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Peak Accelerations from the 1992 Landers and Big Bear, California, Earthquakes

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Abstract Peak ground accelerations (PGA) at 181 sites for the Landers M_w 7.3 earthquake and at 85 sites for the Big Bear M_w 6.2 aftershock are compared to the Joyner and Boore (1988) (JB) attenuation relationships and examined for spatial variations. This study finds the following five results. First, at the 95% confidence level, the mean of PGA values for both earthquakes is significantly higher than the JB median by a factor near 2. Second, for distances greater than 70 km, the observations from the Landers earthquake indicate that attenuation of ground motion with distance is less than that predicted by geometric spreading and by JB. Third, the northward propagation of the Landers rupture significantly reduces PGA values recorded at strong-motion stations south of the epicenter. Fourth, stations in the Los Angeles basin and the Coachella Valley recorded higher PGA values than expected during both events. Finally, site geology, using the site classification scheme of JB, generally does not have a statistically significant effect on PGA, except in the distance range from 60 to 100 km for the Landers earthquake. The observed difference between soil- and rock-site PGA's between 60 and 100 km for the Landers data set may be a combination of higher values of PGA recorded at soil sites in basins, an *S*-wave radiation maximum in the San Bernardino area, and directivity effects.

Introduction

The Landers M_w 7.3 earthquake is the largest earthquake to occur in the contiguous United States since 1952 and the largest strike-slip earthquake with an extensive set of strong-motion recordings. It significantly expands the close-in observations of ground motion for magnitudes greater than 7, including one strong-motion record at a station 2 km from observed ground rupture (Shakal *et al.*, 1992b; Etheredge *et al.*, 1993; Hawkins *et al.*, 1993). Prior to the 1989 Loma Prieta earthquake, little strong-motion data had been recorded for California earthquakes with magnitudes greater than 6.5 at distances less than 20 km from the faulting [Joyner and Boore, 1988 (JB)]. The Loma Prieta earthquake provided close-in (<20 km) strong-motion data for a M_w 7.0 earthquake (Shakal *et al.*, 1989; Maley *et al.*, 1989; Boore *et al.*, 1989). In addition, the 25 April 1992, Cape Mendocino M_w 7.1 earthquake provided close-in strong-motion data with unprecedentedly high accelerations for California (Shakal *et al.*, 1992a; USGS, 1992).

In this note, the attenuation and spatial variation of peak ground acceleration (PGA) data are examined for the Landers sequence data set. The examination includes a comparison of the strong ground motion from the M_w 7.3 Landers and M_w 6.2 Big Bear earthquakes to the attenuation relationships of JB (1988). The JB attenuation relationships are chosen for comparison because they have been widely applied. Other attenuation relationships have been developed, and they provide statistically similar median ground motion predictions to JB relationships (JB, 1988) although they have different variance estimates. However, the JB curves tend to predict lower ground motions than other relationships at distances greater than about 50 km, particularly for M_w 7.5 earthquakes (JB, 1988, Fig. 12 through 14). Thus, the comparison of JB with the recent data provides a further examination of the JB relationships for these distances and magnitudes. (See Campbell and Bozorgnia, 1994, for a comparison of the Landers earthquake PGA data with the attenuation relations of Campbell, 1993, and Sadigh *et al.*, 1986.)

Data

Figure 1 shows the location of the strong-motion stations used in this study. Peak ground accelerations and JB distances were available for 98 stations of the California Strong Motion Instrumentation Program (CSMIP) (Shakal *et al.*, 1992b; Huang *et al.*, 1992), 81 stations of the U.S. Geological Survey (USGS) (Etheredge *et al.*, 1993), and two Southern California Edison (SCE) stations (T. Kelly, 1992, written comm.; Hawkins *et al.*, 1993, 1994). In accordance with JB, the data have been divided between soil- and rock-site classifications using their criterion that rock sites have less than 5 m of soil overlying rock.

The distribution of the recent and JB (1981) data sets with distance and magnitude is shown in Figure 2. Recent data from the Landers, Cape Mendocino, and Loma Prieta earthquakes significantly increase the number of observations within 20 km from earthquakes with magnitudes greater than or equal to 7.

