A NOTE ON THE EFFECTS OF RECORDING SITE CONDITIONS ON AMPLITUDES OF STRONG EARTHQUAKE GROUND MOTION

H. L. Wong[I] and M. D. Trifunac[II]

SYNOPSIS

In this paper we summarize, from the earthquake engineering viewpoint, our recent studies [1-7] dealing with vibrational properties of irregular topography and of soil and alluvium deposits excited by strong earthquake ground motion. The geometry of these features can be quite irregular and may lead to complicated scattering, diffraction and focusing patterns of motion for incident seismic waves.

INTRODUCTION

In an effort to explain often highly localized distribution of damage resulting from strong shaking, many investigators considered ground amplification effects and tried to correlate soil inhomogeneities and surface topography with computed or measured distribution of strong-motion amplitudes. The models considered in this work now range from one-dimensional single and many layer models to three-dimensional finite element models. In the development of these models the solution of the problem which requires computation of motion at a given point, for a given model geometry and input excitation, is easy in principle and can lead to the unique solution. However, the solution of an inverse problem where the recorded motion is given and one is required to find the properties of the model and the input motions usually has no unique solution.

COMMENTS ON WAVELENGTH, SIZE OF INHOMOGENEITY, SCATTERING, INTERFERENCE AND "PREDOMINANT" PERIODS

It is well known that for a seismic wave to "see" an inhomogeneity its wavelength has to be comparable to or shorter than the "size" of the inhomogeneity. For frequencies which are of interest in earthquake engineering and range from about 0.1 cps to about 20 cps and for wave speeds between 0.1 km/sec and 3 km/sec the range of wavelengths to be considered is from about 5 m to 30 km. For waves to "see" an inhomogeneity (e.g., a layer), for example, 30 m long (deep) and in the medium having shear wave velocity of 300 m/sec, the wave frequency would have to be 10 cps and higher. Consequently, to study the effects of local soil and geologic conditions underneath a recording station on the complete spectrum of recorded motions, it may be necessary to model a region surrounding the station and having dimensions comparable to the longest wavelengths of interest; in some cases as large as 10 km. In some engineering investigations only shallow and localized (tens to hundreds of meters) soil and geologic characteristics are considered. While this information is very useful for high-frequency (short wave) studies, it may be necessary to extend these investigations to considerably greater depth and lateral distance (kilometers) if a realistic analysis of a broadband spectrum of strong shaking is required. Fig. 1 [3], for example, illustrates the relationship between the wavelength and the separation of the recording stations. It shows radial and transverse motions recorded at four stations in Los Angeles during the San Fernando, California, earthquake of 1971 (Fig. 2). It displays a high degree of

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[I] Research Fellow, Applied Science, C. I. T., Pasadena, Calif. 91125.

[II] Associate Prof., Civil Eng., U. S. C., Los Angeles, Calif. 90007.

