# Accelerations Near Faulting in Moderate-sized Earthquakes

by

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## ABSTRACT

Peak ground accelerations recently recorded within 10-15 km of faulting during moderate-sized earthquakes (m = 4 to 6) are significantly underestimated by many, if not most, of the empirical acceleration-distance relations commonly used in seismic engineering. The recent data show a rapid decrease of peak acceleration with increasing distances (at a rate between $r^{-1.4}$ and $r^{-1.8}$) beyond 5 to 20 km and suggest a less rapid rate of attenuation closer to the causative fault.

Urban development in seismically active regions throughout the world and the smaller margins of safety in much modern construction have increased the potential loss of life and property from earthquakes occurring near or within developed areas. For example, the 1969 Santa Rosa (m = 5.6 and 5.7) and 1971 San Fernando (m = 6.6) earthquakes in California are sobering reminders of the large potential for damage from even moderate-sized shocks occurring in urban vicinities (1). In view of the increasing demand for nuclear power plants in active tectonic regions and the trend toward optimizing the seismic design of important public structures (hospitals, schools, high-rise office and apartment buildings, dams and bridges), an accurate description of seismic loading imposed by nearby earthquakes is essential. Our knowledge of this loading is derived almost exclusively from strong-motion accelerographs. Although many valuable data have been gathered since the initial deployment of accelerographs by the U.S. Coast and Geodetic Survey in 1932, prior to 1966 few recordings had been obtained within 5 to 10 km of faulting, and thus design values for nearby earthquakes were largely extrapolated from data acquired at greater distances. Since 1966 the number of near-fault records has increased markedly, especially with respect to records for which the distance to faulting is accurately known (2). We wish to draw attention to three particularly informative suites of recent near-fault records, and to compare the observed acceleration-distance behavior with representative published empirical relations.

Ground motion can be characterized in a number of ways. The time history of particle motion is obviously the most complete specification, but for many purposes of seismic design the motion can also be characterized by parameters such as peak acceleration, velocity, and displacement, and some measure of shaking duration. We shall discuss only peak acceleration in this report; it is the most widely referenced parameter in the seismic engineering literature and is measured directly from accelerograms.

The data for this study (Fig. 1A), are from the 1966 Parkfield (m = 5.5) and the 1971 San Fernando (m = 6.6) events in California (4,5) and from three shocks (m = 4.7, 4.9, 5.1) of the 1966 Matsushiro, Japan, earthquake swarm (6). These shocks are unique; they were recorded by several accelerographs within 30 km of the source, including one instrument or more within 5 km. Conclusions regarding the attenuation of acceleration with distance are less likely to be biased by differences in local geologic site conditions or propagation paths if they are based on a few shocks recorded at many sites rather than on many shocks recorded at a few sites. For the California shocks, moreover, the hypocenters and patterns of faulting are unusually well determined.

When plotted as a function of distance from the source (Fig. 1A), the acceleration data for the Matsushiro, Parkfield and San Fernando earthquakes separate according to magnitude. At a given distance the accelerations increase with magnitude. In spite of the scatter in the data for a particular magnitude, which at least partially results from geologic differences in site conditions (7), the similarity in the trend of the sets of data from California is striking. Peak acceleration attenuates with distance (r) at a rate between $r^{-1.4}$ and $r^{-1.8}$ beyond 5-10 km from the fault. In comparison the attenuation within 5-10 km is not well established. The Parkfield data suggest a zone of nearly constant acceleration within about 10 km. For San Fernando, the 1.25 g peak (8) at 3 km lies below a straight line fitted to the data at large distances and is consistent with a zone of little or no attenuation within several kilometers of the fault (9). The trends for the Matsushiro shocks are less certain because of the limited accuracy of the earthquake location.

A number of empirical relations between acceleration and distance have been published (Fig. 1B). Beyond 30 km the trends of the curves are largely similar. This is not surprising since most are derived primarily from data obtained beyond 20 km from the region of faulting. Divergence between the curves at smaller distances reflects the lack of near-fault data and emphasizes the uncertainty in extrapolating such curves beyond distances for which there is sufficient data. Only curve 2 is based on reliable near-fault accelerations. Discrepancies among the relations also reflect differences in the data base and in the interpretation of data. For example, curves 1, 2, and 3 are based on a few records of relatively intense shaking and are not tied to particular geologic site conditions. Curve 4 is a geometric mean fit to a larger set of data that includes many values of relatively weak shaking and is meant to apply to "intermediate soil comparable to a stiff clay or a compact conglomerate." Curve 5 is for peak acceleration at bedrock sites and is a weighted average of bedrock relations proposed by other authors.