Method

Comparisons of the Landers and Big Bear strong-motion data sets to the JB median and standard deviations ($\pm 1\sigma$ and $\pm 2\sigma$) for the larger peak of the two horizontal components of ground motion are presented. The departures of the observations from the JB predictions are characterized by the residual from the JB median value. This residual for each station is computed by taking the difference between the logarithm of the observed PGA and the logarithm of the JB median value at the appropriate magnitude and distance. The mean residual, standard deviation, and 95% confidence limits for the estimate of the mean [using $\log_{10}$ (PGA) values] are also calculated.

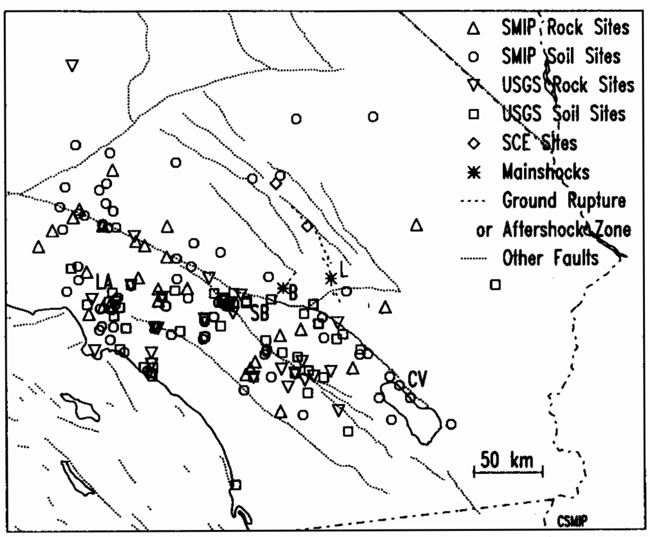

Figure 1. Map of southern California showing 98 CSMIP (28 rock, 70 soil), 81 USGS (29 rock, 52 soil), and 2 SCE (1 rock, 1 soil) stations that recorded the Landers earthquake sequence. The surface rupture associated with the Landers earthquake is indicated by a dashed line extending from its epicenter (*L). The aftershock zone associated with the Big Bear earthquake is indicated by a dashed line extending from its epicenter (*B). CV—Coachella Valley, LA—Los Angeles basin, and SB—San Bernardino area.

A least-squares determination of the PGA attenuation coefficients was also performed. With constant magnitude, the form of the JB attenuation relationship becomes log (PGA) = $A + d * \log(r)$, where the coefficient A combines JB's constant and magnitude-dependent terms. Further, this simplification of the relationship for a single earthquake combines the geometric spreading and anelastic attenuation terms into a single $d * \log(r)$ term [where $r = \text{sqrt}(h * h + r_0 * r_0)$, $h = 8$ km, and r_0 is the JB distance]. The coefficients A and d are determined by least squares (Claerbout, 1976). In addition, the standard error and 95% confidence limits of d were calculated (Draper and Smith, 1981).

The coefficient d indicates how rapidly the ground motion data attenuate with distance on a logarithmic scale. A value for d of -1 corresponds to geometric spreading of $1/r$. In contrast, JB separate anelastic attenuation into a $k * r$ term and a $d * \log(r)$ term. They set $d = -1$ for geometric spreading and estimate a value for the coefficient k of -0.0027 from a suite of earthquakes (Boore and Joyner, 1982).

Results and Discussion

Results are presented for the attenuation of PGA, the spatial variation of PGA, and the estimation of the coefficient d. The discussion will focus on the comparison

