AN EXPERIMENTAL STUDY OF GROUND DEFORMATIONS CAUSED BY SOIL-STRUCTURE INTERACTION

by

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ABSTRACT

Detailed measurements of the surface ground motion generated by forced vibrations of the nine-story Millikan Library building on the campus of the California Institute of Technology are described. The three components of the displacement field were measured at one-hundred points located in the immediate neighborhood of the building and at over two-hundred and fifty points distributed in the Pasadena area at distances up to four miles from the Millikan Library. The measurements were conducted at the lowest resonant frequencies of the building-foundation system in both the north-south (~ 1.8 cps) and east-west (~ 1.3 cps) directions. The excitation was provided by a vibration generator mounted on the roof of the building. Preliminary analysis of the motion recorded in the near and far field indicates the potential of this experimental approach in evaluating the effects of soil-structure interaction as well as the effects of local site conditions on surface ground motion.

INTRODUCTION

Previous forced vibration tests of structures(1) have shown that a multi-story building forced to vibrate at one of its resonant frequencies becomes a very efficient vibrational source of elastic waves in the surrounding soil. Relatively small equipment may be used to generate steady-state vibrations of the ground which may be recorded at distances of several miles from the source. The tests described here take advantage of this characteristic in an attempt to study experimentally the effects of local site conditions as well as the effects of soil-structure interaction. At difference with the more common methods of seismic exploration, the measurements presented here are directed towards the evaluation of the amplitudes of motion at different locations rather than at the determination of arrival times of different waves.

For the present study the nine-story reinforced concrete Millikan Library building located on the campus of the California Institute of Technology was used as a vibrational source. The building was forced into resonance in both the N-S and E-W directions, and the amplitudes of motion were measured in two regions called for convenience the near and far fields. The near field corresponds to the immediate neighborhood of the building. The motion in this region was recorded at the 100 locations shown in Figure 1.a. The far field region corresponds to a portion of the Pasadena area. The amplitudes of motion in this region were recorded at over two-hundred and fifty locations along eleven lines radiating from the building and extending out to four miles as shown in Figure 1.b. The characteristics of the Millikan Library building, vibration generator, and recording devices used have been presented elsewhere(2).

MOTION OF THE FOUNDATION AND NEAR FIELD DISPLACEMENTS

Before proceeding to describe the steady-state motions recorded in the near and far field, it is convenient to estimate the amplitudes of motion of the foundation, as well as the forces that the foundation exerts on the ground. In a

LOCATION OF POINTS WHERE MEASUREMENTS WERE TAKEN

(NOT TO SCALE)