Comparisons of the San Fernando data with the empirical curves reveal that beyond 20-30 km, where the empirical relations are based on data from a number of earthquakes, the San Fernando accelerations are generally below the empirical curves 1, 2 and 3, and thus the shaking was not unusually strong. In contrast, curves 4 and 5 for special site conditions underestimate the data even though the San Fernando earthquake was recorded at both bedrock and alluvium sites. At smaller distances, the peak of 1.25 g falls far above both curve 3 and the extrapolated sections of curves 4 and 5.

The relation of the Parkfield data to the acceleration attenuation curves for magnitude 5.5 is similar to that observed for the San Fernando data. For example, at large distances the accelerations are overestimated by curves 1, 2 and 3; within 10 km of the fault all the relations underestimate the accelerations, except the extrapolated segment of curve 1, which grossly overestimates them. Curve 2 is the best fit to both the Parkfield and San Fernando data, especially at small distances (12).

In conclusion, many of the widely referenced acceleration-distance relations are not applicable or valid within about 20 km of faulting and need to be revised to accommodate the near-fault Parkfield and San Fernando observations. The need is urgent because in the absence of instrumental recordings, the near-fault peak ground accelerations generally have been significantly underestimated (13; Fig. 1B). The recent near-fault strong-motion recordings clearly indicate that nearby moderate-sized earthquakes can generate peak ground accelerations comparable to those from larger earthquakes at greater distances. For example, the peak accelerations from the Parkfield (m = 5.5) shock at 10 km were about twice those from the 1952 Kern County (m = 7.7) shock at 40 km. This is an important consideration for the plan and design of nuclear power plants and important urban structures located where intense shaking even over a limited area can be very destructive. In terms of other ground motion parameters, especially duration and displacement, the nearby moderate earthquakes may be relatively less significant than larger events at greater distances.

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## References and Notes

1. Building damage in Santa Rosa was placed at $6 million [K. V. Steinbrugge, W. K. Cloud and N. H. Scott, The Santa Rosa, California Earthquakes of October 1, 1969, (U.S. Department of Commerce, Washington, 1970), p. 3]. In the San Fernando earthquake, 64 lives were lost and structural damage was estimated to be $500 million [San Fernando Earthquake, Report of Los Angeles County Earthquake Commission (1971)].
2. Accompanying the increase in near-fault data, the maximum acceleration recorded during any earthquake has jumped from 0.33 *g* in 1940, to 0.50 *g* in 1966, and to 1.25 *g* in 1971.
3. Although difficult to specify precisely in the time domain, the dominant frequencies in the accelerograms used in this paper are typically less than 10 Hz and are usually close to 5 Hz. No obvious dependence of frequency on distance from the causative fault was noted.
4. W. K. Cloud and V. Perez, *Bull. Seism. Soc. Am.* *57*, 1179 (1967); G. W. Housner and M. D. Trifunac, *Bull. Seism. Soc. Am.* *57*, 1193 (1967); A. G. Brady and D. E. Hudson, *Cal. Inst. Tech. Earthq. Eng. Res. Lab. EERL70-21* (1970).
5. R. P. Maley and W. K. Cloud in *Strong-Motion Instrumental Data on the San Fernando Earthquake of February 9, 1971*, D. E. Hudson, Ed. (Cal. Inst. Tech. Pasadena and U.S. Dept. of Commerce, Washington, 1971), p. 1; A. G. Brady, D. E. Hudson, and M. D. Trifunac, *Cal. Inst. Tech. Eng. Res. Lab EERL 71-20* (1971).
6. K. Kanai, K. Hirano, S. Yoshizawa, and T. Asada, *Bull. Earthquake Res. Inst.* 44, 1269 (1966).
7. See, for example, R. P. Maley and W. K. Cloud, *Op. cit.*, 41.
8. The peak acceleration of 1.25 *g* recorded adjacent to Pacoima Dam is the largest ever measured for an earthquake of any magnitude. Accordingly, there is much interest in determining if the peak accelerations are representative of a

magnitude 6.5 event or if the recording was significantly influenced by various site factors, such as the rugged topographic relief, the presence of the dam and the reservoir, or the local cracking and landsliding. As yet, no definitive studies of these effects have been published, but some remarks are offered. First, if local cracking and landsliding contributed significantly to the ground motion, their effect would probably be at relatively high frequencies, in which case a crude correction for these factors could be obtained by filtering out higher frequency energy. Removing all energy above 11, 8, and 6 Hz reduces the peak acceleration to 1.1 _g_, 0.9 _g_, and 0.8 _g_, respectively; these values are still larger than any previously observed. Second, numerical studies by one of us (DMB) on a simplified model indicate that the effects of topography are complicated but could cause amplification as large as 60% in the incident waves. The three dimensional character of the topographic relief, however, combined with the distributed nature of the source of energy release, make reliable quantitative evaluations difficult. Third, the recorded accelerations are consistent with field evidence of local vertical accelerations in the neighborhood of 1.0 _g_ [B. J. Morrill, U.S. Geol. Survey Prof. Paper 733, 177 (1971)].