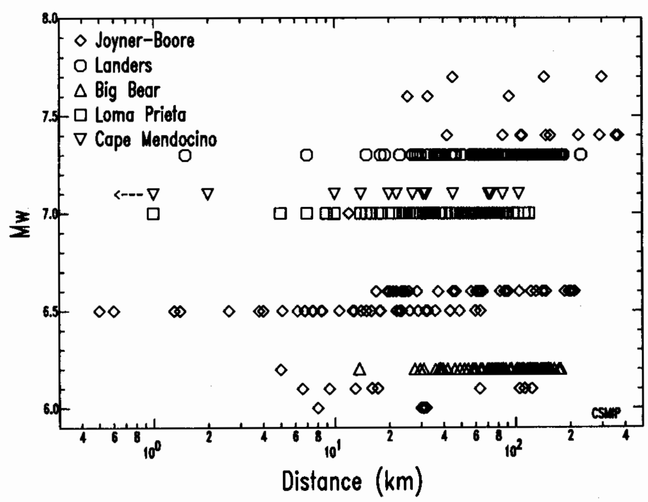

Figure 2. Magnitude versus JB distance for PGA data discussed in this article. The data for $M_w > 5.9$ from JB (1981) are shown with the data from four recent California earthquakes: 1992 M_w 7.3 Landers, 1992 M_w 6.2 Big Bear, 1992 M_w 7.1 Cape Mendocino, and 1989 M_w 7.0 Loma Prieta. The magnitude for the Cape Mendocino earthquake was determined from the seismic moment of Oppenheimer *et al.* (1993).

with JB and possible source and site effects observable in the PGA data.

PGA Attenuation

Figure 3 shows the Landers PGA data plotted versus distance along with the JB median and ± 1 and ± 2 standard deviation (σ) curves. The CSMIP and USGS stations are characterized as rock or soil sites. Hawkins *et al.* (1994) indicate that the SCE station at 2 km is located on rock, while the SCE station at 15 km is located on soil. In general, many of the Landers PGA data points fall within the JB $\pm 2\sigma$ curves (95% confidence limits for a sample). At distances less than about 65 km, the PGA data cluster about the JB median and are mainly within $\pm 1\sigma$. At greater distances, the PGA data mostly fall above the JB median curve. For example, many of the PGA's recorded at Los Angeles basin sites are above $+1\sigma$ (see Fig. 5).

To examine the trend of the Landers PGA data with distance and site classification, the mean residual between the observations and the JB median has been calculated (Table 1). The PGA data at distances less than 70 km have a mean residual from the JB median curve of -0.05σ. This value is not significantly different from the JB median. However, the PGA data at distances greater than 70 km have a mean residual of $+1.31\sigma$. This value is significantly larger, at the 95% confidence level, than the JB median.

The PGA data in Figure 3 do not show a significant difference between values recorded at rock and soil sites, consistent with the previous observations of JB, except in the distance range of 60 to 100 km. At a distance range of 60 to 100 km, soil-site PGA's have a mean residual of 0.89σ, while rock-site PGA's have a mean residual of 0.09σ. The soil-site mean residual is statistically different from the JB median curve and from the rock-site mean residual at the 95% confidence level.

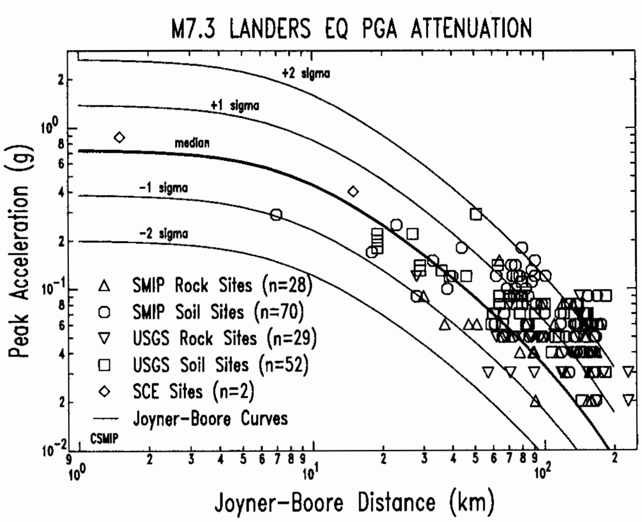

Figure 3. Peak ground acceleration values from the M_w 7.3 Landers earthquake plotted against JB distance and the JB (1988) PGA attenuation relationship (median, $\pm 1\sigma$, $\pm 2\sigma$).

