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PEAK HORIZONTAL ACCELERATION AND VELOCITY FROM STRONG-MOTION RECORDS INCLUDING RECORDS FROM THE 1979 IMPERIAL VALLEY, CALIFORNIA, EARTHQUAKE

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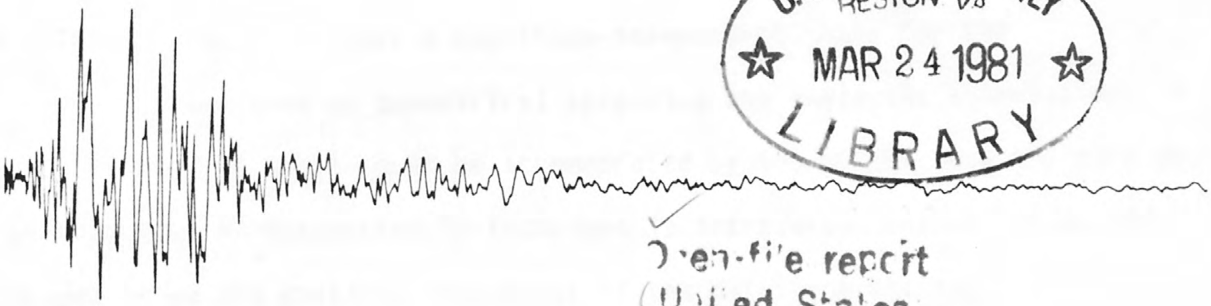

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PEAK HORIZONTAL ACCELERATION AND VELOCITY FROM STRONG-MOTION RECORDS INCLUDING RECORDS FROM THE 1979 IMPERIAL VALLEY, CALIFORNIA, EARTHQUAKE

by

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ABSTRACT

We have taken advantage of the recent increase in strong-motion data at close distances to derive new attenuation relations for peak horizontal acceleration and velocity. Acceleration data from 183 recordings of 24 earthquakes and velocity data from 62 recordings of 10 earthquakes have been used. This new analysis uses a magnitude-independent shape for the attenuation curve based on geometrical spreading and anelastic attenuation. A magnitude-dependent shape could be accommodated by the method, but the data do not support it. An innovation in technique is introduced that decouples the determination of the distance dependence of the data from the magnitude dependence. The resulting equations are

$$\log A = -1.23 + 0.280\mathbf{M} - \log r - 0.00255r + 0.27P$$

$$r = (d^2 + 7.3^2)^{1/2} \quad 5.0 \leq \mathbf{M} \leq 7.7$$

$$\log V = -1.30 + 0.581\mathbf{M} - \log r - 0.00256r + 0.17S + 0.35P$$

$$r = (d^2 + 4.0^2)^{1/2} \quad 5.3 \leq \mathbf{M} \leq 7.4$$

where A is peak horizontal acceleration in g, V is peak horizontal velocity in cm/sec, **M** is moment magnitude, d is the closest distance to the surface projection of the fault rupture in km, S takes on the value of zero at rock sites and one at soil sites, and P is zero for 50 percent exceedance probability and one for 84 percent.

INTRODUCTION

New data, particularly from the 1979 Coyote Lake and Imperial Valley earthquakes in California, provide a much improved basis for making ground-motion predictions at small distances from the source. In this report we update our earlier efforts (Page and others, 1972; Boore and others, 1978; 1980) and we introduce some improvements in statistical technique that should give better determination of the effects of both magnitude and distance on ground motion.

We examine here the dependence of peak horizontal acceleration and peak horizontal velocity on moment magnitude (**M**), distance, and recording-site geology. We do not intend to imply a preference for peak horizontal acceleration or velocity as parameters for describing earthquake ground motion; we are simply recognizing their widespread use. We do not include peak horizontal displacement at this stage pending completion of a study of record processing procedures.

This work differs in several important ways from our previous work. Improvements in statistical analysis techniques permit us to develop prediction equations with an explicit magnitude dependence. The newly available close-in data permit us to extend the prediction equations to zero distance. In doing this we have modified the measure of distance used in the previous work and adopted a different functional form for the prediction equation.

METHOD

We fit the strong motion data by multiple linear regression using the equation

$$\mathrm{Log}\ y = \sum_{i=1}^{N} a_i E_i - \log r - br + cS \qquad (1)$$

$$\begin{aligned} \text{where } E_i &= 1 \text{ for earthquake } i \\ &= 0 \text{ otherwise} \\ S &= 1 \text{ for soil sites} \\ &= 0 \text{ for rock sites} \\ r &= (d^2 + h^2)^{1/2} \end{aligned}$$

y is either peak horizontal acceleration or velocity, N is the number of earthquakes in the data sample, and d is the closest distance from the recording site to the surface projection of that portion of the fault rupture that lies above a depth of 15 km. Values for a_i, b, and c are determined by the linear regression for a chosen value of h and h is determined by a simple search procedure to minimize the sum of squares of the residuals. Once the a_i values are determined they are used to find, by least squares, a first- or second-order polynomial representing the magnitude dependence.

$$a_i = \alpha + \beta \mathbf{M}_i + \mathbf{M}_i^2 \qquad (2)$$

The use of binary variables such as E_i and S to divide the data into classes is a technique known to statisticians as blocking (Draper and Smith, 1966). Similar techniques have been used before for classifying strong-motion data according to site geology (for example, Trifunac, 1976; McGuire, 1978).

