THE EFFECTS OF ELEVATION AND SITE CONDITIONS ON GROUND MOTION OF THE SAN FERNANDO, CALIFORNIA, EARTHQUAKE, 9 FEBRUARY 1971

By

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ABSTRACT

The objectives of this study were to determine site effects on earthquake ground motion and the correlation between acceleration and/or velocity generated during the San Fernando Earthquake of 9 February 1971 and topography of the San Gabriel Mountain Range. It was found that the contours of peak acceleration and peak velocity generally follow the topography of the San Gabriel Mountain Range.

The topographical effects on the ground motion could be interpreted in a simple manner as a function of elevation and direction of wave transmission path. The elevation and direction become the dominant factors in the distribution of the bedrock motion using the ground motion-elevation gradient as applied in the area south of Kagel Mountain and north of Santa Monica Mountain, in the San Fernando Valley. A high acceleration of 2.29 g has been estimated at the top of Kagel Mountain by the extrapolation method. This method is validated using aftershock data. Accelerations recorded in the rock were higher than those recorded in the alluvium as might be expected, but the integrated displacements from the acceleration were indicated in an opposite direction for alluvium. The integrated velocities did not follow a definite trend.

INTRODUCTION

The purposes of this study were to determine site effects on earthquake ground motion in the near field and a general correlation between peak acceleration or peak velocity recorded during the San Fernando, California, earthquake, 9 February 1971, and topography by mapping techniques. Such techniques might produce seismic risk maps that would reflect local geological and soil conditions and also furnish input motion for practical design in earthquake engineering.

MAXIMUM ACCELERATION AND VELOCITY MAPS

Figures 1 and 2 are contour maps of the observed peak accelerations and the integrated peak velocities, respectively. The data are based on Chang (1978). The main part of the maximum acceleration and velocity maps is controlled by instrumentally recorded data from 12 rock sites and 9 soil sites (Figure 1). These sites surround the Pacoima damsite as the center which has the maximum horizontal acceleration and maximum horizontal velocity, 1.25 g and 115 cm/sec, respectively. The contour lines were drawn by an equal linear interpolation method between the Pacoima damsite and these surrounding sites. The interpolation contours do not represent actual accelerations or velocities on the ground surface.

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INTERPRETATION OF MAPS

Lower San Fernando Damsite

Scott (1973) derived the horizontal acceleration-time history from the seismoscope record of the east abutment (composed of shale) of San Fernando Dam and found a number of peaks of substantial amplitude in the range of 0.6-0.8 g. He suggested that the peak accelerations of perhaps 0.55-0.6 g were reasonable. A value of 0.67 g was recorded by the peak recording accelerograph on the crest of the San Fernando Dam, which was displaced by the movement that occurred in the upstream slope.* On the peak acceleration map, the 0.6 g contour line crosses the Lower San Fernando Dam. This provided additional evidence to show that 0.6 g is a reasonable acceleration for the bedrock on the Lower San Fernando Dam. Furthermore, this value can be determined from the acceleration-elevation gradient of the Pacoima Dam-Universal Sheraton Hotel path. This will be demonstrated in the following sections of topographic corrections. Figure 3 shows the topographic profile of the Lower San Fernando Dam-Pacoima Dam-Kagel Mountain path.

Bedrock Motion of Pacoima Dam

The maximum accelerations, velocities, and elevations for the Pacoima damsite and the Lower San Fernando damsite (seismoscope site of east abutment) are 1.25 g, 115 cm/sec, and 2067 ft; and 0.6 g, 60 cm/sec (obtained from Figure 2), and 1137 ft, respectively. The horizontal distance between the Pacoima damsite and Lower San Fernando damsite is about 9.5 km. The acceleration and velocity gradients between them can be calculated by:

$$\frac{1.25 - 0.60}{2067 - 1137} = \frac{0.65}{930} = 0.0007 \text{ g/ft (acceleration gradient)}$$

$$\frac{115 - 60}{2067 - 1137} = \frac{55}{930} = 0.05914 \text{ cm/sec/ft (velocity gradient)}$$