For the distance range 100 to 130 km (130 km is a cutoff distance chosen, similar to JB, to avoid upward bias because of missing PGA's from more distant, nontriggered accelerographs), soil-site PGA's have a mean residual of 1.29σ, while rock-site PGA's have a mean residual of 0.78σ. In this distance range, both rock- and soil-site mean residuals are statistically higher than the JB median curve, but are not different from each other. Moho reflections (*SmS*) (Somerville and Yoshimura, 1990), which have been observed in Landers aftershock data (A. Frankel, 1992, oral comm.; Mori, 1993), may have an effect on PGA at these distances (also see Fig. 5).

For the entire PGA data set, the mean residual is $+0.97\sigma$ from the JB median. This value is also significantly higher than the JB median PGA curve and reflects the high PGA values at distances greater than 70 km. These significant differences may not be surprising because the JB curve for M_w 7.3 is based on fewer than 20 observations (see Fig. 2). There are 181 observations in the Landers data set, which allows a better estimation of the median curve.

The CSMIP PGA data from the M_w 6.2 Big Bear aftershock are shown in Figure 4. PGA's were recorded at 85 stations, but only one of these stations (Big Bear Civic Center) is located within 20 km of the rupture. Overall, the PGA values for the Big Bear earthquake are higher than the JB predictions, and generally fall between the median and $+2\sigma$ curves. Only five of 85 observations are below the JB median. The mean residual is $+1.21\sigma$ (Table 1). This value is significantly larger, at the 95% confidence level, than the JB median. These observations are consistent with earlier results from the Whittier (Shakal *et al.*, 1988; Campbell, 1988) and Loma Prieta (Boore *et al.*, 1989; Reichle *et al.*, 1990; Campbell, 1991) earthquakes, which indicate that observed PGA's are significantly higher than the JB median predictions for these earthquakes.

For the distance range 60 to 100 km, the Big Bear soil-site PGA values are not significantly larger than the rock-site PGA's, as was observed in the Lander's data set. The soil-site mean residual (0.90σ), like the Landers PGA's, is significantly different from the JB median at the 95% confidence level (see Table 1). In contrast, the rock-site mean residual (0.50σ) based on six samples is not significantly different from either the JB median curve or the soil-site mean residual.

Spatial Variation of PGA

Figure 5 shows the spatial variation of the residuals in PGA from JB predictions for the Landers and the Big Bear earthquakes. For the Landers earthquake, Figure 5a shows that sites with PGA values less than the JB median

Table 1
The Mean of the Residuals from Joyner and Boore Peak Ground Acceleration Median Values for Four Data Sets

	mr[†] ± se[†]	(±clm)[†‡]	sig
Landers PGA data for $r < 70$ km (45 sites):	−0.05 ± 0.67	(±0.20)	No
Landers PGA data for $r \geq 70$ km (136 sites):	1.31 ± 0.76	(±0.13)	Yes
Landers PGA data for $60 \leq r \leq 100$ km:			
Soil sites (46 sites):	0.89 ± 0.59	(±0.18)	Yes
Rock sites (21 sites):	0.09 ± 0.59	(±0.27)	No
Landers PGA data for $100 \leq r \leq 130$ km:			
Soil sites (12 sites):	1.29 ± 0.55	(±0.35)	Yes
Rock sites (6 sites):	0.78 ± 0.56	(±0.59)	Yes
Landers PGA data (181 sites):	0.97 ± 0.95	(±0.14)	Yes
Big Bear PGA data for $60 \leq r \leq 100$ km:			
Soil sites (13 sites):	0.90 ± 0.45	(±0.27)	Yes
Rock sites (6 sites):	0.50 ± 0.49	(±0.51)	No
Big Bear PGA data (85 sites):	1.21 ± 0.77	(±0.17)	Yes

*The standard error (se) of the observations about the mean of the residuals (mr) and the 95% confidence limits of the mean (clm) for the mr are given. Also, the significance (sig), at the 95% confidence level, of the difference of the mr from the JB median is listed.

†The mr, se, and clm values are given in units of JB standard deviation ($\sigma_{\log(PGA)} = 0.28$).

‡For comparison, the 95% confidence limit for the JB PGA median value is $\pm 0.05\sigma$.