Extension of the technique by employing the variable E_i has the advantage that it decouples the determination of magnitude dependence from the determination of distance dependence. To see an example of this advantage note that the data from a single earthquake is typically recorded over a limited range of distance. If the regression analysis were done in terms of magnitude and distance simultaneously, errors in measuring magnitude would affect the distance coefficient obtained from the regression. Another advantage of the approach is that it causes each earthquake to have the same weight in determining magnitude dependence and each recording to have the same weight in determining distance dependence, which intuitively seems appropriate. The method can be considered the analytical equivalent of the graphical method employed by Richter (1935, 1958) in developing the attenuation curve that forms the basis for the local magnitude scale in southern California. The method described here might prove to be useful in the development of local magnitude scales.

The form chosen for the regression is the equivalent of

$$y = \frac{k}{r} e^{-qr}$$

where k is a function of $\mathbf{M}$ and q is a constant. This corresponds to simple point-source geometric spreading with constant-Q anelastic attenuation. Strictly speaking this form would apply only to a harmonic component of the ground motion, not to peak acceleration or peak velocity. Since the coefficients are determined empirically, however, we believe the application to peak parameters is an appropriate approximation.

We realize that the rupture surface is not a point source for recording sites close to the rupture in a large earthquake. The source of the peak motion, however, is not the whole rupture surface but rather some more restricted portion of it. Even if rupture were instantaneous over the whole surface, which would seem unlikely, the whole surface could not contribute to the motion at any one time because of finite propagation velocities.

The parameter *h* is introduced to allow for the fact that the source of the peak motion values may not be the closest point on the rupture. If the source of the peak motion were directly below the nearest point on the surface projection of the rupture, the value of *h* would simply represent the depth of that source. In reality the value obtained for *h* incorporates all the factors that tend to limit or reduce motion near the source, including any tendency for the peak horizontal acceleration to be limited by the finite strength of near-surface materials (Ambraseys, 1974). The value of *h* also incorporates any factors that tend to enhance the motion near the source, in particular, directivity (Boore and Joyner, 1978).

We use moment magnitude (Hanks and Kanamori, 1979) defined as

$$\mathbf{M} = 2/3 \log M_0 - 10.7$$

where M_0 is seismic moment in dyne cm. We prefer $\mathbf{M}$ to surface-wave magnitude or local magnitude because $\mathbf{M}$ corresponds to a well-defined physical property of the source. Furthermore the rate of occurrence of earthquakes with different $\mathbf{M}$ can be related directly to the slip rate on faults (Brune, 1968; Molnar, 1979; Anderson, 1979; Herd and others, 1981). It has been argued that local magnitude is preferable for use in predicting ground motion for engineering purposes because local magnitude is based on measurements at frequencies in the range of engineering significance. It is not clear that local magnitude is in fact a better predictor of ground motion in that frequency range, but, even if it were, the use of local magnitude for predicting ground motion in a future earthquake might merely have the effect of transferring the uncertainty from the step of predicting ground motion given the local magnitude to the step of predicting the local magnitude. (We have done an analysis predicting peak horizontal acceleration and velocity in terms of Richter local magnitude [Joyner and others, 1981] similar to the analysis presented here in terms of moment magnitude. The results are comparable.)

The closest distance to the surface projection of the fault rupture is taken as the horizontal component of the station distance rather than the epicentral distance or the distance to the surface projection of the center of the rupture, because the latter two alternatives are clearly inappropriate in such important cases as Parkfield 1966 or Imperial Valley 1979 where recording sites are located close to the rupture but far from both epicenter and rupture center. Ideally one would work with the distance to the point on the rupture that contributes the peak motion, but it would be difficult to determine the location of that point for past earthquakes and in the present state of knowledge impossible for future earthquakes. The use of our measure of distance in the development of prediction equations is the equivalent of considering the placement of strong-motion instruments and the placement of structures as analogous experiments from the statistical point of view.

In our earlier work (Page and others, 1972; Boore and others, 1978; 1980) we used the shortest distance to the rupture as the measure of distance whereas here we use the shortest distance to the surface projection of the rupture. The reason for the change is the introduction of the parameter $\underline{h}$, which makes allowance, among other things, for the fact that the source of the peak motion may lie at some depth below the surface. If we used the former measure of distance for $\underline{d}$ then we would be compensating twice for the effect of depth.

The procedure outlined here gives the same attenuation with distance for all magnitudes **M** greater than 5.0, which is the range considered, though the attenuation is different for peak acceleration than for peak velocity. We see no compelling reason a priori why this is not appropriate, and the data are consistent with it. If the data had required attenuation curves whose shape depended upon magnitude, the method could readily have been modified to provide them.

To estimate σ_y, the standard error of a prediction made using the procedures described here, we use the equation

$$\sigma_y = (\sigma_s{}^2 + \sigma_a{}^2)^{1/2}$$

where σ_s is the standard deviation of the residuals from the regression described by equation (1) and σ_a is the standard deviation of the residuals from the regression described by equation (2). This is based on two assumptions: first, that the error in determining the attenuation curve in equation (1) is negligible compared to the residual of an individual data point relative to that curve and second, that all the variability σ_a is due to the stochastic nature of the relationship between a_i and **M** and none is due to measuring error in a_i or $\mathbf{M}_i$ such as might be caused by inadequate sampling. We believe that the first assumption is probably true, and the second, though not strictly true, is close enough to give a satisfactory approximation to σ_y.

DATA

The data set for peak acceleration consists of 183 recordings from 24 earthquakes and for peak velocity 62 recordings from 10 earthquakes. The data sets are restricted to earthquakes in western North America with **M** greater than 5.0 and to shallow earthquakes, defined as those for which some portion of the fault rupture lies above a depth of 15 km. For peak values we use the larger of the two horizontal components in the directions as originally recorded.