9. If a zone of slow rate of attenuation exists, it could be described by a zero distance acceleration and a corner-distance beyond which the more rapid attenuation rate commences. These parameters need not be primarily functions of magnitude. Clearly, additional near-fault data from more earthquakes are needed to confirm the existence and properties of such a zone of nearly uniform acceleration. Sufficient information is now available, however, for a synthesis of recent work regarding source mechanisms and near-source wave propagation that could be of value in understanding the possible behavior of

near-fault acceleration fields. The data in Fig. 1A will serve as an important constraint on the theory.

10. L. Esteva and E. Rosenblueth (1963), as given in Seed, et al., below; G. W. Housner, Proc. Third World Conf. on Earthquake Eng., v. I, III-94 (1965); H. B. Seed, I. M. Idriss, and F. W. Kiefer, J. Soil. Mech. and Foundations Div. ASCE 95, 1199 (1969); L. Esteva in Seismic Design for Nuclear Power Plants, R. J. Hanson, Ed. (M.I.T. Press, Cambridge, Mass., 1970), p. 142. References to other acceleration-distance relations are found in the bibliographies of the above.

11. For the near-fault Parkfield data an effective hypocentral distance was used. This was based on the assumption that the radiation source was at a depth of 5 km beneath the portion of the ruptured fault which was closest to the accelerograph. The actual hypocenter was about 30 km from the point of closest approach. Use of an effective hypocenter affords a more physically meaningful comparison of the empirical relations to the data than is provided by using the actual hypocenter. For San Fernando, the geometric relations between the faulting and stations were such that this problem did not arise.

12. Kanai et al. (6) combined an empirical acceleration-distance formula for strong earthquakes at moderate distances with a separate formula for the Matsushiro earthquakes at small distances. Although it seems to be a better fit to the data than the other curves in Fig. 1B, the combined relations (eqs. 3 and 4 of ref. 6) does not predict the Matsushiro data satisfactorily, and the behavior of the combined relation at small distances is inconsistent with the separate near-fault formula (eq. 2 of ref. 6). Furthermore, although the curves of Kanai et al. appear to level off as distance to the fault decreases, they actually increase very rapidly for distances less than 5 km.

13. In a recent compendium on earthquake engineering, the maximum ground accelerations in the vicinity of the causative fault for magnitude 5.5 and 6.5 earthquakes are listed as .15 and .29 g, respectively [G. W. Housner in Earthquake Engineering, R. L. Wiegel, Ed., (Prentice-Hall, Englewood Cliffs, N. J., 1970), p. 79].

14. We thank Keiiti Aki for translating part of Ref. 6 and Carl Wentworth for his helpful comments.

# Figure Legends

Fig. 1A. Peak acceleration as a function of closest distance from the slipped fault for San Fernando (closed circles), Parkfield (open circles), and Matsushiro (triangles) earthquakes. The ordinate is the largest value of the peak (maximum absolute) acceleration from the three orthogonal accelerograms at a given station (3). In each case the largest peak value occurred on a horizontal component. To avoid influence from man-made structures, only data recorded in the ground floor or basement of structures two stories or less in height were used. To make the California and Japanese data compatible, corrections for instrument response were necessary for the Matsushiro values. The vertical bars reflect uncertainties in the corrected values for those records containing interfering wave trains that are not readily separated into spectral components by visual analysis. The closest Parkfield point plots off the graph at 0.08 km. Surface faulting was not observed for the Matsushiro events, hence hypocentral distance was used to approximate closest distance to the fault.

1B. Representative sets of empirical peak acceleration-distance relations (6, 10) for magnitude 5.5 and 6.5 shocks compared with data from the Parkfield (m = 5.5) and San Fernando (m = 6.6) earthquakes. Most other published empirical curves fall between the extremes in these sets. The "ground period" of Kanai et al. (6) is taken to be 0.3 sec, an appropriate mean value for much of the data. Empirical relations are plotted in terms of hypocentral distance, assuming a focal depth of 5 km, and are dashed where extrapolated. Peak acceleration data are plotted against closest distance to slipped surface and also against hypocentral distance (right-hand point of data pair) if the two distances differ substantially (11). Letters denote surficial geologic materials at station sites (A = alluvium, G = intrusive rock, S = sandstone, V = volcanic rock and shale). For the sake of clarity, the information for m = 6.5 has been separated horizontally from that for m = 5.5.