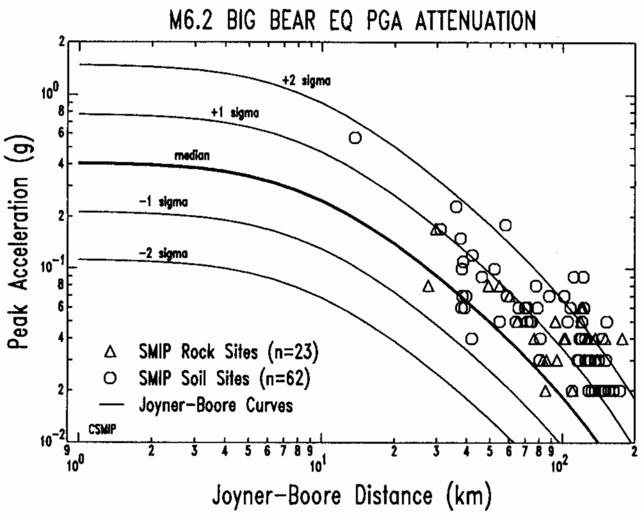

Figure 4. Peak ground acceleration values from the M_w 6.2 Big Bear earthquake plotted against JB distance and the JB (1988) attenuation relationship (median, $\pm 1\sigma$, $\pm 2\sigma$).

fall predominantly to the south of the mainshock. Sites with PGA values near the JB $+2\sigma$ curve are located predominantly to the west of the mainshock in the Los Angeles basin area, and at distances greater than 90 km (as in Fig. 3). For the Big Bear earthquake, Figure 5b shows that PGA values are nearly all greater than the JB median, and that PGA values near the JB $+2\sigma$ curve are also recorded at distances greater than 90 km (as in Fig. 4). Some sites, such as in the Los Angeles basin, have similar differences from JB predictions for both earthquakes. However, stations south of the two epicenters have marked changes in the residuals from the Landers to the Big Bear earthquake, as described below.

Because the Landers earthquake ruptured several faults over a distance greater than 70 km, source as well as path and site effects may have affected ground motion during the Landers earthquake. Kanamori *et al.* (1992) determined the source characteristics of the Landers earthquake and showed that the earthquake ruptured northward from the hypocenter. They also observed that peak velocities and accelerations recorded on broadband seismographs were higher than expected to the north of the epicenter and lower than expected to the south of the epicenter, which they inferred was due to the effect of directivity on the radiation pattern. The strong-motion data show similar effects of directivity. Figure 5a shows higher observations than the JB median peak accelerations to the north of the Landers epicenter, and lower observations than JB median peak accelerations to the south. The effects of directivity are not readily apparent in the Big Bear data, perhaps because of the shorter rupture length and the station distribution (Fig. 5b).

Cao *et al.* (1992) concluded that the differences in the *S*-wave radiation pattern between the Landers and the Big Bear earthquakes affect observed PGA's at many CSMIP stations. An *S*-wave radiation lobe is pointed to the west for the Landers earthquake, and to the southwest and to the northwest for the Big Bear earthquake (Cao *et al.*, 1992). For the San Bernardino area (SB in Fig. 5), the *S*-wave radiation is near a maximum for the Landers earthquake and near a minimum for the Big Bear earthquake. This difference in radiation pattern may be reflected in Figure 5. The PGA values recorded near San Bernardino from the Landers earthquake are generally larger than the median. The PGA values recorded near San Bernardino from the Big Bear earthquake are generally closer to the median. In addition, the Big Bear Civic Center station located 11 km northwest of the Big Bear epicenter (Fig. 1) recorded a PGA value near $+2\sigma$. This large value may have been affected by the *S*-radiation lobe.

Major structural basins may also affect ground motion attenuation. Figure 5 shows that stations in the Los Angeles basin (LA) and the Coachella Valley (CV) recorded larger than the median PGA from both the Landers and the Big Bear earthquakes. However, for the Landers earthquake, directivity may have reduced the overall level of PGA values for stations in the Coachella Valley. Basin effects have been observed previously in the Los Angeles basin after the 1971 San Fernando and 1987 Whittier earthquake sequences (e.g., Hanks, 1975; Trifunac, 1988).

