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SYNOPSIS The amplitudes of strong ground motions from the Loma Prieta earthquake recorded in the San Francisco and Oakland areas exceeded the levels predicted by standard empirical attenuation relations. Preliminary analysis of accelerograms having known trigger times suggests that the elevation of ground motion amplitudes in the distance range of approximately 40 to 100 km was due to critical reflections from the base of the crust. These reflections were large and occurred at relatively close range because of the deep focal depth of the earthquake and the strong velocity gradient at the base of the crust, and were enhanced by rupture directivity. These motions were further amplified, presumably by impedance contrast effects, at soft soil sites in San Francisco and Oakland. The effect of the critical reflections in amplifying peak accelerations of the Loma Prieta earthquake in the San Francisco and Oakland regions was as large as the effect of soft soil site conditions.

INTRODUCTION

The peak accelerations of the Loma Prieta earthquake showed more gradual attention with distance than predicted by standard attenuation relations. Campbell (1990) showed that the peak accelerations on rock had no attenuation in the distance range of 40 to 80 km, with distance defined as the closest distance to the rupture surface. The peak accelerations recorded in the San Francisco and Oakland areas, which are located in the epicentral distance range of about 90 to 100 km, also exceeded the levels predicted by standard empirical attenuation relations, as shown in figure 1 (Joyner and Boore, 1988) for all categories of site conditions. In these empirical attenuation relations, the effects of different focal depths and propagation paths on ground motion attenuation are averaged to obtain a median estimate of the ground motions (shown by the solid line in figure 1). The variability of ground motions due to differences in source depth and crustal structure is included, together with other sources of variability, in the standard deviation of the median estimate (shown by the dashed lines in Figure 1). The objective of this paper is to investigate the influence of source, path and site effects in causing this difference between the observed ground motion attenuation and that predicted by standard empirical attenuation relations.

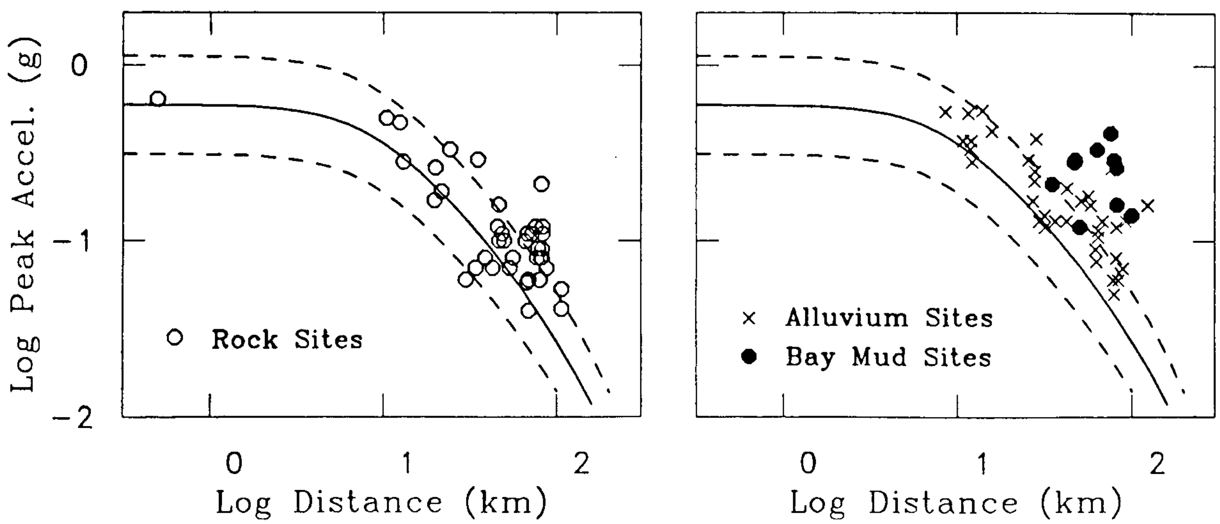

Fig. 1. Recorded peak horizontal acceleration as a function of distance from the surface projection of the rupture zone of the Loma Prieta earthquake for rock sites (left) and alluvium and Bay Mud sites (right). Source: Boore et al., 1990.