Table 1 lists the earthquakes and gives the source of data used in assigning magnitudes and station distances. For earthquakes through 1975 the sources of strong motion data and geologic site data are given in a previous publication (Boore and others, 1978). Much of the acceleration data for these earthquakes was taken from Volume I of the series "Strong-Motion Earthquake Accelerograms" published under the direction of D. E. Hudson by the Earthquake Engineering Research Laboratory of the California Institute of Technology. Volume I of that series was used for acceleration instead of Volume II because the procedures used in producing Volume II tended to bias the peak acceleration toward lower values. For more recent earthquakes sources of strong-motion data include Porter (1978), Porcella (1979), Porcella and others (1979), Brady and others (1980), and Boore and Porcella (1981). In addition, unpublished data were made available by the California Division of Mines and Geology, by J. N. Brune for the stations of the cooperative program of the University of California at San Diego and the Universidad Nacional Autonoma de Mexico, and by Kinemetrics Inc. for the Shell Oil Company station at Munday Creek, Alaska. Acceleration values for the recent earthquakes were scaled from the original records where possible. Sources of site descriptions for records obtained since 1975 include the U.S. Geological Survey (1977) and Shannon and Wilson Inc. and Agbabian Associates (1978; 1980a; 1980b). In the case of two stations (290 Wrightwood, California, and 1096 Fort Tejon, California), site classifications made by Boore and others (1978) were changed on the basis of new information given by Shannon and Wilson Inc. and Agbabian

Associates (1978; 1980a; 1980b). The strong-motion data and site classifications are given in Table 2. For some of the recent earthquakes geologic data were not available for all sites. Since only acceleration data were available for those earthquakes and since earlier studies (Boore and others, 1980) had shown that peak acceleration is not correlated with geologic site conditions, we proceeded with the analysis without geologic site data for those earthquakes.

The **M** values (Table 1) are calculated from seismic moments if moment determinations are available. In cases where they are not available **M** is taken to be equal to M_L and the values are enclosed in parentheses in Table 1. The largest such value is 6.2 for the 1972 Managua, Nicaragua, earthquake. The value corresponds to an M_S of 6.2 (U.S. Dept. of Commerce, 1973) and an M_L of 6.2 calculated from the strong-motion record at the Esso Refinery (Jennings and Kanamori, 1979).

On the basis of evidence (Boore and others, 1980; Crouse, 1978) suggesting that large structures may bias the ground-motion data recorded at the base of the structure, we excluded from the data set records made at the base of buildings three or more stories in height and on the abutments of dams. We excluded all earthquakes for which the data were in our opinion inadequate for estimating the source distance to an accuracy better than 5 km.

Bias may be introduced into the analysis of strong-motion data by the fact that some operational instruments are not triggered. To avoid this bias we employed the following procedure: For each earthquake the distance to the nearest operational instrument that did not trigger was determined or in some cases estimated. All data from equal or greater distances for that earthquake were excluded. In contrast to our earlier work the cutoff distance was different for each earthquake. In a few cases records with peak accelerations less than 0.05 g had not been scaled. In those cases we noted the smallest distance for such a record and excluded all data recorded at equal or greater distances for that event. There exists a possibility of bias in analyzing peak velocity data because high-amplitude records may have been preferentially chosen for integration. To avoid this bias we noted the distance of the nearest record that had not been integrated, except records for which we knew definitely that the reason they were not integrated had nothing to do with amplitude. We then excluded all velocity data recorded at equal or greater distances for that event.

Recording sites were classified into two categories, rock and soil, using the best available information in the same way as done in earlier work (Boore and others, 1978; 1980). Sites described by such terms as "granite", "diorite", "gneiss", "chert", "graywacke", "limestone", "sandstone", or "siltstone" were assigned to the rock category, and sites described by such terms as "alluvium", "sand", "gravel", "clay", "silt", "mud", "fill", or "glacial outwash" were assigned to the soil category, except that if the description indicated soil material less than 4 to 5 m thick overlying rock, the site was classified as a rock site. Resonant frequencies of soil layers as thin as that would generally be greater than 10 Hz and thereby outside the range of frequencies making up the dominant part of the accelerogram.

RESULTS AND DISCUSSION

Residuals of peak acceleration data from the regression analysis of equation (1) are shown on Figure 1 plotted as departures from the center curve, which is the mean attenuation curve finally determined for a moment magnitude of 6.5. The flanking curves represent departures of plus and minus σ_s, the standard deviation of the residuals from the regression analysis of equation (1). Hexagons represent earthquakes with **M** between 5.0 and 5.9; x's represent earthquakes with **M** between 6.0 and 6.9; and squares represent earthquakes with **M** greater than or equal to 7.0. No obvious differences in trend are apparent among the three different magnitude classes.

The a_i values resulting from the regression analysis of peak acceleration data using equation (1) are plotted against **M** in Figure 2. In fitting a polynomial to the data points in Figure 2 the coefficient of the second degree term is found not to be statistically significant at the 90 percent level and the term is omitted. The two lowest points in Figure 2 are the two Santa Rosa earthquakes, each represented by a single record from the same site. These points are undoubtedly in error in the sense that the records in the data set are not representative of the earthquakes, and they are excluded from the determination of the straight line in Figure 2. In both earthquakes instruments at eight sites recorded higher peak horizontal acceleration than the record included in the data set even though they were at greater distances (Boore and others, 1978). (These other records were excluded because their distances exceed the distance of the closest operational instrument that did not trigger.) The effect on the final prediction equations of excluding the Santa Rosa data points is small, ranging from 29 percent at **M** = 5.0 down to 3 percent at **M** = 7.7. We excluded them in an effort to obtain the best possible estimates of the parameters of the prediction equation.