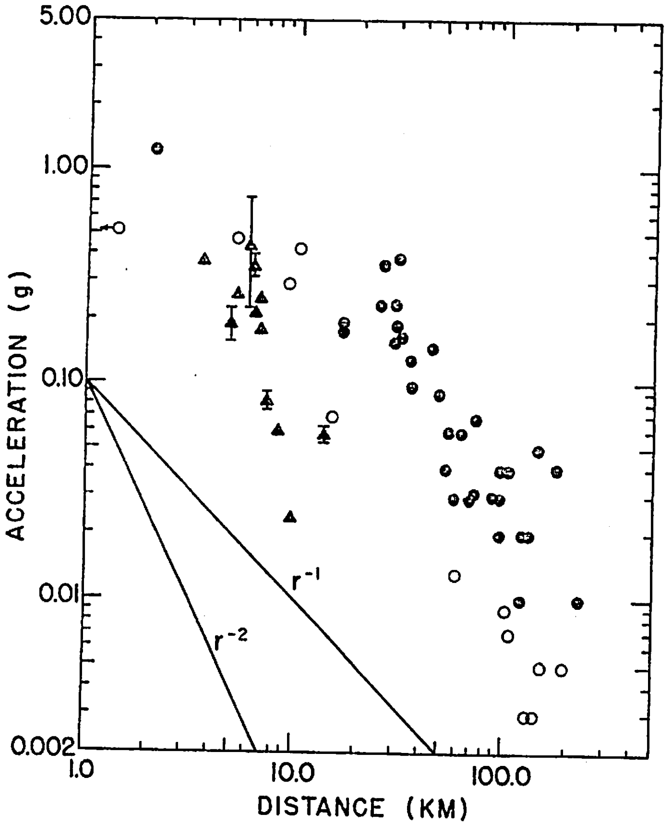
5.00
1.00
0.10
0.01
0.002
ACCELERATION (g)
1.0
10.0
100.0
DISTANCE (KM)
r^-1
r^-2

Fig. 1A

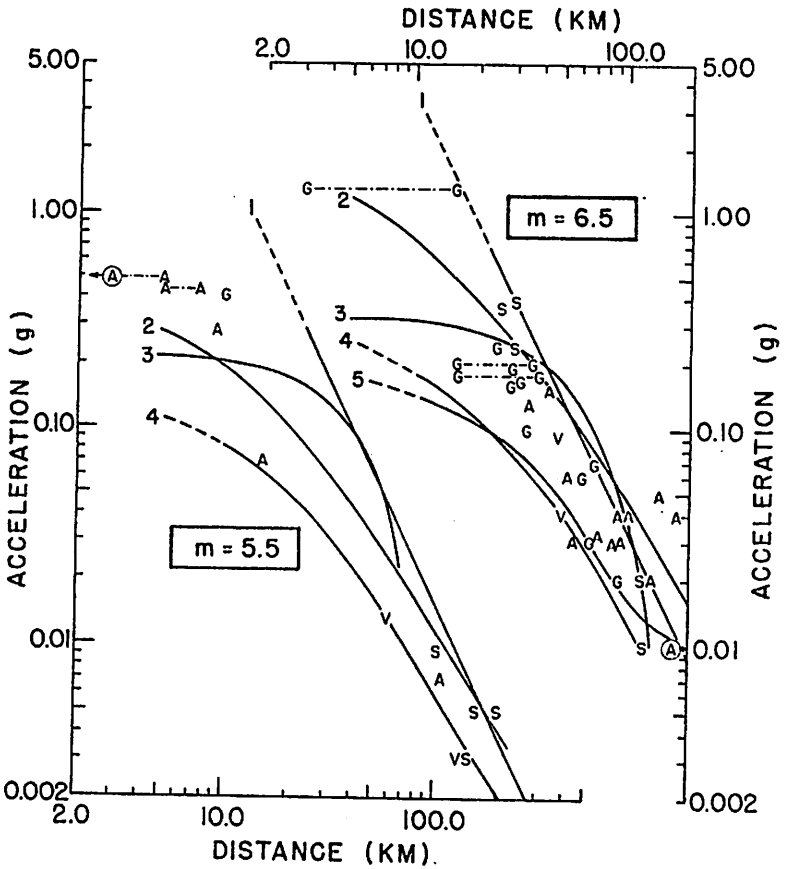
DISTANCE (KM)
2.0
10.0
100.0
5.00
1.00
0.10
0.01
0.002
ACCELERATION (g)
m = 6.5
m = 5.5
1
2
3
4
5
A
G
S
V
VS
DISTANCE (KM)

Fig. 1B