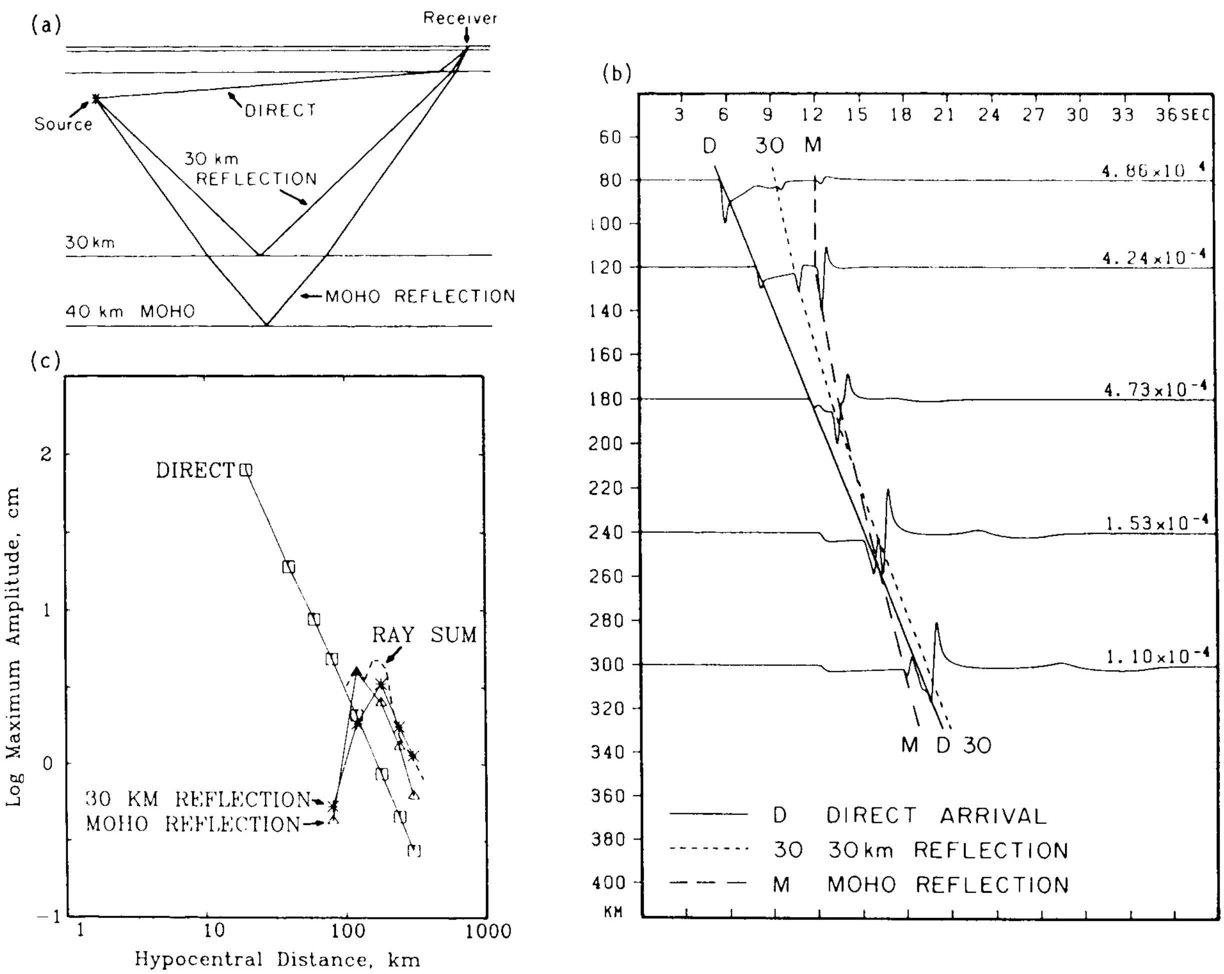

Fig. 2. (a) Simplified model of wave propagation in a layered crust. (b) Synthetic displacement seismograms for the crustal model shown in (a). (c) Attenuation of direct and reflected arrivals shown in (b). Source: Burger et al., 1987.