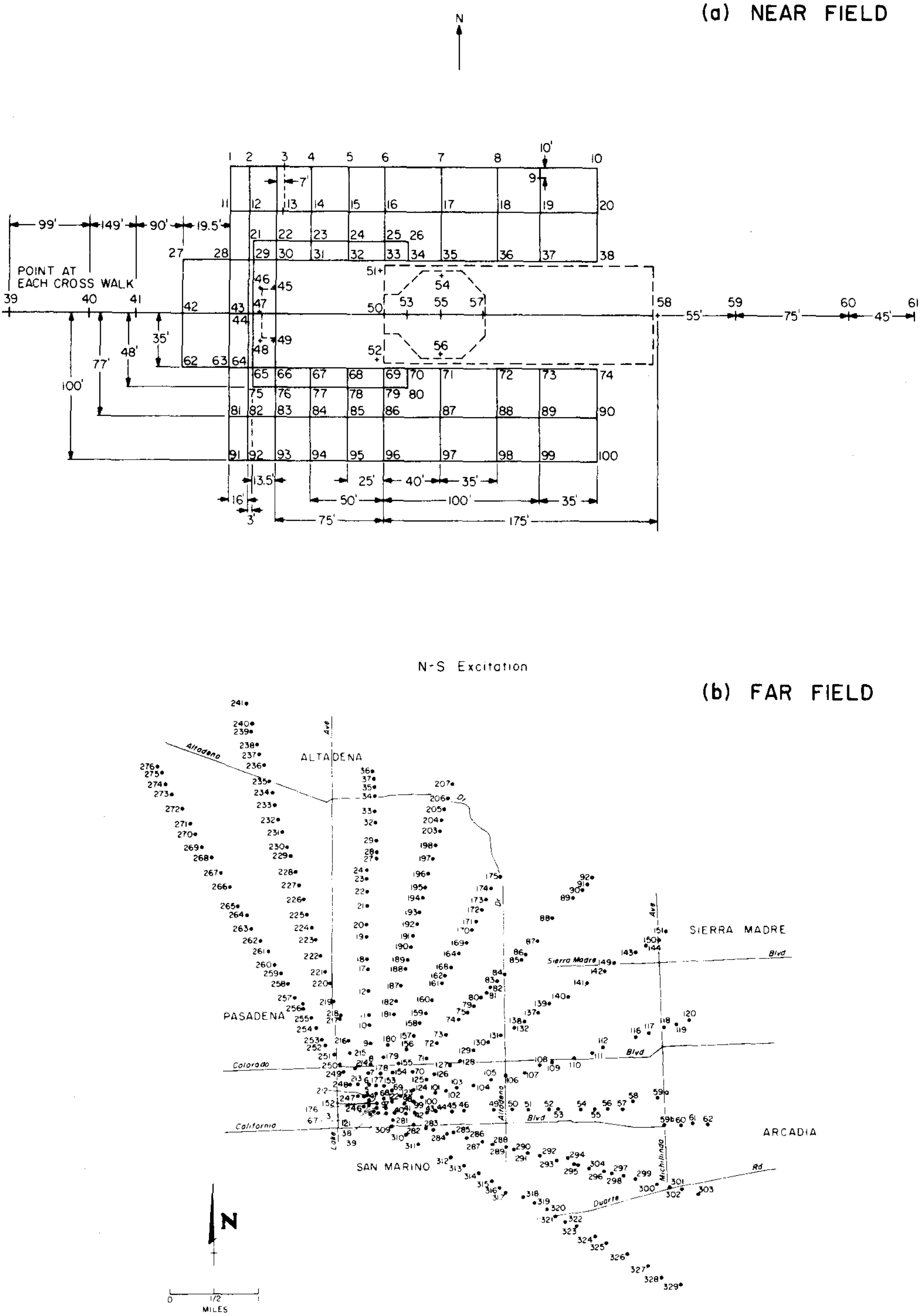

Figure 1. Location of points where measurements were taken: (a) near field, (b) far field.

