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THE INFLUENCE OF CRITICAL MOHO REFLECTIONS ON STRONG GROUND MOTIONS RECORDED IN SAN FRANCISCO AND OAKLAND DURING THE 1989 LOMA PRIETA EARTHQUAKE

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Abstract. 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 strongly 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, which are identified on the basis of their arrival times and phase velocity, and by comparison with simulated accelerograms, 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. 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. Focal depth has an important influence on strong motion attenuation at distances beyond about 40 km, and empirical attenuation relations derived from shallow crustal earthquakes may underpredict the ground motions of deeper crustal events in this distance range. Further analyses using an expanded data base that includes recordings of aftershocks are required to rigorously test the proposed explanation of the ground motions recorded in San Francisco and Oakland, and the conclusions drawn from that explanation.

Introduction

The peak accelerations of the Loma Prieta earthquake showed more gradual attenuation 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 [Joyner and Boore, 1988; Figure 1] 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 contribution of focal depth and crustal structure to the difference between the observed ground motion attenuation of the Loma Prieta earthquake and that predicted by standard empirical attenuation relations.

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

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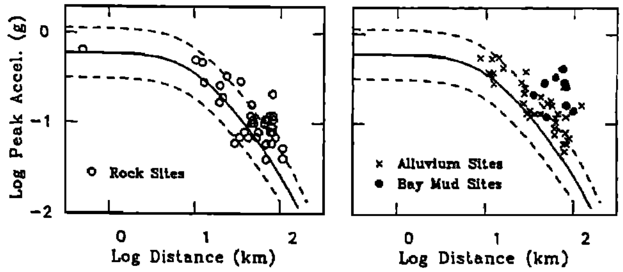

Fig. 1. Recorded peak horizontal acceleration as a function of distance from the surface projection of the rupture zone of the Loma Prieta earthquake for rock sites (left) and alluvium and Bay Mud sites (right). Source: Boore *et al.*, 1990.

motion attenuation curve. 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 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 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

A record section of recorded accelerograms (Figure 2, left side) was compiled using all accelerograms to the north of the epicenter (i.e. in the San Francisco Bay region) that have known trigger time. The recordings 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 traces are copies of film records published by Shakal *et al.* [1989] and Maley *et al.* [1989], and were compiled at a travel time reduction of 3.5 km/sec.

Arrival time curves for three principal waves are shown in Figure 2: 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 by averaging the models on either side of the San Andreas fault used in preliminary locations of aftershocks [Dietz, personal communication, 1989].

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	

The source function of the Loma Prieta earthquake as seen teleseismically has a small initial pulse preceding by two seconds a much larger pulse whose duration is about 6 seconds [Nabelek, 1990; Kanamori and Satake, 1990], as shown in Figure 3. The energy release was centered in the depth range of 12 to 15 km [Nabelek, 1990; Kanamori and Satake, 1990]. Accordingly, the arrival time curves in Figure 2 are for a point source at a depth of 12 km located above the hypocenter and occurring 2 seconds after the origin time of the earthquake. The S_mS curve is repeated at a delay of 6 seconds to represent the duration of the strong source pulse seen teleseismically. 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 2. 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 strong source pulse in Figure 3.

A profile of simulated accelerograms is shown on the right side of Figure 2. At these high frequencies, we do not expect the simulated accelerograms to match the waveforms of the recorded accelerograms. 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,