The difference in elevation between the Pacoima strong-motion recorder site (2067 ft) and the lowest elevation (1692 ft) of bedrock under the dam is about 375 ft. Therefore, the input bedrock motion for the Pacoima Dam estimated from the above acceleration gradient could be inferred to be about 0.995 g. This is about 20 percent less than 1.25 g, the highest horizontal peak acceleration recorded. Trifunac (1973) proposed that 10-20 percent less than 1.25 g would be the right order of input bedrock motion for the Pacoima Dam. Since the Pacoima accelerograph is located on the bedrock, the difference is caused by the effect of topographic irregularities (elevation) in bedrock. Reimer et al. (1973) found 0.40 g for the base rock by the finite element method. However, their model considered the Pacoima damsite only, while estimates of the actual ground motion should consider Kagel Mountain as a whole. Seed (1973) suggested 0.76 g for the bedrock motion of Pacoima Dam.

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* R. P. Maley, U. S. Geological Survey, Personal communication, 1974.

Rock Motion at the Universal Sheraton Hotel Site

The Universal Sheraton Hotel is located on the west side of Universal City and south of the Los Angeles River. The epicentral distance is about 30.8 km. Three accelerographs were deployed, one at ground level and one each at the 11th and 20th floors, respectively. The accelerograph at ground level recorded 0.18 g on the north-south component for the main shock of the San Fernando Earthquake. The integrated maximum particle velocity and displacement were 15 cm/sec and 5.4 cm, respectively. The site geology is interlayered soft sandstone and shale. The elevation at the site is about 560 ft above sea level. The acceleration-elevation and velocity-elevation gradients can be calculated between the two sites of Pacoima Dam and the Universal Sheraton Hotel as follows:

$$\frac{1.25 - 0.18}{2067 - 560} = \frac{1.07}{1507} = 0.00071 \text{ g/ft}$$

(acceleration-elevation gradient)

$$\frac{115 - 15}{1507} = 0.06636 \text{ cm/sec/ft}$$

(velocity-elevation gradient)

This shows that the acceleration-elevation gradients of the Pacoima Dam-Lower San Fernando Dam path and the Pacoima Dam-Universal Sheraton Hotel are the same. Thus, by using the Universal Sheraton Hotel site as a reference site, the ground motion at the Lower San Fernando Dam can be checked as:

$$(1137 - 560) \text{ ft} \times 0.00071 \text{ g/ft} + 0.18 \text{ g} = 0.59 \text{ g}$$

$$(1137 - 560) \text{ ft} \times 0.06636 \text{ cm/sec/ft} + 15 \text{ cm/sec} = 53.3 \text{ cm/sec}$$

It is therefore indicated that the amount of acceleration obtained from the mapping technique is of the right order, but the velocity is somewhat higher than the velocity obtained using the above gradient method.

Surface Ground Motion at the Holiday Inn Site

The strong-motion instrument at the Holiday Inn site was located on the alluvium at the elevation of about 800 ± 20 ft. The thickness of alluvium at this site is about 800 ft. The ground motion of 0.27 g (or 31.9 cm/sec) for this earthquake was recorded on the north component. If the Holiday Inn site at the surface elevation of 800 ± 20 ft were rock instead of alluvium, then the ground motions calculated by the acceleration- and velocity-gradients of 0.00071 g/ft and 0.06636 cm/sec/ft, respectively, in relation to 0.18 g and 15 cm/sec, respectively, at the Universal Sheraton Hotel site at the elevation of 560 ft would be:

$$(800 - 560) \text{ ft} \times 0.00071 \text{ g/ft} + 0.18 \text{ g} = 0.35 \text{ g (on rock)}$$

$$(800 - 560) \text{ ft} \times 0.06636 \text{ cm/sec/ft} + 15 \text{ cm/sec} = 30.93 \text{ cm/sec (on rock)}$$

Comparison of these results calculated by this method on the rock with the data of 0.27 g or 31.9 cm/sec observed on the alluvium at the Holiday Inn site suggests a higher acceleration on the rock than on the alluvium, but essentially no difference in the velocity values.