similarity between the displacements (low-frequency long waves) at the four stations. This similarity decreases when velocities (intermediate frequency waves) are considered and disappears completely for accelerations (high-frequency short waves). Qualitative explanation of these observations can be illustrated by Figs. 3 and 4 [5]. These figures show the amplitudes and phases of surface displacement computed for semi-elliptical alluvial valleys and for incident plane harmonic SH waves of unit amplitude [5]. The angle of incidence THETA varies from 0° to 90° (THETA = 90° - γ in Fig. 5), ETA = $2A/\lambda$ represents the ratio of the width of the valley, $2A$, to the length of the incident waves, λ. R is the ratio of major, A, to minor, H, dimensions of the ellipse, and MUV/MU and ROV/RO represent the ratios of the moduli of the rigidity and the material density in the valley to the corresponding quantities in the underlying half space. It can be seen that the waves long compared to the depth and width of the valley propagate past this inclusion (Fig. 4) with only minor amplitude distortions, whereas short waves (Fig. 3) develop complicated interference patterns inside and outside the valley. Figs. 3 and 4 also show the surface amplitudes that would be predicted by the horizontal layer approximation, often used in earthquake engineering, and show that this simplified approach might lead to good approximation of surface amplitudes only where ETA is small [5]. Fig. 3 illustrates many other characteristics of wave scattering, diffraction and interference which we recently examined in some detail for several two-dimensional models [1,2,4-7]. Within the alluvial valley $|x/A| < 1$, surface displacements display many peaks and troughs. For nearly vertical incidence the average amplitudes are not significantly different than the free field amplitudes equal to 2, i.e., the peaks tend to be above the free field level but many troughs are below this level showing that at a point the destructive interference can lead to attenuation of incident amplitudes. For horizontal and near horizontal incidence, and for the geometry considered, there appears to exist a trend towards more consistent increase of amplitudes for $|x/A| < 1$ (see also Fig. 5). Outside the valley, on the side from which incident waves arrive, the waves scattered from the inhomogeneity tend to interfere with incident waves and may form a significant component of standing waves whose amplitudes, superimposed on the overall energy propagation from left to right in Figs. 3, 4 and 5, will depend on the geometry, angle of incidence and the impedance across the material discontinuity. Behind the inhomogeneity and depending on its shape and the angle of incidence, a shadow zone may be observed where the amplitudes will tend to be smaller for the free field motion and will have a tendency to be less variable with distance.

It has been proposed by many investigators that alluvium and soil deposits might be characterized by their "predominant" period of vibration. While this idea may be plausible for certain sites which are characterized by a very large contrast in material properties between the soil and the underlying medium, it should be pointed out that the frequencies of these "predominant" periods may depend on the direction of incident waves so that different earthquakes occurring at different sites could lead to different "predominant" periods. This possibility is illustrated in Fig. 5 where the spectral amplitudes are plotted versus dimensionless frequency $\eta = 2a/\lambda$ [1]. Comparison of spectral amplitudes at $x/a = 0.8$ and for horizontal ($\gamma = 90°$) and vertical ($\gamma = 0°$) incidence of plane SH waves shows that the two spectra locally may have quite different peaks. While the simple model in Fig. 5 does not permit any generalization, a study [8] of many spectra recorded at the same station and for different earthquakes has also indicated that the "predominant" periods may be an exception rather than the rule for a typical recording station in the Western United States of America. If the overall spectra are smoothed to eliminate some of the sharp peaks similar to those shown in Fig. 5 and if the broadband trends are considered, then it can be stated that the spectra do show greater spectral amplitudes in certain broad frequency bands. However, our recent studies [9] have suggested that the controlling factors there are related to the source mechanism of earthquakes and to the distance from the source rather than only to the local site conditions.

Full scale tests which could be used to test under controlled conditions some of the simple two- and three-dimensional models are lacking at this time. As an example, Fig. 6 summarizes results from one such test [7] which has indicated that such comparisons could prove to be very useful in selecting and testing the theoretical models. The bottom of Fig. 6 shows three cross-sections, A, B and C, through the alluvium in the southwestern part of Pasadena, California [7] and the relative position of Millikan Library. This 9-story reinforced concrete building was excited in its fundamental mode of vibration in the NS direction to produce waves which could be measured in the directions of predominant SH radiations [7]. The top of Fig. 6 shows experimentally measured (triangles) and computed amplitudes (full and dashed lines) of ground motion and shows that the layer with depth variation labeled "A" may explain the experimental results in some detail. This single experiment is, of course, far from adequate to explain numerous detailed properties of simple two- and three-dimensional theoretical models. It suggests, however, that other full scale experiments should be considered so that the theoretical models can be tested critically before being accepted and/or recommended for applications in earthquake engineering assessment of local site effects on strong earthquake ground shaking.

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†In press.

