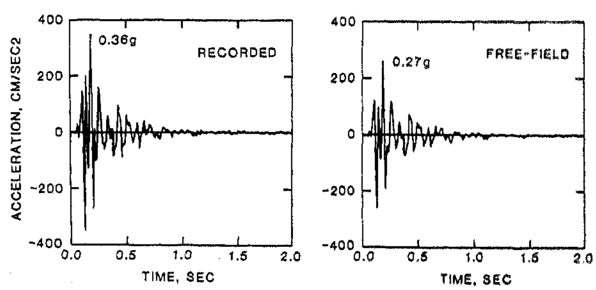

FIGURE 4. RECORDED AND COMPUTED FREE-FIELD ACCELEROGRAMS.

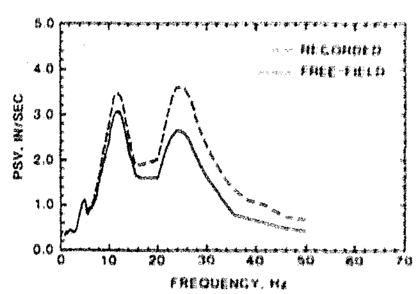

FIGURE 5. RESPONSE SPECTRA OF ACCELEROGRAMS IN FIGURE 4.