Rock Motion at the
Crest of Kagel Mountain

The ratio of peak amplitudes (crest to base) at the Kagel Mountain site was found to be 1.75 by Davis and West (1973) from the aftershock of Event C on 18 May 1971 of the San Fernando Earthquake. The epicentral location of Event C was near the main shock at a distance of 8 km north of the Pacoima Dam. The epicenters of other aftershocks were far from the main shock, with different sources and paths. Figure 4 shows the topography, and station locations at the Kagel Mountain site. The base station was deployed near the Pacoima Dam accelerograph site, and the elevation difference between the two recording sites (crest and base) was about 1470 ft. Therefore, the rock motion at the elevation of 3537 ft on the crest of Kagel Mountain for the main shock of the San Fernando Earthquake can be calculated by the amplification factor of 1.75 times the peak acceleration of 1.25 g recorded at the Pacoima damsite. It also can be computed from the acceleration-elevation gradient of 0.00071 g/ft times the elevation of 1470 ft added to 1.25 g. The accelerations calculated by the two methods are 2.19 and 2.29 g, respectively. The values are in good agreement. The difference is probably caused by the degree of accuracy of the elevation data and the actual elevation of the instruments for the aftershock measurements. This shows that the acceleration-elevation gradient of 0.00071 g/ft derived between the Pacoima and Lower San Fernando damsites can also be applied to a region at the front of the San Fernando Fault since the acceleration contour lines are parallel in the northwest-southeast direction.

DISCUSSION OF GROUND MOTION DATA

The acceleration-elevation relationship found in the interpretation of the recorded strong-motion data on the rock sites within the San Fernando Valley region in the above sections is plotted in Figure 5. In addition to the two rock sites of Pacoima Dam and the Universal Sheraton Hotel, a rock site on the top of Kagel Mountain which recorded an aftershock measurement is also plotted in Figure 5a to demonstrate that the aftershock measurement could be used to predict the ground motion at a site for which no instrument recordings are available. The rest of the acceleration data in Figure 5a were recorded on the sites of alluvium; the values of acceleration are generally lower than the acceleration recorded on the rock. Figure 5b has the same data points as in Figure 5a, but they are plotted as velocity versus elevation; these data on the alluvial sites are generally higher than on the rock sites. In Figure 5c, the data are plotted as displacement versus elevation; the displacements on the alluvial sites are generally higher than on the rock sites. These observations have also been confirmed by other investigators.

In other directions or paths in which the topography was irregular and the recording stations were few, the relationship between ground motion and elevation was not as simple as in the region of the San Fernando Valley. If there were sufficient recording stations and the elevation for each station were known, then local relationships between the ground motion and elevation could be estimated on a piecewise linear basis on the assumption that the topographic effect of ground motion is caused mainly by the natural period and evaluation of the local geological structure.

The linear relationship of acceleration-elevation found on the rock for the Lower San Fernando Dam-Pacoima Dam-Kagel Mountain path was in agreement with that of the Pacoima Dam-Universal Sheraton Hotel path based on the ground motion-elevation gradients of 0.00071 g/ft, 0.06636 cm/sec/ft, and 0.02143 cm/ft between Pacoima Dam and the Universal Sheraton Hotel sites, or from Figures 5a, b, and c. From this relationship, base rock motions of acceleration, velocity, and displacement were found as shown for the following sites:

	Elevation ft	Acceleration g	Velocity cm/sec	Displacement cm
Kagel Mountain	3537	2.29	212.55	69.2
Pacoima Dam	1692	0.99	90.11	29.7
Lopez Dam	1207	0.65	57.93	19.3
Lower San Fernando Dam	1137	0.60	53.30	17.7

Based on the extrapolated values of 2.29 g, 212.55 cm/sec, and 69.2 cm at the top of Kagel Mountain in relation to the values of 0.99 g, 90.11 cm/sec, and 29.7 cm at the base of Pacoima Dam, an average common amplification factor of 2.32 for acceleration, velocity, and displacement was found. However, this amplification factor was elevation-dependent. The relative velocity spectra (north-south component) of Kagel Mountain (Davis and West, 1973), Pacoima Dam, and Lower San Fernando Dam (Reimer et al. 1973) show a peak value at a period of about 0.5 sec. The natural period of Kagel Mountain calculated by the elastic formula for a wedge, $T = 2.6\ H/V_s$, is 0.47 sec, where H is the height of Kagel Mountain (1470 ft) and V_s is the shear-wave velocity of uniform granite (assumed to be 2500 m/sec). Kagel Mountain rises directly above the Pacoima Dam station. In short, the natural period of Kagel Mountain, the predominant period of the ground motion, the uniform composition of the granite rock of the San Gabriel Mountain range located directly above the focus, and especially, the topographic structure which decreases in elevation monotonically between Kagel Mountain and Santa Monica Mountain are probably the main causes of the linear relationship between the ground motion and elevation.