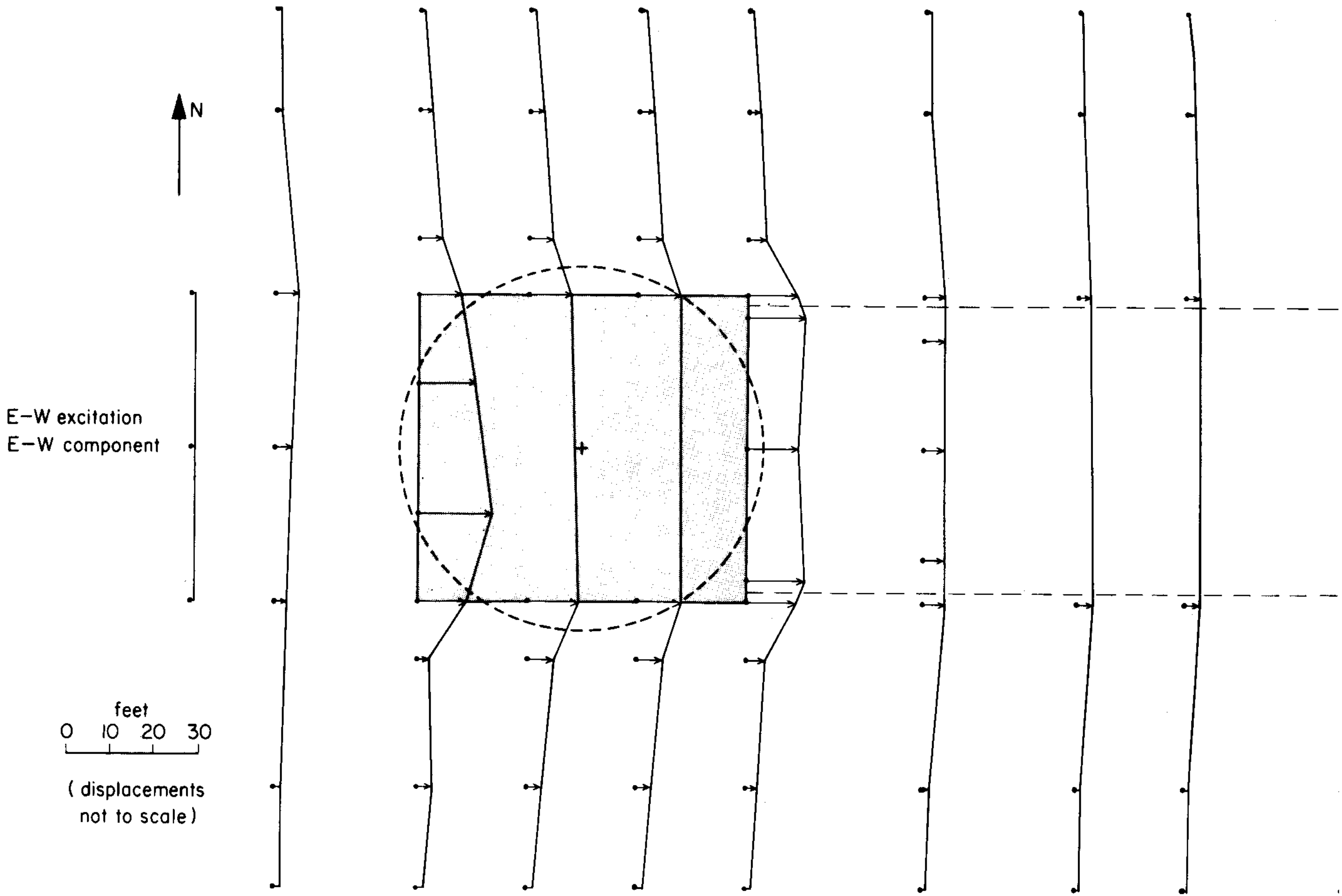

Figure 2. E-W component of the near field motion for E-W excitation.

related experiment(2) the deformation of the basement slab of the building was measured for the same type of excitation. Although it was found that the basement slab did not move as a rigid plate, it is still possible to evaluate an average amplitude of translation and rocking of the foundation in accordance with the general practice in the analysis of soil-structure interaction. The estimates of the average values obtained are listed in Table I. Horizontal force and the rocking moment estimates have been made from measurements of building motions.

TABLE I

Excitation	Frequency (c.p.s.)	Average Translation (inches)	Average Rocking (radians)	Horizontal Force (lb)	Rocking Moment (lb-ft)
N-S	~1.8	$\sim 3.0 \times 10^{-3}$	$\sim 1.2 \times 10^{-5}$	$\sim 2.8 \times 10^{5}$	$\sim 2.7 \times 10^{7}$
E-W	~1.3	$\sim 1.7 \times 10^{-3}$	$\sim 0.45 \times 10^{-5}$	$\sim 1.7 \times 10^{5}$	$\sim 1.7 \times 10^{7}$

It may be observed that due to the increased flexibility of the building in the E-W direction there is proportionally less rocking of the foundation in that direction than for the N-S shaking of the building. Since the wavelengths involved in the test are much larger than the dimensions of the foundation, it is possible to use the average motion of the foundation together with the static stiffness coefficients for a rigid rectangular foundation(3) to estimate the values of H/μ and M/μ, where H and M are the amplitudes of the horizontal force and rocking moment acting on the ground and μ is the shear modulus of the soil. On the other hand, estimates of H and M may be obtained from the inertial forces acting on the building. Combining these two estimates, it is possible to determine the range of values of the shear modulus of the soil, μ, to be between 5.2×10^6 lb/ft^2 12×10^6 lb/ft^2, for a Poisson's ratio of $\frac{1}{3}$. For a unit weight of soil of 100 lb/ft^3, this result leads to a range of shear wave velocities in the soil from 1300 ft/sec to 2000 ft/sec. The forces acting on the ground are almost two orders of magnitude larger than the force that the vibration generator exerts on the roof of the building.