MODELING GROUND MOTION ATTENUATION USING WAVE PROPAGATION METHODS

Burger et al. (1987) investigated the effect of wave propagation in the crustal waveguide on the shape of the ground motion attenuation curve, using the procedure illustrated in Figure 2. At close distances, peak horizontal ground motions are controlled by direct upgoing shear waves. As distance increases, the reflections of the shear wave from interfaces in the lower crust reach the critical angle and undergo total internal reflection. The strong contrast in elastic moduli at these interfaces, especially at the Moho, causes these critically reflected waves to have large amplitudes. Using synthetic seismograms, Burger et al. (1987) found that for a source at a depth of 7 km in a 40 km thick crust, peak ground motion amplitudes at distances beyond about 100 km are controlled by critical reflections, causing a flat trend in the attenuation relation in the distance range of about 100 to 200 km.

As evidence that postcritical reflections from the lower crust may control peak strong motion amplitudes in the critical distance range, Burger et al. (1987, figure 15) showed that the largest ground motion velocities recorded at San Onofre at a distance of 135 km from the 1968 Borrego Mountain earthquake were due to critical Moho reflections. In central California, Bakun and Joyner (1984) suggested that the large positive residual in M_L at distances between 75 and 125 km was due to Moho reflections. Also, large-amplitude reflections from the Moho (P_mP) were observed in seismic refraction data near the source region of the Loma Prieta earthquake (Walter and Mooney, 1982, Figure 6a).

Further evidence of the influence of critical reflections from the lower crust on ground motion attenuation was found in the large set of strong motion recordings of the Saguenay, Quebec earthquake of October 25, 1988 by Somerville et al. (1990) and Somerville and Helmberger (1990). At distances beyond 64 km, the peak ground motions occurred at times corresponding not to the direct S wave but to strong critical reflections from the lower crust. The amplitudes of the recorded ground motions did not decrease significantly between 50 and 120 km, but abruptly decreased beyond 120 km. The reflections became critical at close distances because of the deep focal depth (28 km) of the source, causing the elevation of ground motion amplitudes at distances between 50 and 120 km. This