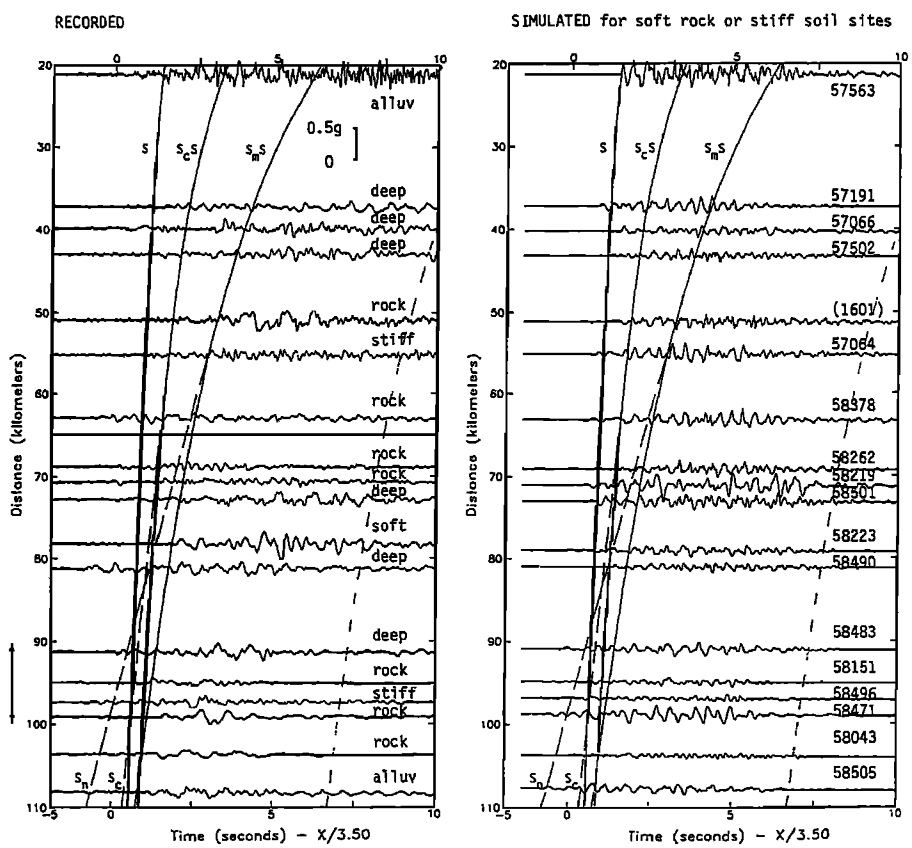

Fig. 2. Profiles of recorded (left) and simulated (right) accelerograms of the 1989 Loma Prieta earthquake, compiled using epicentral distance and a travel-time reduction of 3.5 km/sec. Arrival time curves are explained in the text. Soil conditions are annotated on recorded accelerograms, and CSMIP (and USGS in parentheses) station numbers are annotated on simulated accelerograms. The distance range of San Francisco and Oakland (90-100 km) is shown by the arrow.

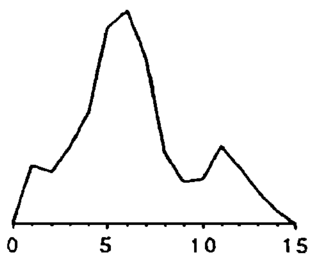

Fig. 3. Source time function of the Loma Prieta earthquake derived from broadband teleseismic P-waves. Source: Nabelek, 1990.

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 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 4. 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 50 to 100 km, the largest simulated motions at a given station are due to critical Moho 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 Moho 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 2, 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 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].

The Loma Prieta earthquake was modeled by a rupture surface 36 km long and 15 km wide. The rupture spread circularly from the 18 km-deep hypocenter at an average speed of 3.3 km/sec and with a rise time of 3.2 sec. Half of the moment release took place on an asperity centered above the hypocenter at a depth of 14 km (compatible with the teleseismic estimates of centroid depth cited above) and having a radius of 6 km. The seismic moment of 3.0×10^{26} dyne-cm and the strike, dip and rake of 128, 70, and 138 degrees respectively

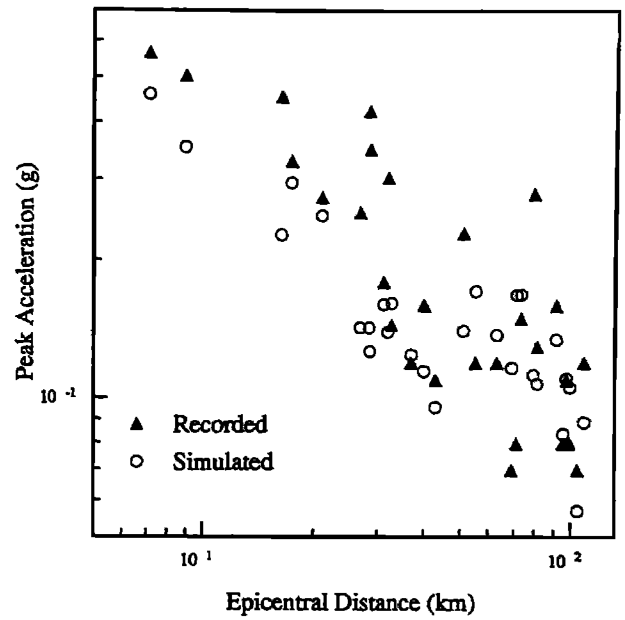

Fig. 4. Recorded (solid triangles) and simulated (open circles) peak horizontal acceleration as a function of epicentral distance for sites within 30 km and for Bay Area sites having known trigger times.

of Kanamori and Satake, [1990] were used. 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 frequency-independent Q of 500.

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 accelerograms in Figure 2 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 and 4.

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.

An effect that potentially could explain the elevation of amplitudes in Oakland and other parts of the East Bay is the trapping of waves as they enter a thickening basin [Vidale and Helmberger, 1987; 1988]. From seismic refraction studies by Mooney and Luetgert [1982] and Mooney and Colburn [1985] in the Santa Clara Valley, it is known that a basin exists beneath the Santa Clara Valley opposite the source region of the Loma Prieta earthquake. This basin thickens toward the east, away from the source region of the Loma Prieta earthquake, providing the conditions for trapping energy within the southern Santa Clara Valley. The northward continuation of the basin beneath the Santa Clara Valley is not well known, but it is generally believed to extend underneath San Francisco Bay, fault-bounded to the east by the Hayward fault and bounded to the west by unconformities along the western shore of San Francisco Bay. This basin geometry could cause trapping of seismic waves in the East Bay, but is less likely to do so in the San Francisco Peninsula, and thus may not explain the elevated ground motion levels in both San Francisco and Oakland.

Determining which of these effects was the dominant cause of the large motions recorded in San Francisco and Oakland during the Loma Prieta earthquake has important implications for estimating ground motions from future large earthquakes on the San Andreas and Hayward faults. The basin response model would imply that amplification of ground motions throughout San Francisco and Oakland can be expected from nearby earthquakes as well as from distant ones like the Loma Prieta event, while the critical reflection model would not. The critical reflection model can be tested further by analyzing seismograms from aftershocks of the Loma Prieta sequence. The shorter rupture duration of these smaller events is expected to provide enhanced resolution of critically reflected phases.

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