The large steady-state forces described above induce substantial deformations in the near field, i.e., in the region adjacent to the building(2). Typical results are presented in Figure 2 where the E-W component of motion is shown for E-W excitation of the building. Figures presenting the three-dimensional deformation of the ground in the near field for excitation in both the N-S and E-W directions may also be found in reference (2). The large deformation in the near field indicates that the experimental procedure described here may be used to study the interaction between adjacent structures. The motion of the near field may also be used to further test the existing solutions for the soil-structure interaction problem. The results presented here were used, for instance, to estimate the equivalent radius of a rigid circular foundation that would best fit the observed near field motion (Figure 2). The results lead to an equivalent radius of 40 to 42 feet. These values compare well with the usual estimates of the equivalent radius for a rectangular foundation 75 feet long by 69 feet wide.

FAR FIELD DISPLACEMENTS

The amplitudes of the N-S, E-W, and vertical components of motion along the lines N0°E, N45°E, and N90°E are shown in Figures 3 and 4 versus the distance to the center of the building. Results for both N-S and E-W shaking are presented. The amplitudes have been normalized with respect to the amplitude of motion at a reference point in both the N-S and E-W directions. Acting on the

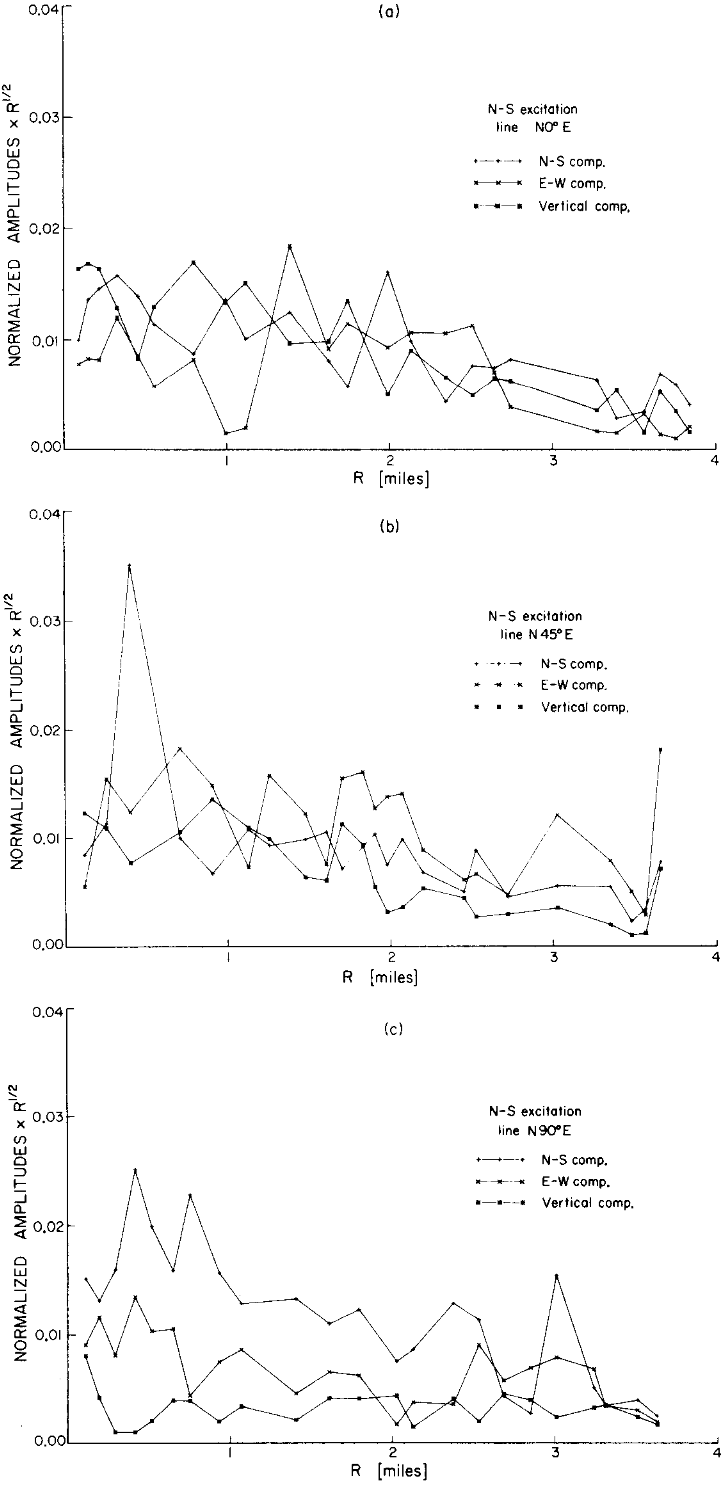

Figure 3. Far field displacements along lines (a) N0°E, (b) N45°E and (c) N90°E for N-S excitation.