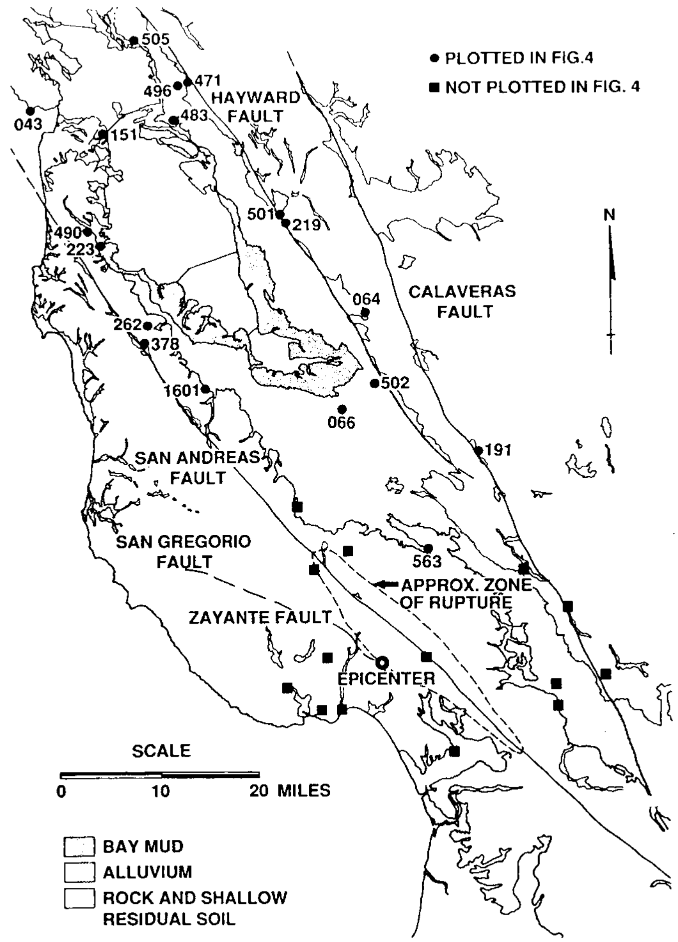

Fig. 3. Locations of strong motion recording stations used in this analysis, showing the distribution of rock or shallow soil, alluvium, and bay mud. Modified from Seed et al. (1990), Fig. 4.1.

interpretation of the strong motion recordings was confirmed by generating a profile of simulated accelerograms in which the arrival times of the largest shear waves and the attenuation of peak amplitudes of these shear waves were in close agreement with the data.

MODELING THE GROUND MOTION ATTENUATION OF THE LOMA PRIETA EARTHQUAKE

The following analysis updates that of Somerville and Yoshimura (1990) by using a detailed rupture model of the Loma Prieta earthquake derived by Wald et al. (1990). A record section of recorded accelerograms was compiled using all accelerograms to the north of the epicenter (i.e. in the San Francisco Bay region) that have known trigger times, shown by circles in Figure 3. The recordings in the record section (Figure 4, left side) are from a variety of site conditions, as annotated in the figure and discussed further below, and are for the East (or closest to East) component of motion. The accelerograms are copies of film records published by Shakal et al. (1989) and Maley et al. (1989), and are plotted at a travel time reduction of 3.5 km/sec.

Arrival time curves for three principal waves are shown in Figure 4: the direct shear wave (S), the shear wave reflected from the Conrad at a depth of 18 km (S_cS), and the shear wave reflected from the Moho at a depth of 25 km (S_mS). The curves were computed using the crustal structure model shown in table 1, which was derived from the model of Dietz and Ellsworth (1990), using a focal depth of 12 km to represent the center fo energy release (Nabalek, 1990; Kanamori and Satake, 1990; Wald et al., 1990). The S_mS curve is repeated at a delay of 6 seconds to represent the duration of the strong source pulse seen teleseismically (Nabelek, 1990). To facilitate the interpretation of the strong motion data using these point source travel time curves, the accelerograms are plotted in the profile at their epicentral distances rather than at their closest distance to the fault.

At the high frequencies that control peak accelerations, we do not expect to see coherent waveforms in the profile of recorded accelerograms in Figure 4. However, the onset of the largest accelerations at each station coincides with the arrival time of the critical Moho reflection S_mS at distances beyond about 50 km. The moveout of this onset with distance clearly follows the S_mS arrival time curve and not that of direct S. The duration of strong motion following the S_mS arrival time curve is about 5 seconds, which is compatible with the 6-second duration of the source observed teleseismically.

A profile of simulated accelerograms is shown on the right side of Figure 4. We do not expect the simulated accelerograms to match the waveforms of the recorded accelerograms at high frequencies. However, the simulated accelerograms have large S_mS waves whose onset coincides with the S_mS arrival time curve and whose moveout is that of the S_mS arrival and not that of direct S. The duration of strong motion of the simulated S_mS waves is about 5 sec. In all of these respects, the simulated accelerograms resemble the recorded accelerograms, and support the interpretation of the recorded accelerograms given above. The simulated accelerograms were generated using the crustal structure model shown in Table 1, which has a surface shear wave