Combining the results of the analyses using equations (1) and (2) we obtain the following prediction equation for peak horizontal acceleration:

$$\log A = -1.23 + 0.280\,\mathbf{M} - \log r - 0.00255r + 0.27P$$

$$r = (d^2 + 7.3^2)^{1/2} \qquad 5.0 \leq \mathbf{M} \leq 7.7 \tag{3}$$

where d is defined as in equation (1) and P equals zero for 50 percent probability that the prediction will exceed the real value and one for 84 percent probability. The value of P is based on the assumption that the prediction errors are normally distributed, and one could obtain the values of P for other exceedance probabilities from a table of the normal distribution function. Because of the limited number of data points, however, the assumption of normality cannot be tested for large exceedance probabilities, and values of P greater than one should be used with caution. For a few of the recent earthquakes geologic site data are not available at all sites (Table 2). A preliminary analysis using only the earthquakes for which site data are available indicated that the soil term is not statistically significant for peak acceleration--a conclusion reached in earlier work (Trifunac, 1976; Boore and others, 1980)--and it is therefore not included. Equation (3) is illustrated in Figure 3 for 50 percent and 84 percent exceedance probability.

Residuals of peak velocity data from the regression analysis of equation (1) are plotted in Figure 4 as departures from the attenuation curve finally determined for $\mathbf{M} = 6.5$ at soil sites with symbols defined the same as for Figure 1. The a_i values are plotted against $\mathbf{M}$ in Figure 5. As with the acceleration data the coefficient of the second degree term in the polynomial is not significant at the 90 percent level and the term is omitted. The prediction equation for peak velocity is

$$\log V = -1.30 + 0.581\,\mathbf{M} - \log r - 0.00256r + 0.17S + 0.35P$$

$$r = (d^2 + 4.0^2)^{1/2} \quad 5.3 \leq \mathbf{M} \leq 7.4 \qquad (4)$$

where d and S are as defined in equation (1) and P as defined in equation (3). Equation (4) is illustrated in Figure 6.

The soil term in equation (4) is statistically significant at the 98 percent level in contrast with the case of peak acceleration where it is not significant. Similar results have been reported by Duke and others (1972), Trifunac (1976), and Boore and others (1978, 1980). It seems likely that some sort of amplification mechanisms are operating on the longer periods that are dominant on velocity records and that for the shorter periods dominant on the acceleration records these mechanisms are counterbalanced by anelastic attenuation. It is important to note that the determination of the soil effect is dominated by data from southern California where the thickness of low-Q material near the surface is typically large. Net amplification of peak acceleration at soil sites may occur for some other distributions of Q.

Figures 1 and 4 do not show any indication that the data support a magnitude-dependent shape for the attenuation curves.

The prediction equations are presented in terms of moment magnitude for convenience and for ease of comparison with other studies. Seismic moment, however, is the fundamental parameter, and we believe it desirable to repeat the prediction equations, expressed directly in terms of moment.

$$\log A = -4.23 + 0.187 \log M_0 - \log r - 0.00255r + 0.27P$$

$$r = (d^2 + 7.3^2)^{1/2} \qquad 23.5 \leq \log M_0 \leq 27.6$$

$$\log V = -7.52 + 0.387 \log M_0 - \log r - 0.00256r + 0.17S + 0.35P$$

$$r = (d^2 + 4.0^2)^{1/2} \quad 24.0 \leq \log M_0 \leq 27.2$$

The prediction equations (3) and (4) are constrained by data at soil sites over the whole distance range of interest for $\mathbf{M}$ less than or equal to 6.5, the value for the Imperial Valley earthquake. The data set contains no recordings at rock sites with d less than 8 km for earthquakes with $\mathbf{M}$ greater than 6.0, and caution is indicated in applying the equations to rock sites at shorter distances for earthquakes of larger magnitudes. Some indication of the applicability of the equations can be obtained by comparing the predicted and observed values, given in Table 3, for the Pacoima Dam record of the San Fernando earthquake (d = 0.0 km, $\mathbf{M} = 6.6$). The Pacoima Dam site is a rock site, but the record was excluded from the data set used in the regression analysis because it was recorded on a dam abutment. The observed values are higher than the predicted values for both acceleration and velocity, but the difference is less than the standard error of prediction (σy) for velocity and also for acceleration if the observed acceleration is corrected for topographic amplification (Boore, 1973).

For distances less than 40 km from earthquakes with $\mathbf{M}$ greater than 6.6 the prediction equations are not constrained by data and the results should be treated with caution. Use of the prediction equation for distances less than 40 km and magnitudes in the range 6.6-7.7 requires the assumption that the attenuation curves at higher $\mathbf{M}$ values have the same shape as at $\mathbf{M} = 6.6$. Except for possible limitations in peak acceleration caused by limited strength in the near surface materials, we believe this to be a reasonable assumption. One would expect the shape of the attenuation curve to depend upon the depth of the source and its extent in depth. For a region of shallow earthquakes, at least, the extrapolation beyond a $\mathbf{M}$ of 6.6 should be valid because at that value the rupture breaks through the entire depth of the seismogenic zone and the depth extent will not change for higher magnitudes.

The prediction equations predict peak velocities greater than 200 cm/sec for **M** greater than or equal to 7.0 at close distances. No values that high have ever been observed but we know of no physical reason why they could not occur. At soil sites in an earthquake of **M** greater than 6.5, the finite strength of the soil might limit the peak acceleration to values smaller than those given by the prediction equations, but determining what that limit would be would require adequate _in situ_ determination of the dynamic soil properties.