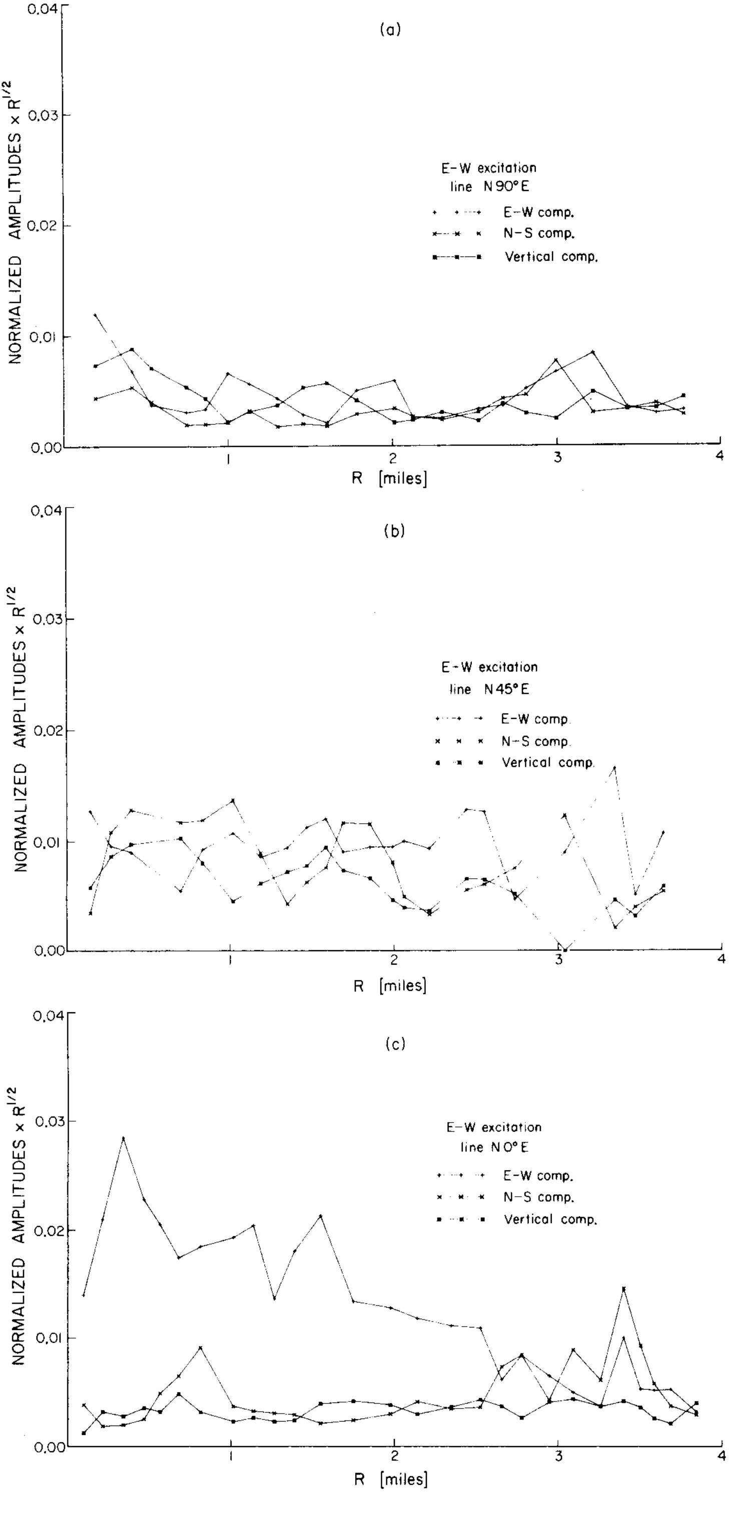

Figure 4. Far field displacements along lines (a) N90°E, (b) N45°E and (c) N0°E for E-W excitation.

assumption that the far field displacements correspond mainly to surface waves, the amplitudes shown have been multiplied by the square root of the distance to the building in an attempt at eliminating the geometrical attenuation.

Inspection of Figure 3 indicates that the attenuation with distance is slightly higher than $R^{1/2}$, suggesting the possibility of energy dissipation in the soil, the presence of body waves, or both. This tendency, however, is not so marked for the case of E-W excitation, as shown in Figure 4. The data presented in Figure 3.a for a line along the direction of the excitation indicates that, on an average, the vertical displacement up to a distance of two miles from the source is about 1.1 times the N-S displacement. If these displacements were to correspond to a Rayleigh wave propagating through a uniform elastic medium, then the ratio of vertical to horizontal motion should be higher (1.85 for a Poisson's ratio $\nu = \frac{1}{2}$, 1.60 for $\nu = \frac{1}{3}$). Similar behavior is observed in Figure 4.a for the E-W excitation, indicating the presence of harder layers of soils at depths shallower than 200 feet. Again, referring to Figures 3.a and 4.a, it may be noticed that the transverse components of motion (E-W component for N-S excitation and N-S component for E-W excitation) are not zero along lines coinciding with the direction of the excitation, suggesting the presence of lateral heterogeneities. Also, the normalized vertical and longitudinal displacements for the E-W excitation (Figure 4.a) are lower than the corresponding displacements for the N-S excitation (Figure 3.a) due to the lower rocking of the foundation in the E-W direction.

The transverse components of motion are most pronounced along lines at 45 degrees from the direction of excitation, as may be seen in Figures 3.b and 4.b. Along these lines, the average longitudinal and transverse components are approximately equal. The most marked feature of the recorded displacements shown in Figures 3.c and 4.c corresponds to very pronounced motion in the direction of the excitation along lines at 90 degrees with respect to these directions. These components of motion indicate the presence of Love waves or multiple-reflected SH waves and again represent the effect of the layering on the surface ground motion. The normalized amplitudes of these waves are about the same for the E-W and N-S excitations as should be expected, since they are associated with only the horizontal force at the source.

The radiation patterns of the three normalized components of motion for shaking in the N-S and E-W directions are presented in Figure 5 for the range of azimuths covered in the experiment. The radiation patterns are shown for the displacements at distances of one and three miles from the building and include the assumed geometrical attenuation factor of $R^{1/2}$. Figures 5.a and 5.e correspond to motion in the direction of the excitation and Figures 5.b and 5.d correspond to motion perpendicular to the direction of the excitation, while Figures 5.c and 5.f correspond to the vertical components of motion. The theoretical radiation patterns for Rayleigh and Love waves are shown at the lower left corner of each figure.