TABLE 1. Loma Prieta Velocity Model

V_p (km/sec.)	V_s (km/sec.)	density (g/cm^3)	depth (km)
1.7300	1.0000	1.5000	0.1000
3.3800	1.9500	1.5500	0.5000
4.2900	2.4800	1.8500	1.0000
4.7950	2.7700	2.0500	3.0000
5.3650	3.1000	2.2600	5.0000
5.7400	3.3100	2.4500	7.0000
6.1500	3.5500	2.5800	9.0000
6.2450	3.6100	2.6200	13.000
6.2700	3.6200	2.6300	18.000
6.6650	3.8500	2.7700	25.000
8.0000	4.6200	3.2800	

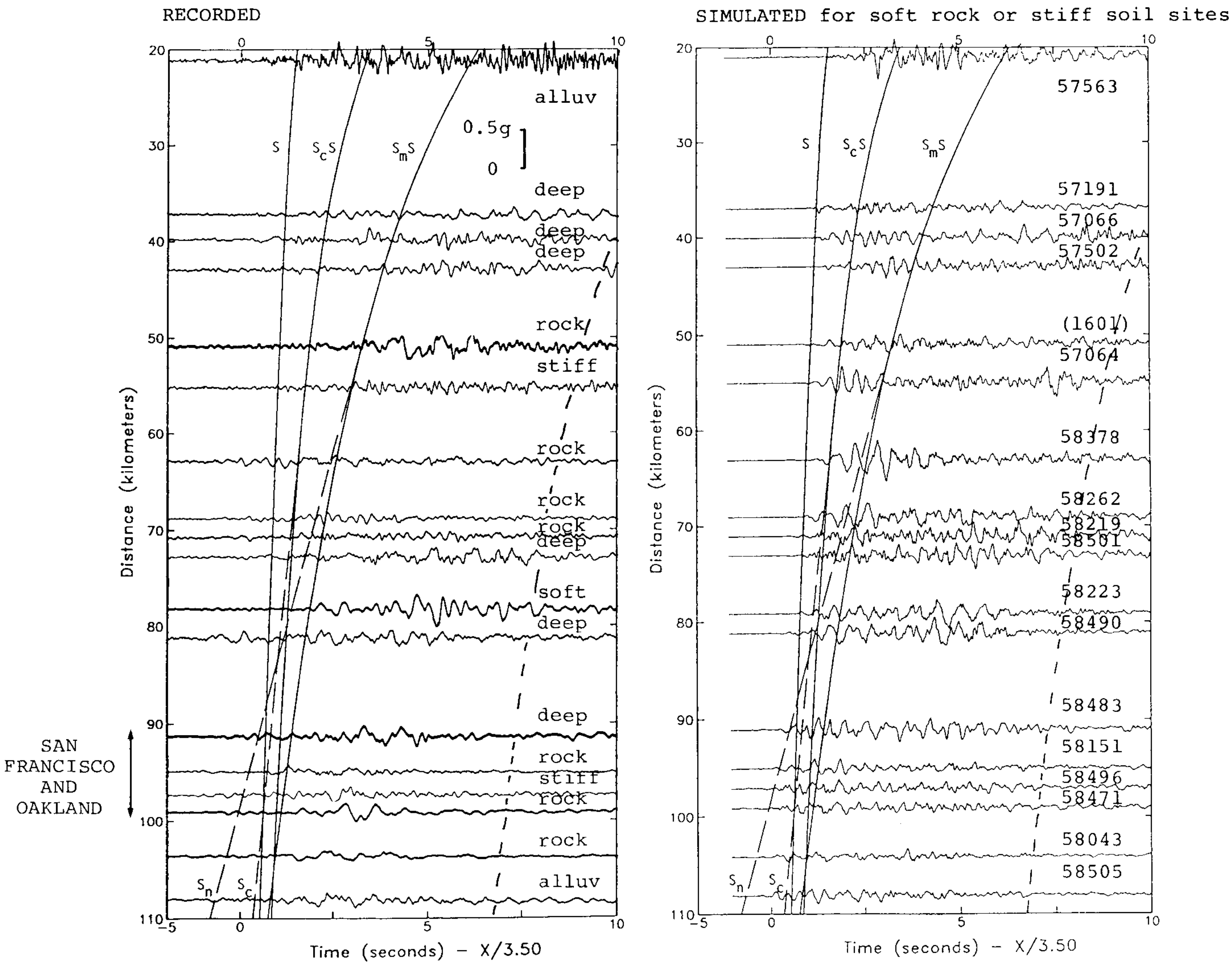

Fig. 4. Profiles of recorded (left) and simulated (right) accelerograms of the 1989 Loma Prieta earthquake, compiled using epicentral distance and a travel time reduction of 3.5 km/sec. Arrival time curves are explained in the text. Soil conditions are annotated on recorded accelerograms, and CSMIP (and USGS in parentheses) station numbers are annotated on simulated accelerograms.

velocity of 1 km/sec, appropriate for soft rock or stiff soil conditions.

The peak accelerations of the simulated accelerograms show a trend similar to that of the recorded accelerograms, as shown in Figure 5. In this figure, the northerly profile of stations of Figure 2 has been augmented by stations that lie within 30 km of the epicenter. The peak accelerations attenuate normally to about 40 km, but then do not attenuate further until reaching an epicentral distance of 80 km. In the distance range of 60 to 100 km, the largest simulated motions at a given station are due to critical reflections, and we infer this to be also true of the recorded motions based on the similarity in arrival times and phase velocity described above. While site conditions are presumably responsible for the larger amount of scatter in recorded peak accelerations (compared with the simulated ones) at a given distance, it does not appear that site conditions explain the overall lack of attenuation between 40 and 80 km in both the recorded and simulated values. Instead, it appears that the shape of the attenuation curve is due to critical reflections, with the scatter of recorded peak values about this shape attributable in part to local site effects.