On the basis of fewer available data, Trifunac (1976) made estimates comparable to ours for the peak velocity at small distances from earthquakes of magnitude 7.0 and above. Kanamori (1978) gave an estimate of 200 cm/sec for the peak velocity at 10 km from an earthquake like Kern County ($\mathbf{M} = 7.4$), a value quite close to ours (Figure 6). Both Trifunac (1976) and Kanamori (1978) employed the attenuation curve used for local magnitude determinations in southern California. That curve is only weakly constrained by data at short distances. Recent data, especially from the 1979 Imperial Valley earthquake, enable us to develop more closely constrained curves for both acceleration and velocity.

The attenuation relationships developed by Campbell (1980; Campbell and others, 1980) for peak horizontal acceleration are compared in Figure 7 with our results. He selected magnitudes to be consistent with a moment-magnitude scale, essentially M_L for $M \leq 6$ and M_s for $M > 6$. His measure of distance was "the shortest distance from the site to the rupture zone", whereas our measure is the shortest distance to the surface projection of the rupture. This will make no difference for the large magnitude events, which typically break the surface, but the difference may be significant for the smaller events in which the rupture zone may be at significant depth below the surface. He included only data with distances less than 50 km, which severely limits the number of data points included from higher magnitude events.

The most conspicuous differences on Figure 7 are at distances less than 3 km. The differences shown are small compared to the statistical prediction uncertainty except for **M** = 5.5 at distances less than 1 km. In that case the difference may be due at least in part to the different definition of distance. His curves show a substantial change of shape with magnitude. We see no evidence of such a phenomenon in our Figure 1, and again the explanation may be the different definition of distance. He states that the coefficient of the term in his equation that gives the magnitude-dependent shape is not significant at better than the 75 percent level. He includes it for theoretical reasons--reasons that may not apply if our definition of distance is used.

It is of some interest to consider the physical interpretation of the parameters in the attenuation relationship. If the values agree with what we would expect from other considerations, we gain more confidence that the model, though oversimplified, is appropriate. The value determined for the attenuation coefficient in the relationship for peak acceleration corresponds to a Q of 700 for an assumed frequency of 4 Hz and 350 for a frequency of 2 Hz. The latter value is probably the more appropriate one to consider because the distant records with frequencies closer to 2 Hz than 4 Hz dominate in the determination of the attenuation coefficient. The value of the attenuation coefficient in the relationship for peak velocity corresponds to a Q of 180 for an assumed frequency of 1 Hz. These Q values lie in the range generally considered appropriate on the basis of other data and increase our confidence in the model. The smaller value for velocity than for acceleration is consistent with the frequency dependence of Q described by Aki (1980), but in view of the oversimplified character of the model we do not propose this as evidence for a frequency-dependent Q.

The values of 7.3 and 4.0 km for h in the relationships for peak acceleration and peak velocity seem reasonable in the sense that they lie in the range of one quarter to one half of the thickness of the seismogenic zone in California, where most of the data were recorded. Why the value is less for velocity than for acceleration is not clear. It might be argued that the larger value of h for peak acceleration represents a limitation in acceleration near the source by the limited strength of the near-surface materials. If that were the case, however, one would expect the attenuation curve for earthquakes of magnitude less than 6 to differ in shape from that of earthquakes greater than 6. Figure 1 shows no such indication. Another possibility relates to directivity. The effect of directivity would be to increase the peak velocity preferentially at sites near the fault. This effect would be reflected in a smaller value for h. Directivity would be expected to have a similar effect on peak acceleration (Boore and Joyner, 1978; Boore and Porcella, 1980), but one might speculate that local variations in the direction of rupture propagation or scattering and lateral refraction might in some way reduce the effect of directivity upon the higher frequency waves dominant in the acceleration record.

The magnitude coefficient in the relationship for peak acceleration is 0.28 and has a standard error of 0.04. It thus lies within one standard error of the value 0.30, which corresponds to the scaling of peak acceleration as $M_0^{1/5}$ derived theoretically by Hanks and McGuire (1981) by treating the acceleration record as a stochastic process. The magnitude coefficient for peak velocity is 0.58 with a standard error of 0.14. It lies within one standard error of the value 0.5, which corresponds to the scaling of peak velocity as $M_0^{1/3}$, appropriate for a deterministic rupture propagating outward from a point (Boatwright, 1980; oral communication, 1981). It seems quite reasonable that the acceleration should look like a stochastic process and the velocity like a deterministic process.

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Table 1. Sources of data used in assigning magnitudes and station distances

			Date (GMT)			
Earthquake	**M**	M_L	Month	Day	Year	Sources
Imperial Valley, California	7.0	6.4	5	19	40	Trifunac and Brune (1970); Trifunac (1972); Richter (1958); Hanks and others (1975).
Kern County, California	7.4	7.2	7	21	52	Richter (1958); Page, and others (1972); Bolt (1978); Dunbar and others (1980); Hanks and others (1975); Boore and Kanamori (unpublished).
Daly City, California	(5.3)	5.3	3	22	57	Tocher (1959); Cloud (1959).
Parkfield, California	6.1	5.5	6	28	66	McEvilly and others (1967); Lindh and Boore (1981); Trifunac and Udwadia (1974); Tsai and Aki (1969).
Fairbanks, Alaska	(5.6)	5.6	6	21	67	Gedney and Berg (1969).
Borrego Mountain, California	6.6	6.7	4	9	68	Kanamori and Jennings (1978); Hamilton (1972); Hanks and Wyss (1972); Swanger and Boore (1978); Hanks and others (1975).
Santa Rosa, California (2 events)	(5.6) (5.7)	5.6 5.7	10	2	69	Bolt and Miller (1975); Unger and Eaton (1970); J. D. Unger and J. P. Eaton (written commun., 1976).
Lytle Creek, California	5.3	5.4	9	12	70	T. C. Hanks (written commun., 1971); Hanks and others (1975).
San Fernando, California	6.6	6.4	2	9	71	Allen and others (1973); Heaton and Helmberger (1979).