Inspection of Figures 5.a and 5.e shows again the presence of a strong Love wave with maximum values along the E-W line for N-S excitation and along the N-S line for E-W excitation. The Rayleigh wave is more pronounced for the N-S excitation due to the higher rocking of the foundation. The maximum values of the transverse components of motion occur at approximately 45 degrees as shown in Figures 5.b and 5.d and correspond to the combined effects of Rayleigh and Love waves. In this case the radiation patterns coincide fairly well with the theoretical patterns. Due to the different phase velocities of the Rayleigh and Love waves, it may be possible to find interference between these two types of waves at certain distances along the line at 45 degrees. The radiation pattern for the vertical component of motion for N-S excitation coincides well with the

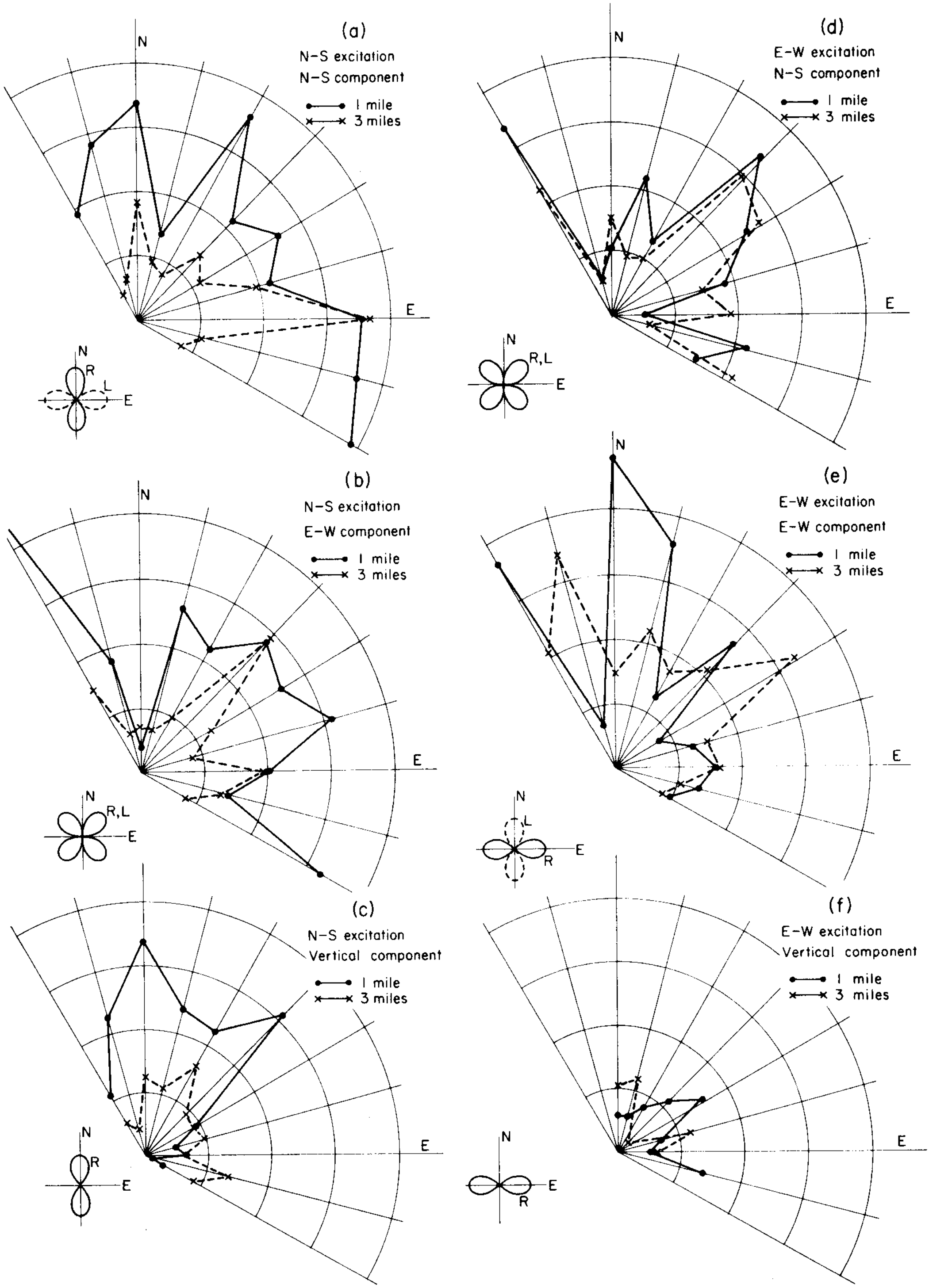

Figure 5. Observed far field radiation patterns.

theoretical radiation pattern (Figure 5.c). However, for the E-W excitation, the vertical component is smaller because of the reduced rocking moment in this direction.