Both the peak acceleration and velocity maps show a strong shaking area or a heavy damage zone in the near field within the contour line of 0.2 g (20 cm/sec), an area of about 5000 sq km (Figure 1). Pasadena and downtown Los Angeles are located outside the zone. There are still three other small local loops of 0.2 g on the contour map of the observed acceleration (Figure 1) that may be caused by local soil conditions. Both the Hollywood Storage Building site and Pasadena Millikan Library site recorded 0.22 g, a measurement that seems to be amplified by 1000 ft of alluvium. On the southernmost part of the velocity map, the contour line of 10 cm/sec was pushed back twice the average interval, indicating that the particle velocity of long-period surface waves in the far field was amplified on the thick alluvium deposit as compared to the crystalline rock.

CONCLUSIONS

The conclusions of this study on the San Fernando Earthquake are outlined as follows:

a. Contour maps of the observed peak acceleration and peak velocity were found in correlation with the topographic feature of the San Gabriel Mountain range. It was found approximately that 0.1 g is equivalent to 10 cm/sec within the strong shaking area which is defined within the contours of 0.2 g or 20 cm/sec on the peak velocity map.

b. A linear relationship between the ground motion and elevation was found within the San Fernando Valley region, possibly due to the monotonic decrease in elevation from the top of Kagel Mountain toward the southern rim of the San Fernando Valley. However, this decrease was not generalized to the other direction or area.

c. Ground motion-elevation gradients between the two strong-motion instrument sites of Pacoima Dam and Universal Sheraton Hotel were found to be 0.00071 g/ft, 0.06636 cm/sec/ft, and 0.02143 cm/ft, for acceleration, velocity, and displacement, respectively.

d. Ground motions at the crest of Kagel Mountain calculated by the above gradients were found to be 2.29 g, 212.55 cm/sec, and 69.2 cm, respectively, values which are supported by the aftershock measurement.

e. The base rock motions computed for the Pacoima Dam, Lopez Dam, and Lower San Fernando Dam are 0.99 g, 90.11 cm/sec, and 29.7 cm; 0.65 g, 57.93 cm/sec, and 19.3 cm; and 0.60 g, 53.3 cm/sec, and 17.7 cm, respectively.

f. Comparisons have been made of the acceleration values recorded on the rock and the alluvium in the area of the San Fernando Valley, and of the velocities and displacements integrated from the recorded accelerations. Accelerations recorded on the rock were higher than those recorded on the alluvium; displacements, on the other hand, were greater in the alluvium than in the rock. The velocities determined for the alluvium did not follow a definite trend, with some velocities higher and some lower.

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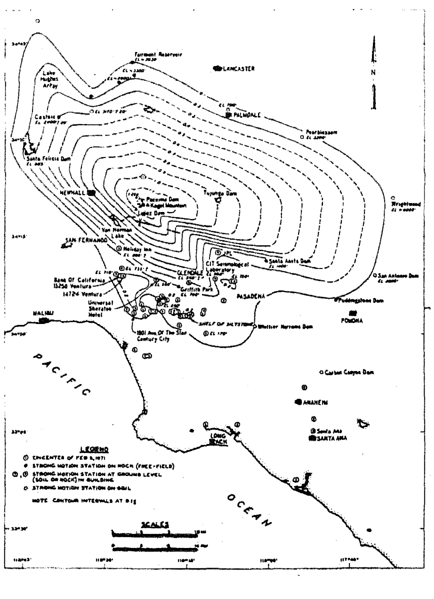

Fig. 1. Contour map of observed A_p of the San Fernando Earthquake, extended Los Angeles