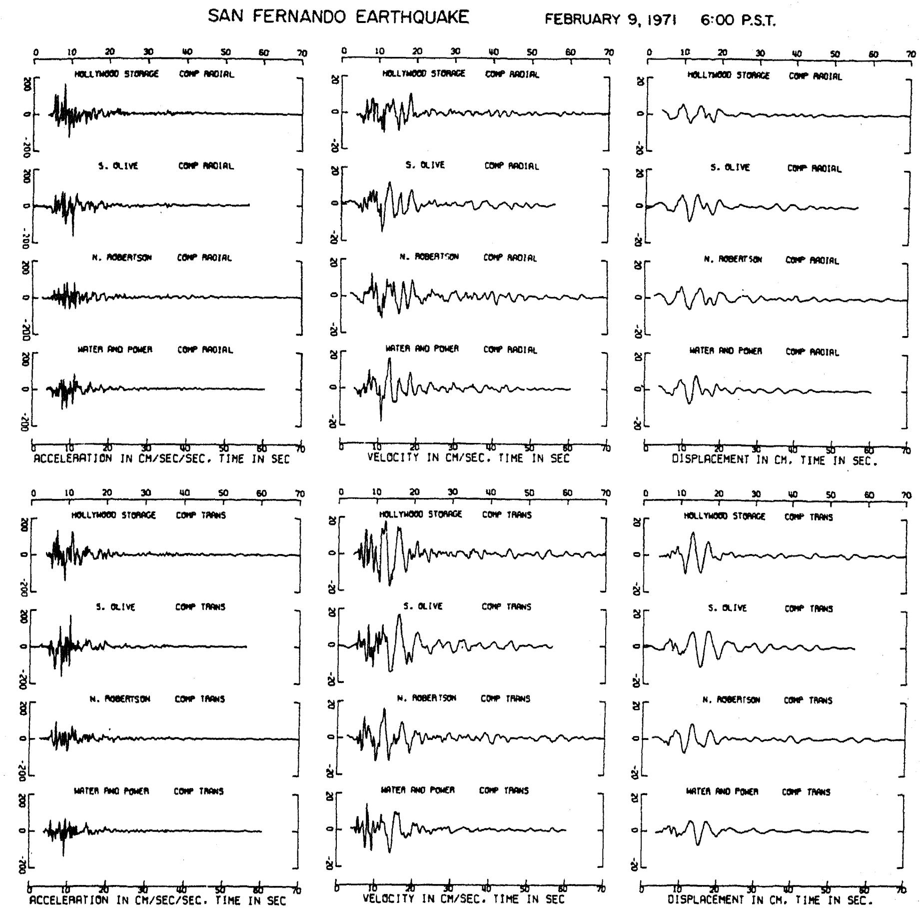
SAN FERNANDO EARTHQUAKE
FEBRUARY 9, 1971 6:00 P.S.T.
HOLLYWOOD STORAGE COMP RADIAL
S. OLIVE COMP RADIAL
N. ROBERTSON COMP RADIAL
WATER AND POWER COMP RADIAL
HOLLYWOOD STORAGE COMP TRANS
S. OLIVE COMP TRANS
N. ROBERTSON COMP TRANS
WATER AND POWER COMP TRANS
ACCELERATION IN CM/SEC/SEC. TIME IN SEC
VELOCITY IN CM/SEC. TIME IN SEC
DISPLACEMENT IN CM. TIME IN SEC.
0
10
20
30
40
50
60
70
200
-200
20
-20