To generate the synthetic accelerograms shown in Figure 4, we used a simulation method developed by Hadley, Helmberger and Orcutt (1982) and refined by Wald et al. (1988). For crustal earthquakes, the ground motions of the large event are obtained by summing contributions from fault elements having dimensions of about 3 km. Strong ground motion recordings very close to the source of a magnitude 5 earthquake, scaled back to the source, are used to represent the source functions of the fault elements. Green's functions including the direct S wave and primary reflections from interfaces, calculated from the regional structure model, are used to represent the propagation path. The contributions from each fault element are lagged, scaled

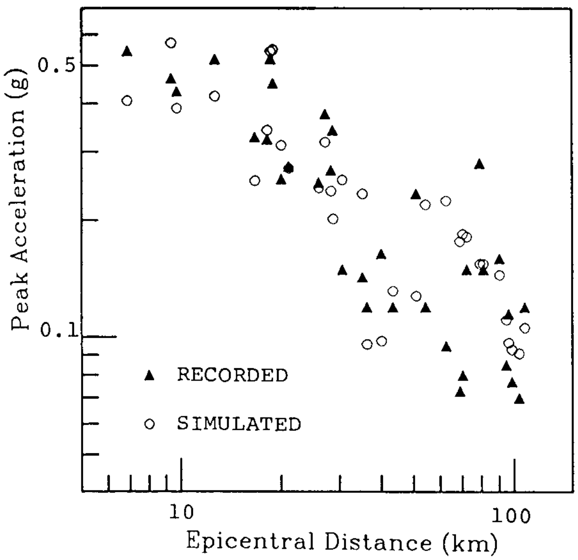

Fig. 5. Recorded (solid triangles) and simulated (open circles) peak horizontal acceleration as a function of epicentral distance for sites within 30 km and for Bay Area sites having known trigger times.

and summed in such a way as to simulate the propagation of rupture over the fault surface. Asperities are modeled by weighting the contributions of the fault elements. The decrease in coherence of the radiation pattern that is observed to occur as frequencies increase is represented empirically using a suite of empirical source functions. The reliability of this simulation procedure was demonstrated using recorded strong ground motions of the 1979 Imperial Valley, 1985 Nahanni, and 1987 Whittier Narrows earthquakes (Abrahamson et al., 1989).