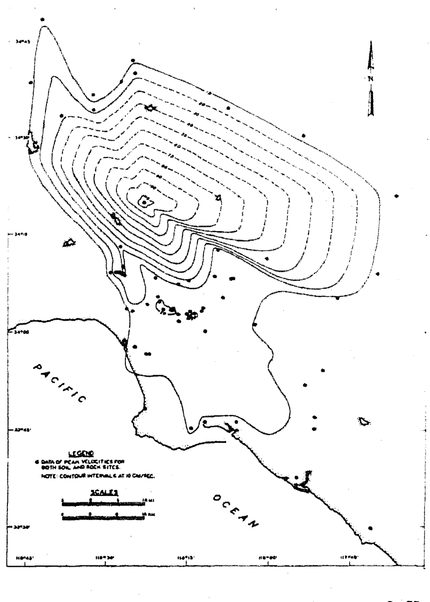

Fig. 2. Contour map of observed V_p of the San Fernando Earthquake, extended Los Angeles

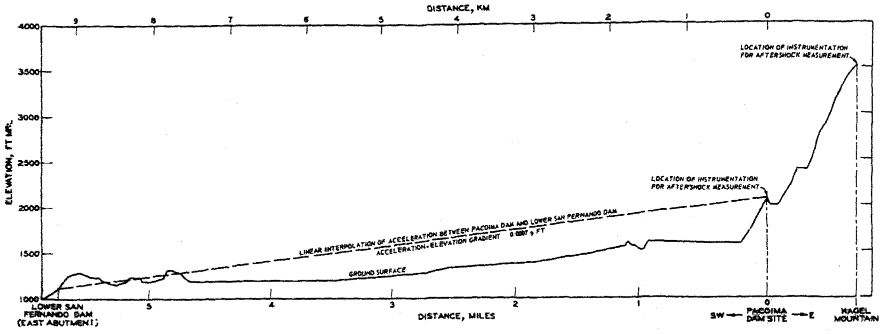

Fig. 3. Topographic profile of Lower San Fernando Dam-Pacoima Dam-Kagel Mountain Path

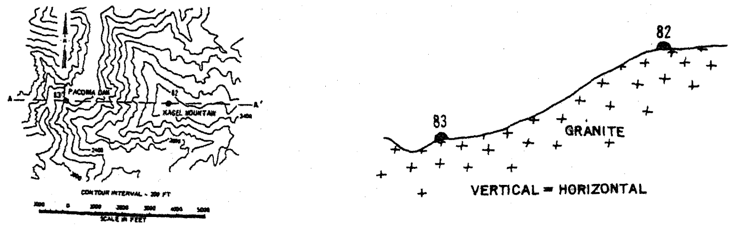

Fig. 4. Topography, geology, and station locations, Kagel Mountain (Courtesy of Seismological Society of America)

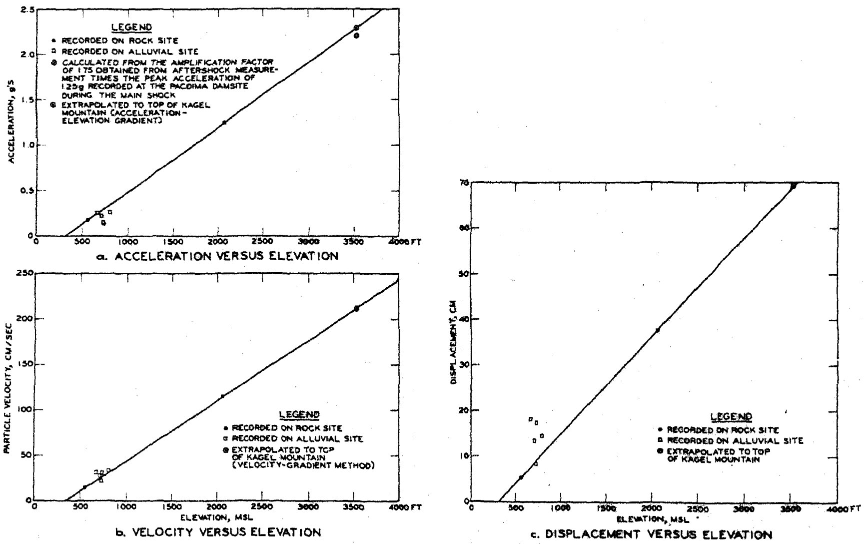

Fig. 5. Acceleration, velocity, and displacement versus elevation and site condition in the San Fernando Valley during the San Fernando Earthquake