Fig. 1

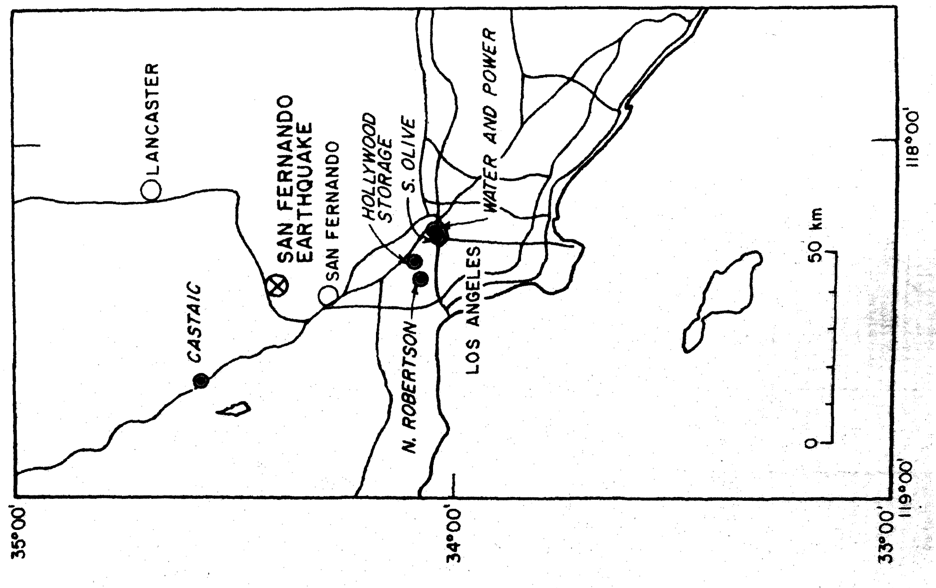
LANCASTER
SAN FERNANDO EARTHQUAKE
SAN FERNANDO
HOLLYWOOD STORAGE
S. OLIVE
WATER AND POWER
CASTAIC
N. ROBERTSON
LOS ANGELES
50 km
0
35°00'
34°00'
33°00'
118°00'
119°00'

Fig. 2

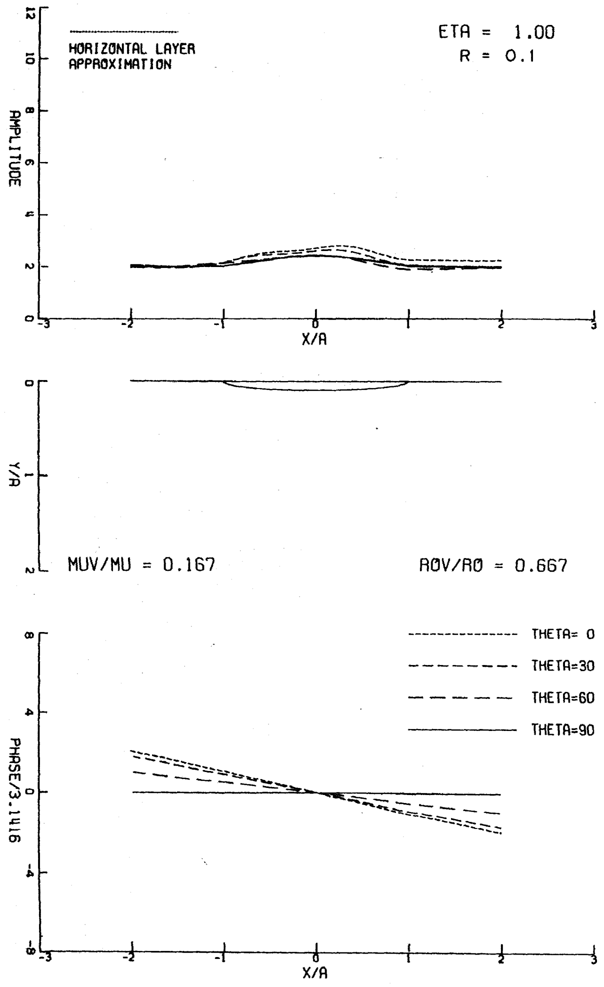
HORIZONTAL LAYER
APPROXIMATION
ETA = 1.00
R = 0.1
AMPLITUDE
12
10
8
6
4
2
0
X/A
-3
-2
-1
0
1
2
3
Y/A
0
1
2
MUV/MU = 0.167
ROV/RO = 0.667
THETA= 0
THETA=30
THETA=60
THETA=90
PHASE/3.1416
8
4
0
-4
-8