Distance Attenuation Coefficient

Table 2 lists the estimate of the coefficient *d* [in the $d * \log(r)$ term] from the least squares fit to PGA data from four recent California earthquakes. Similarly to the method of JB, the data used in the fit have been limited to distance less than the first nontriggered station. This selection criterion avoids an upward bias because of low peak accelerations that did not trigger more distant accelerographs. The estimates of the coefficient *d* were made from stations with distances less than 130 km for the Landers, 110 km for the Big Bear, 90 km for the Loma Prieta, and 78 km for the Cape Mendocino earthquakes. The estimate of *d* from the Landers and Loma Prieta PGA data sets is near -0.75, showing significantly less attenuation with distance than expected from geometric spreading. In contrast, the estimates of *d* from the Big Bear and Cape Mendocino PGA data sets are not significantly different from geometric spreading ($d = -1$). However, these two earthquakes are not as well recorded, in terms of the number and distribution of observations, as the Landers and Loma Prieta earthquakes. Specifically, the Big Bear data lack observations at distances less than 20 km. The application of the selection criterion to the Cape Mendocino earthquake data limits the observations to only 14 stations at distances less than 78 km. To adequately estimate *d*, sufficient observations are needed both at distances less than 20 km, and at distances greater than about 70 km to define the trend in attenuation with distance.

The significantly higher PGA values and lower attenuation with distance than JB predict for the Landers