Table 1. Continued

Earthquake	**M**	M_L	Date (GMT) Month	Day	Year	Sources
Bear Valley, California	5.3	5.1	2	24	72	Bolt and Miller (1975); Ellsworth (1975); Johnson and McEvilly (1974).
Sitka, Alaska	7.7		7	30	72	Page and Gawthrop (1973); Page (oral commun., 1976); Purcaru and Berckhemer (1978).
Managua, Nicaragua	(6.2)	6.2	12	23	72	Jennings and Kanamori (1979); Plafker and Brown (1973); Ward and others (1973); Knudson and Hansen A. (1973); U.S. Dept. of Commerce (1973).
Point Mugu, California	5.6	6.0	2	21	73	Ellsworth and others (1973); Boore and Stierman (1976); Stierman and Ellsworth (1976).
Hollister, California	(5.2)	5.2	11	28	74	Cloud and Stifler (1976); W.H.K. Lee (written commun., 1976).
Oroville, California	6.0	5.7	8	1	75	Fogleman and others (1977); Bufe and others (1976); Lahr and others (1976); Langston and Butler (1976); Hart and others (1977).
Santa Barbara, California	5.1	5.1	8	13	78	Wallace and Helmberger (1979); Lee and others (1978).
St. Elias, Alaska	7.6		2	28	79	Hasegawa and others (1980); C. D. Stephens (written commun., 1979); J. Boatwright (oral commun., 1979).

Table 1. Continued

			Date (GMT)			
Earthquake	**M**	M_L	Month	Day	Year	Sources
Coyote Lake, California	5.8	5.9	8	6	79	Uhrhammer (1980); Lee and others (1979).
Imperial Valley, California	6.5	6.6	10	15	79	Kanamori (oral commun., 1981); C. E. Johnson (oral commun., 1979); Boore and Porcella (1981).
Imperial Valley, California aftershock	(5.0)	5.0	10	15	79	C. E. Johnson (oral commun., 1979).
Livermore Valley, California	5.8	5.5	1	24	80	Bolt and others (1981); R. A. Uhrhammer (oral commun., 1981); J. Boatwright (oral commun., 1980).
Livermore Valley, California	5.5	5.6	1	27	80	Bolt and others (1981); R. A. Uhrhammer (oral commun., 1981); J. Boatwright (oral commun., 1980); Cockerham and others (1980).
Horse Canyon, California	(5.3)	5.3	2	25	80	L. K. Hutton (written commun., 1980).

Table 2. Strong-Motion Data

Earthquake	Station[1]	Distance km	Peak Horizontal Acceleration g	Peak Horizontal Velocity cm/sec	Site Condition
Imperial Valley 1940	117	12.0	0.359	36.9	soil
Kern County 1952	1083	148.0	0.014		rock
	1095	42.0	0.196	17.7	soil
	283	85.0	0.135	19.3	soil
	135	107.0	0.062	8.9	soil
	475	109.0	0.054	9.1	soil
	113	156.0	0.014		soil
	1008	224.0	0.018		soil
	1028	293.0	0.010		soil
	2001	359.0	0.004		soil
	117	370.0	0.004		soil
Daly City 1957	1117	8.0	0.127	4.9	rock
Parkfield 1966	1438	16.1	0.411	22.5	rock
	1083	63.6	0.018	1.1	rock
	1013	6.6	0.509	78.1	soil
	1014	9.3	0.467	25.4	soil
	1015	13.0	0.279	11.8	soil
	1016	17.3	0.072	8.0	soil
	1095	105.0	0.012	2.2	soil
	1011	112.0	0.006		soil
	1028	123.0	0.003		soil
Fairbanks 1967	2707	14.0	0.060		rock
Borrego Mountain 1968	270	105.0	0.018		rock
	280	122.0	0.048		rock
	116	141.0	0.011		rock
	266	200.0	0.007		rock
	117	45.0	0.142	25.8	soil
	113	130.0	0.031		soil
	112	147.0	0.006		soil

Table 2. (continued)

Earthquake	Station[1]	Distance km	Peak Horizontal Acceleration g	Peak Horizontal Velocity cm/sec	Site Condition
Borrego Mountain 1968 (continued)	130	187.0	0.010		soil
	475	197.0	0.010		soil
	269	203.0	0.006		soil
	135	211.0	0.013		soil
Santa Rosa 1969 first event	1093	62.0	0.005		soil
Santa Rosa 1969 second event	1093	62.0	0.003		soil
Lytle Creek 1970	111	19.0	0.086	5.6	rock
	116	21.0	0.179		rock
	290	13.0	0.205	9.6	soil
	112	22.0	0.073		soil
	113	29.0	0.045		soil
San Fernando 1971	128	17.0	0.374	14.6	rock
	126	19.6	0.200	8.6	rock
	127	20.2	0.147	4.8	rock
	141	21.1	0.188	20.5	rock
	266	21.9	0.204	11.6	rock
	110	24.2	0.335	27.8	rock
	1027	66.0	0.057	2.8	rock
	111	87.0	0.021		rock
	125	23.4	0.152	18.0	soil
	135	24.6	0.217	21.1	soil
	475	25.7	0.114	14.3	soil
	262	28.6	0.150	14.2	soil
	269	37.4	0.148	5.4	soil
	1052	46.7	0.112	8.5	soil
	411	56.9	0.043	5.0	soil
	290	60.7	0.057	3.8	soil
	130	61.4	0.030	10.4	soil