Fig. 4

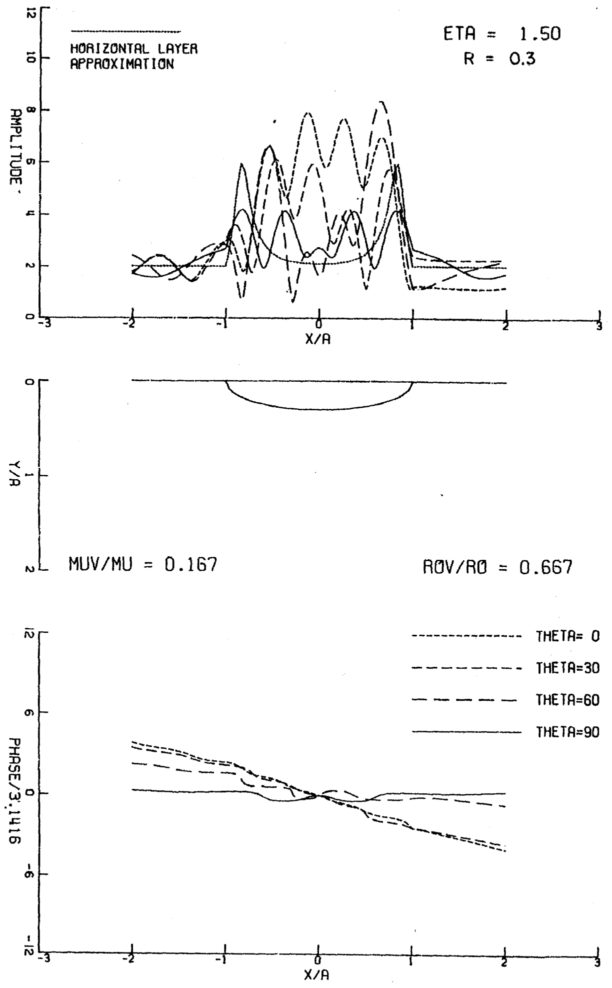
HORIZONTAL LAYER
APPROXIMATION
ETA = 1.50
R = 0.3
AMPLITUDE
12
10
8
6
4
2
0
X/A
-3
-2
-1
0
1
2
3
Y/A
0
1
2
MUV/MU = 0.167
ROV/RO = 0.667
THETA= 0
THETA=30
THETA=60
THETA=90
PHASE/3.1416
12
6
0
-6
-12