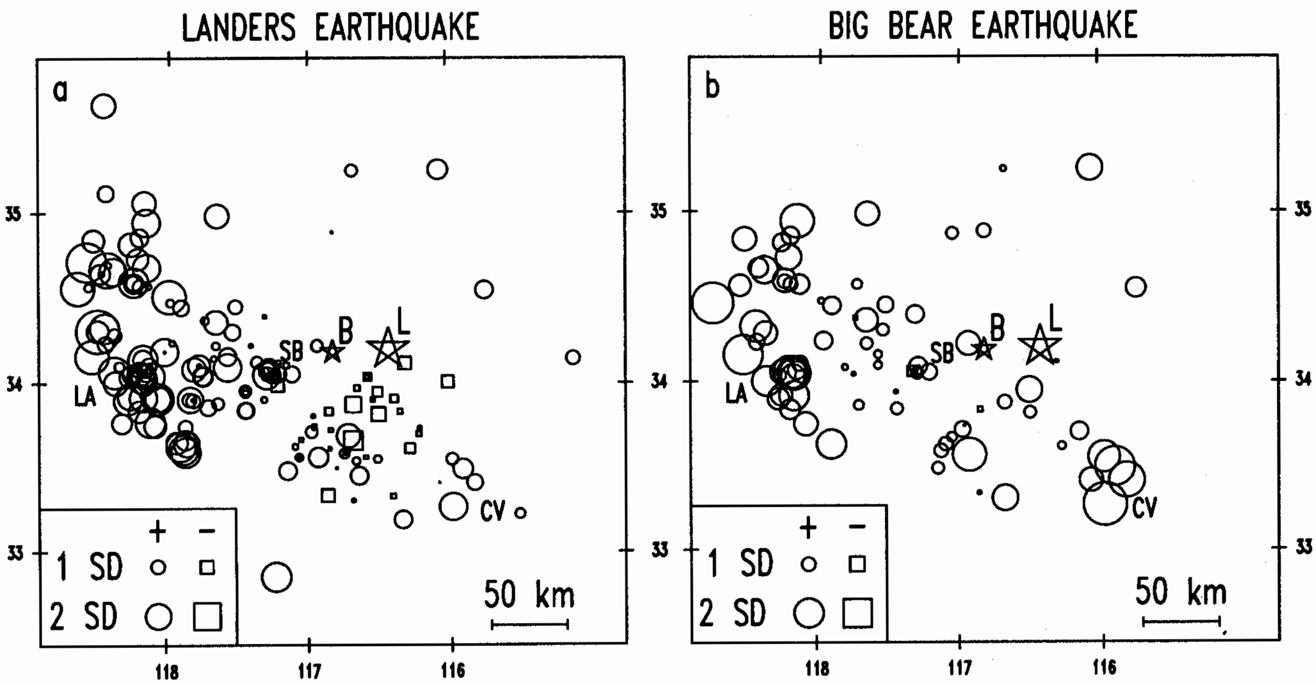

Figure 5. Map view of the 179 CSMIP and USGS stations showing the PGA residuals relative to JB predictions: (a) M_w 7.3 Landers earthquake, (b) M_w 6.2 Big Bear earthquake. Circles show positive residuals (observations greater than JB median curve), and squares show negative residuals (observations less than JB median curve). Units on the residuals are JB PGA standard deviation (SD; SD $= \sigma_{\log(\mathrm{PGA})} = 0.28$). Large and small stars indicate the location of the Landers (L) and Big Bear (B) earthquakes, respectively. CV—Coachella Valley, LA—Los Angeles basin, and SB—San Bernardino area.

Table 2
The Least-Squares Estimate of the Coefficient (d) in the Attenuation with Distance Term [$d * \log(r)$]

Least-squares-fit data set	$d \pm$ se	($\pm$cld)	sig
Landers PGA data for $r < 130$ km (112 sites):	-0.79 ± 0.08	($\pm$0.15)	Yes
Big Bear PGA for $r < 110$ km (49 sites):	-1.17 ± 0.14	($\pm$0.28)	No
Loma Prieta PGA for $r < 90$ km (84 sites)†:	-0.76 ± 0.09	($\pm$0.17)	Yes
Cape Mendocino PGA for $r < 78$ km (14 sites)‡:	-1.28 ± 0.19	($\pm$0.42)	No

*The standard error (se) and the 95% confidence limits (cld) for the coefficient d are given (Draper and Smith, 1981). Also, the significance (sig), at the 95% confidence level, of the difference of the estimate of d from the value for geometric spreading ($d = -1$) is listed.

†Based on Loma Prieta PGA data published by Boore *et al.* (1989) and Shakal *et al.* (1989).

‡Based on Cape Mendocino PGA data published by Shakal *et al.* (1992a) and USGS (1992).

earthquake are consistent with the observation from other recent California earthquakes (Shakal *et al.*, 1988; Campbell, 1988; Boore *et al.*, 1989; Reichle *et al.*, 1990; Campbell, 1991; Cramer *et al.*, 1992) that the JB and other attenuation relationships (e.g., Campbell, 1988, 1991) underpredict peak acceleration for certain magnitude and distance ranges. At large distances, the underprediction is enhanced in the JB relationship by the inclusion of an anelastic attenuation term proportional to distance ($k * r$), as well as a geometric spreading term proportional to log distance [$-1.0 * \log(r)$]. These terms cause a more rapid attenuation with distance than other attenuation relationships (JB, 1988, Fig. 12 through 14). The coefficient k is estimated to be -0.0027 in JB. The addition of PGA data from the Landers and Loma Prieta earthquakes may increase the estimate of k and reduce the statistical significance of the $k * r$ term. For the Landers and the Loma Prieta earthquakes, the anelastic attenuation term's coefficient (k) may be more a measure of source, path, and site effects on ground motion than real anelastic attenuation in the earth.

Conclusions

This comparison of peak acceleration recorded during the M_w 7.3 Landers and M_w 6.2 Big Bear earthquakes to the JB (1988) attenuation relationships finds the following five results. First, at the 95% confidence level, the mean of PGA values for both earthquakes is significantly higher than the JB median by a factor near 2. Second, for distances greater than 70 km, the observations from both the Landers and Loma Prieta earthquakes indicate that attenuation of ground motion with distance is less than that predicted by geometric spreading and JB. Third, the northward propagation of the Landers rupture significantly reduces PGA values recorded at strong-motion stations south of the epicenter. Fourth, stations in the Los Angeles basin and the Coachella Valley recorded higher PGA values than expected during both events. Finally, site geology, using the site classification scheme of JB, generally does not have a statistically significant effect on PGA, except in the distance range from 60 to 100 km for the Landers earthquake. The observed difference between soil- and rock-site PGA's between 60 and 100 km for the Landers data set may be a combination of higher values of PGA recorded at soil sites in basins (Coachella Valley and San Bernardino area), an S-wave radiation maximum in the San Bernardino area where observations of PGA are mainly soil sites, and directivity effects that lowered PGA values on rock sites south of the Landers rupture.

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