Table 2. (continued)

Earthquake	Station[1]	Distance km	Peak Horizontal Acceleration g	Peak Horizontal Velocity cm/sec	Site Condition
San Fernando 1971 (continued)	272	62.0	0.027	7.3	soil
	1096	64.0	0.028	1.4	soil
	1102	82.0	0.034	2.5	soil
	112	88.0	0.030		soil
	113	91.0	0.039		soil
Bear Valley 1972	1028	31.0	0.030		soil
Sitka 1972	2714	45.0	0.110		rock
	2708	145.0	0.010		rock
	2715	300.0	0.010		soil
Managua 1972	3501	5.0	0.390		soil
Point Mugu 1973	655	50.0	0.031		rock
	272	16.0	0.130		soil
Hollister 1974	1032	17.0	0.011		rock
	1377	8.0	0.120		soil
	1028	10.0	0.170		soil
	1250	10.0	0.140		soil
Oroville 1975	1051	8.0	0.110	5.0	rock
	1293	32.0	0.040		rock
	1291	30.0	0.070		soil
	1292	31.0	0.080		soil
Santa Barbara 1978	283	2.9	0.210		
	885	3.2	0.390		
	Goleta substation[2]	7.6	0.280		
St. Elias 1979	2734	25.4	0.160		
	Munday Creek[3]	32.9	0.064		
	2728	92.2	0.090		

Table 2. (continued)

Earthquake	Station[1]	Distance km	Peak Horizontal Acceleration g	Peak Horizontal Velocity cm/sec	Site Condition
Coyote Lake 1979	1413	1.2	0.420	43.8	rock
	1445	1.6	0.230	20.5	rock
	1408	9.1	0.130	10.3	rock
	1411	3.7	0.260	32.2	soil
	1410	5.3	0.270	29.4	soil
	1409	7.4	0.260	31.9	soil
	1377	17.9	0.110		soil
	1492	19.2	0.120		soil
	1251	23.4	0.038		soil
	1422	30.0	0.044		soil
	1376	38.9	0.046		soil
Imperial Valley 1979	Cerro Prieto[4]	23.5	0.170		rock
	286	26.0	0.210	9.0	rock
	Meloland Overpass[5]	0.5	0.320		soil
	5028	0.6	0.520	110.0	soil
	942	1.3	0.720	110.0	soil
	Aeropuerto[4]	1.4	0.320		soil
	5054	2.6	0.810	44.0	soil
	958	3.8	0.640	53.0	soil
	952	4.0	0.560	87.0	soil
	5165	5.1	0.510	68.0	soil
	117	6.2	0.400		soil
	955	6.8	0.610	78.0	soil
	5055	7.5	0.260	48.0	soil
	Imperial Co. Center[5]	7.6	0.240		soil
	Mexicali SAHOP[4]	8.4	0.460		soil
	5060	8.5	0.220	37.0	soil
	412	8.5	0.230	44.0	soil
	5053	10.6	0.280	19.0	soil
	5058	12.6	0.380	39.0	soil
	5057	12.7	0.270	46.0	soil
	Cucapah[4]	12.9	0.310		soil
	5051	14.0	0.200	17.0	soil

Table 2. (continued)

Earthquake	Station[1]	Distance km	Peak Horizontal Acceleration g	Peak Horizontal Velocity cm/sec	Site Condition
Imperial Valley 1979 (continued)	Westmoreland[5]	15.0	0.110		soil
	5115	16.0	0.430	31.0	soil
	Chihuahua[4]	17.7	0.270		soil
	931	18.0	0.150	19.0	soil
	5056	22.0	0.150	15.0	soil
	5059	22.0	0.150	15.0	soil
	5061	23.0	0.130	15.0	soil
	Compuertas[4]	23.2	0.190		soil
	5062	29.0	0.130		soil
	5052	32.0	0.066		soil
	Delta[4]	32.7	0.350		soil
	724	36.0	0.100		soil
	Victoria[4]	43.5	0.160		soil
	5066	49.0	0.140		soil
	5050	60.0	0.049		soil
	2316	64.0	0.034		soil
Imperial Valley 1979 aftershock	5055	7.5	0.264		
	942	8.8	0.263		
	5028	8.9	0.230		
	5165	9.4	0.147		
	952	9.7	0.286		
	958	9.7	0.157		
	955	10.5	0.237		
	117	10.5	0.133		
	412	12.0	0.055		
	5053	12.2	0.097		
	5054	12.8	0.129		
	5058	14.6	0.192		
	5057	14.9	0.147		
	5115	17.6	0.154		
	5056	23.9	0.060		
	5060	25.0	0.057		

Table 2. (continued)

Earthquake	Station[1]	Distance km	Peak Horizontal Acceleration g	Peak Horizontal Velocity cm/sec	Site Condition
Livermore Valley 1980 January 24	1030	10.8	0.120		
	1418	15.7	0.154		
	1383	16.7	0.052		
	1308	20.8	0.045		
	1298	28.5	0.086		
	1299	33.1	0.056		
	1219	40.3	0.065		
Livermore Valley 1980 January 27	Fagundes Ranch[5]	4.0	0.259		
	Morgan Terrace Park[5]	10.1	0.267		
	1030	11.1	0.071		
	1418	17.7	0.275		
	1383	22.5	0.058		
	Antioch Contra Loma[5]	26.5	0.026		
	1299	29.0	0.039		
	1308	30.9	0.112		
	1219	37.8	0.065		
	1456	48.3	0.026		
Horse Canyon 1980	5045	5.8	0.123		
	5044	12.0	0.133		
	5160	12.1	0.073		
	5043	20.5	0.097		
	5047	20.5	0.096		
	C168	25.3	0.230		
	5068	35.9	0.082		
	C118	36.1	0.110		
	5042	36.3	0.110		
	5067	38.5	0.094		
	5049	41.4	0.040		
	C204	43.6	0.050		
	5070	44.4	0.022		
	C266	46.1	0.070		