Fig. 3

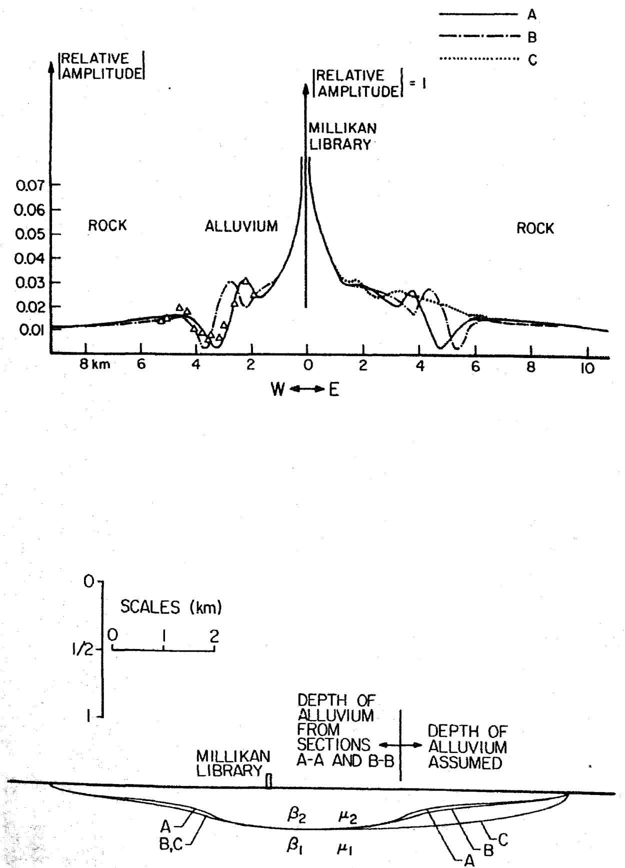
A
B
C
|RELATIVE AMPLITUDE|
|RELATIVE AMPLITUDE| = 1
MILLIKAN LIBRARY
0.07
0.06
0.05
0.04
0.03
0.02
0.01
ROCK
ALLUVIUM
ROCK
8 km
6
4
2
0
2
4
6
8
10
W ↔ E
SCALES (km)
0
1/2
1
0
1
2
DEPTH OF ALLUVIUM FROM SECTIONS A-A AND B-B
DEPTH OF ALLUVIUM ASSUMED
MILLIKAN LIBRARY
β_2
μ_2
β_1
μ_1
A
B,C
A
B
C

Fig. 6

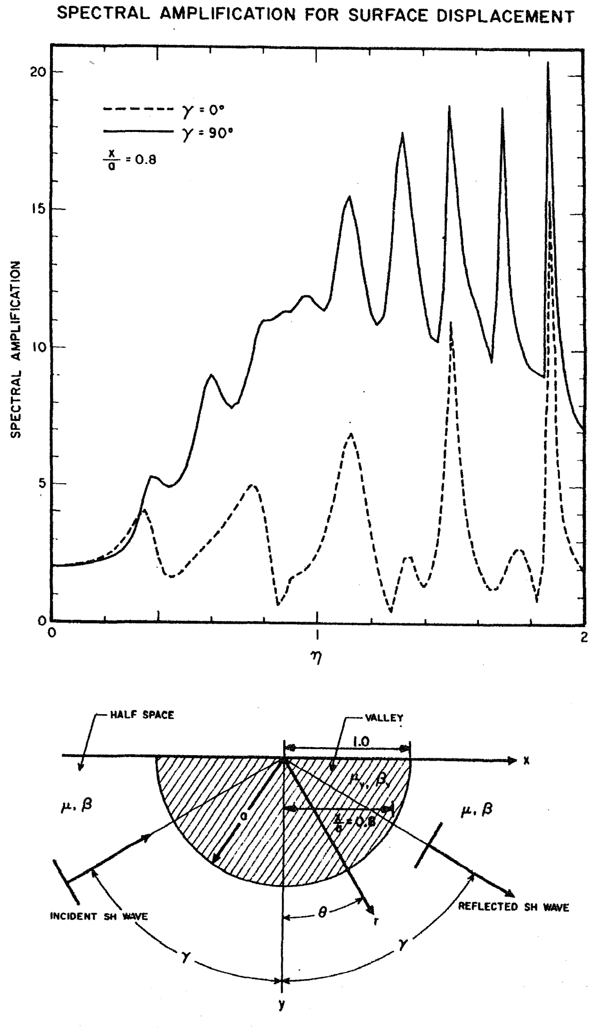
SPECTRAL AMPLIFICATION FOR SURFACE DISPLACEMENT
$\gamma = 0°$
$\gamma = 90°$
$\frac{x}{a} = 0.8$
SPECTRAL AMPLIFICATION
20
15
10
5
0
0
1
2
η
HALF SPACE
VALLEY
1.0
x
μ, β
μ_1, β_1
μ, β
a
$\frac{x}{a} = 0.8$
θ
r
INCIDENT SH WAVE
REFLECTED SH WAVE
γ
γ
y

Fig. 5