The major changes in the radiation patterns with distance occur at the northern part of the region covered, suggesting that these changes may be associated with the proximity of the mountains in this area. The depth of alluvium decreases from 900 feet at the Millikan Library site to practically nothing at the contact with the mountains some four to five miles due north. Also, some reflection of waves may be expected at this contact.

Although it has been mentioned that the layering of the soil has a strong influence on the recorded data, a preliminary analysis has been conducted by neglecting these effects. In particular, the vertical components of motion have been used in an attempt at estimating the shear wave velocity in the soil. Assuming that the vertical components of motion at the ground surface, $u_z(R, \theta, 0)$, may be represented by a Rayleigh wave radiating from a point source in a uniform elastic half-space, then(4)

$$u_z(R, \theta, 0) = -\frac{i}{2} H_1^{(2)}\left(\frac{\omega s R}{\beta}\right)\left[s L_o \left(\frac{\omega}{\beta}\right)^2 \frac{M}{\mu} + M_o \left(\frac{\omega}{\beta}\right) \frac{H}{\mu}\right] e^{i\omega t} \cos\theta$$

where, β and μ are the shear velocity and shear modulus of the soil; s is the ratio of the shear wave velocity to the Rayleigh wave velocity; L_o and M_o are known functions of the Poisson's ratio ν(4); ω is the frequency of the excitation; and M and H, which are assumed to be in phase with one another, are the moment and force that the building exerts on the ground.

Since M and H have already been estimated from the displacement of the building, it is then possible to fit a function of the type described above to the the measured vertical motion, thus evaluating the shear wave velocity β for an assumed value of the Poisson's ratio. The results obtained lead to estimates of β = 1400 ft/sec for $\nu = \frac{1}{2}$ and β = 1800 ft/sec for $\nu = \frac{1}{3}$. These estimates of the shear wave velocity coincide well with values obtained by considering only the motion of the base of the building, considering the fact that we are using only first order approximations based on the half-space theory. This suggests that inversion of the recorded displacements for a more realistic model of the soil will permit an evaluation of some of its average characteristics.

CONCLUSIONS

The results presented here lead to the following conclusions:

1. It is possible to generate sufficiently large displacements during forced vibration tests of structures so as to obtain an easily detectable signal, which can be recorded with standard recording devices, at distances up to four miles.

2. The displacements measured in the far field during forced vibration tests contain valuable information as to the properties of the medium of propagation. In particular, for the test described here, it was found that layering of the soil had an important effect on the recorded motion, and, thus, the detailed analysis of the far field displacements cannot be done on the basis of the theory of wave propagation on a uniform elastic half-space.

3. By measuring the three components of motion at different locations, it is possible to analyze different types of waves, thus increasing the number of conditions posed on the problem of determining the characteristic of the soil given the recorded motion and the characteristics of the excitation. The accuracy in the determination of the model for the soil may be increased by recording phases in addition to the amplitudes of motion.

4. The motion of the foundation of the building together with estimates of the forces that the building exerts on the ground can be used for the experimental determination of the compliance functions for the foundation.

5. The displacements measured in the near field are sufficiently large as to permit the study of the interaction effects between adjacent structures.

REFERENCES

1. Jennings, P. C., "Distant Motions from a Building Vibration Test," Bull. Seism. Soc. Amer., 60, 2037-2043 (1970).

2. Foutch, D. A., Luco, J. E., Trifunac, M. D., and Udwadia, F. E., "Full Scale, Three-Dimensional Tests of Structural Deformations during Forced Excitation of a Nine-Story Reinforced Concrete Building," Proceedings, U.S. National Conference on Earthquake Engineering, Ann Arbor (1975).

3. Wei, Y., "Steady State Response of Certain Foundation Systems," Ph. D. Thesis, Rice University (1971).

4. Luco, J. E., and Westmann, R. A., "Dynamic Response of Circular Footings," Journal of the Engr. Mech. Div., A.S.C.E., 97, 1381-1395 (1971).