We used a rupture model of the Loma Prieta earthquake derived by Wald et al. (1990) from the inversion of near-source strong motion data. The rupture surface is 40 km long and 15 km wide, and rupture spreads circularly from the 18 km-deep hypocenter at an average speed of 2.7 km/sec and with a rise time of 1.5 sec. The seismic moment is 2.9×10^{26} dyne-cm and the strike and dip of 128 and 70 degrees respectively of Kanamori and Satake, (1990) were used. The rake varies on the fault plane. Slip is concentrated in two asperities, the stronger one centered about 6 km northwest of the hypocenter at a depth of 11 km and the weaker one centered about 6 km southeast of the hypocenter at a depth of 15 km. A near-source, range-independent component of anelastic absorption was represented empirically by that contained in the empirical source functions, and a range-dependent component was added assuming a crustal shear-wave Q of 150 $f^{0.6}$.

DISCUSSION

In the preceding analysis, we have concentrated on the effect of critical reflections from the base of a flat-layered crustal structure model as an explanation of the elevated ground motion levels recorded in San Francisco and Oakland. However, ground motion amplitudes are influenced by a variety of effects, several of which may contribute together. It is important to establish which of these different effects was the predominant cause of the widespread elevation of recorded ground motion amplitudes in San Francisco and Oakland.

The profile of simulated accelerograms shown on the right side of Figure 4 includes the effects of strongly radiating patches (asperities) in the slip model of Wald et al. (1990). Using a uniform slip model in place of this heterogeneous slip model reduces the overall amplitudes of the simulated motions, but does not change the shape of the attenuation curve. These simulations also include the effect of rupture directivity. Simulation studies indicate that the bilateral rupture of the Loma Prieta earthquake enhanced the ground motion amplitudes in San Francisco and Oakland compared with those from a unilaterally southeastward propagating rupture. The dip in the attenuation curve at about 40 km is due to a cluster of stations in the Southeast Bay region which are influenced less by directivity than those in the San Francisco Peninsula. This accentuates the flattening of the attenuation curve caused by the critical reflections.

The profile of accelerograms in Figure 4 includes recordings from a variety of site conditions, although only one accelerogram (from San Francisco Airport at an epicentral distance of 79 km) is from a soft soil site. While these varying site conditions evidently caused local variations in ground motion amplitudes and frequency content, they cannot explain the absence of attenuation between 40 km and 80 km in both the recorded and simulated peak accelerations shown in Figures 1, 4 and 5.

It is of interest to assess the relative contributions of critical reflections and site conditions to the damaging ground motion levels experienced in San Francisco and Oakland. The critical reflections are expected to increase the peak motions at all sites in the affected distance range regardless of site conditions, since they control the amplitude of the motions arriving beneath the site. The effect of soft site conditions is to locally further amplify these critical reflections in a frequency-dependent manner. The peak accelerations at rock sites at a distance of about 80 km in Figure 1 are about a factor of 3 above the median attenuation relation, while bay mud and artificial fill sites are about a factor of 5 above the median at the same distance. The amplification of peak acceleration due to bay mud and artificial fill was thus about a factor of 2, consistent with the value of 2.6 obtained by EERI (1989), Table 2.3. The effect of critical reflections in amplifying peak accelerations of the Loma Prieta earthquake in the San Francisco and Oakland regions was therefore as large as the effect of soft soil site conditions. Soil amplification may have been larger than a factor of 2 to 3 at the resonant frequencies of the soil columns.

ACKNOWLEDGMENTS

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