Table 2. (continued)

Earthquake	Station[1]	Distance km	Peak Horizontal Acceleration g	Peak Horizontal Velocity cm/sec	Site Condition
Horse Canyon 1980 (continued)	C203	47.1	0.080		
	5069	47.7	0.033		
	5073	49.2	0.017		
	5072	53.1	0.022		

[1] Station numbers preceded by the letter C are those assigned by the California Division of Mines and Geology. Other numbers are those assigned by the U.S. Geological Survey (1977; the stations not necessarily being U.S.G.S. stations).

[2] Station operated by the Southern California Edison Company.

[3] Station operated by the Shell Oil Company.

[4] Station operated by the Universidad Nacional Autonoma de Mexico and the University of California at San Diego.

[5] Station operated by the California Division of Mines and Geology.

Table 3. Comparison of Observed and Predicted Values of Peak Horizontal Acceleration and Velocity at the Pacoima Dam Abutment in the 1971 San Fernando Earthquake ($d = 0.0$ km, $\mathbf{M} = 6.6$)

	Observed	Predicted
Peak horizontal acceleration	1.25 g	0.54 g
Peak horizontal acceleration corrected for the effect of topography (Boore, 1973)	0.73 g	
Peak horizontal velocity	113 cm/sec	84 cm/sec

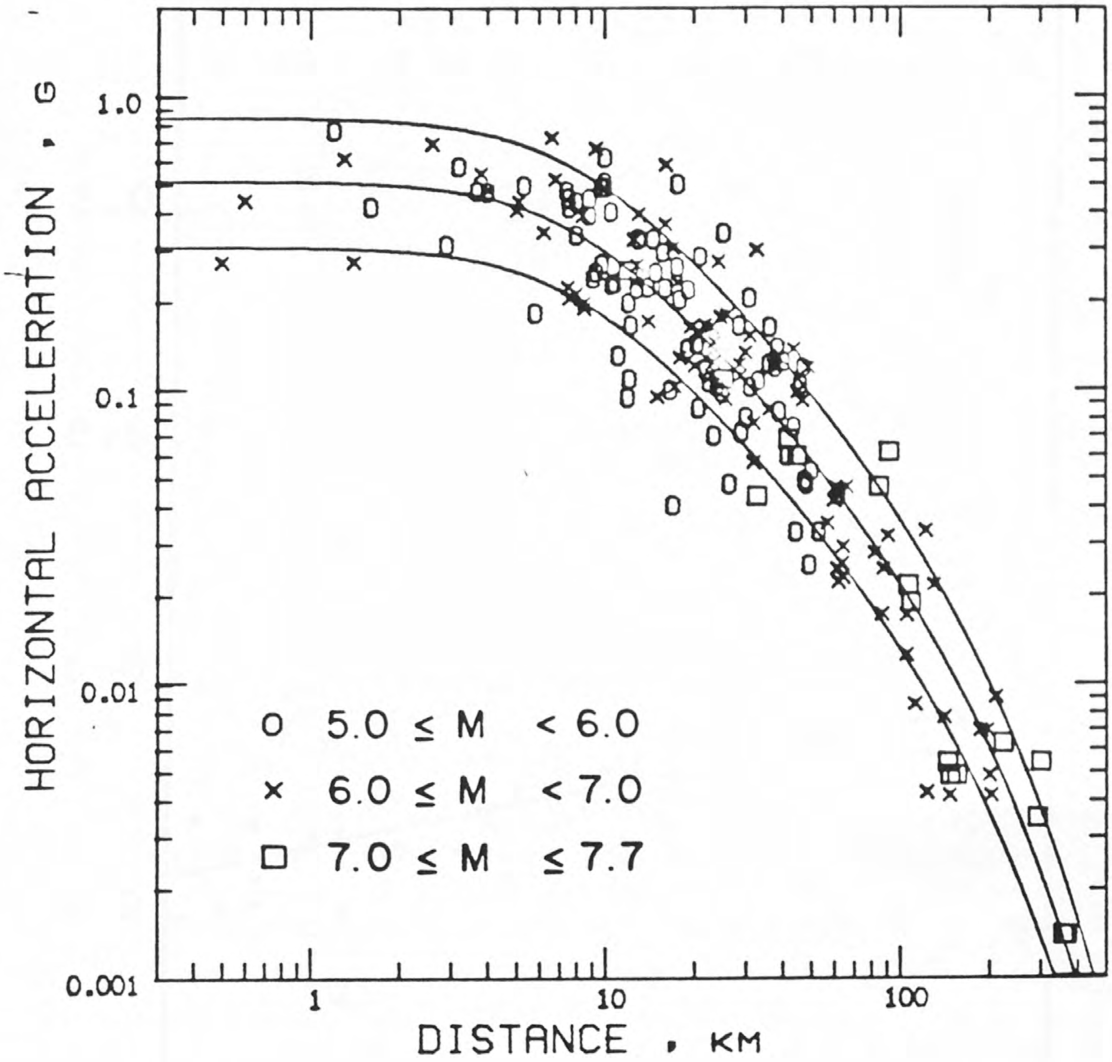

Figure 1. Residuals of peak horizontal acceleration data from the regression analysis of equation (1), plotted as departures from the center curve, which is the mean attenuation curve finally determined for a moment magnitude of 6.5. The flanking curves represent departures of plus and minus σ_s.

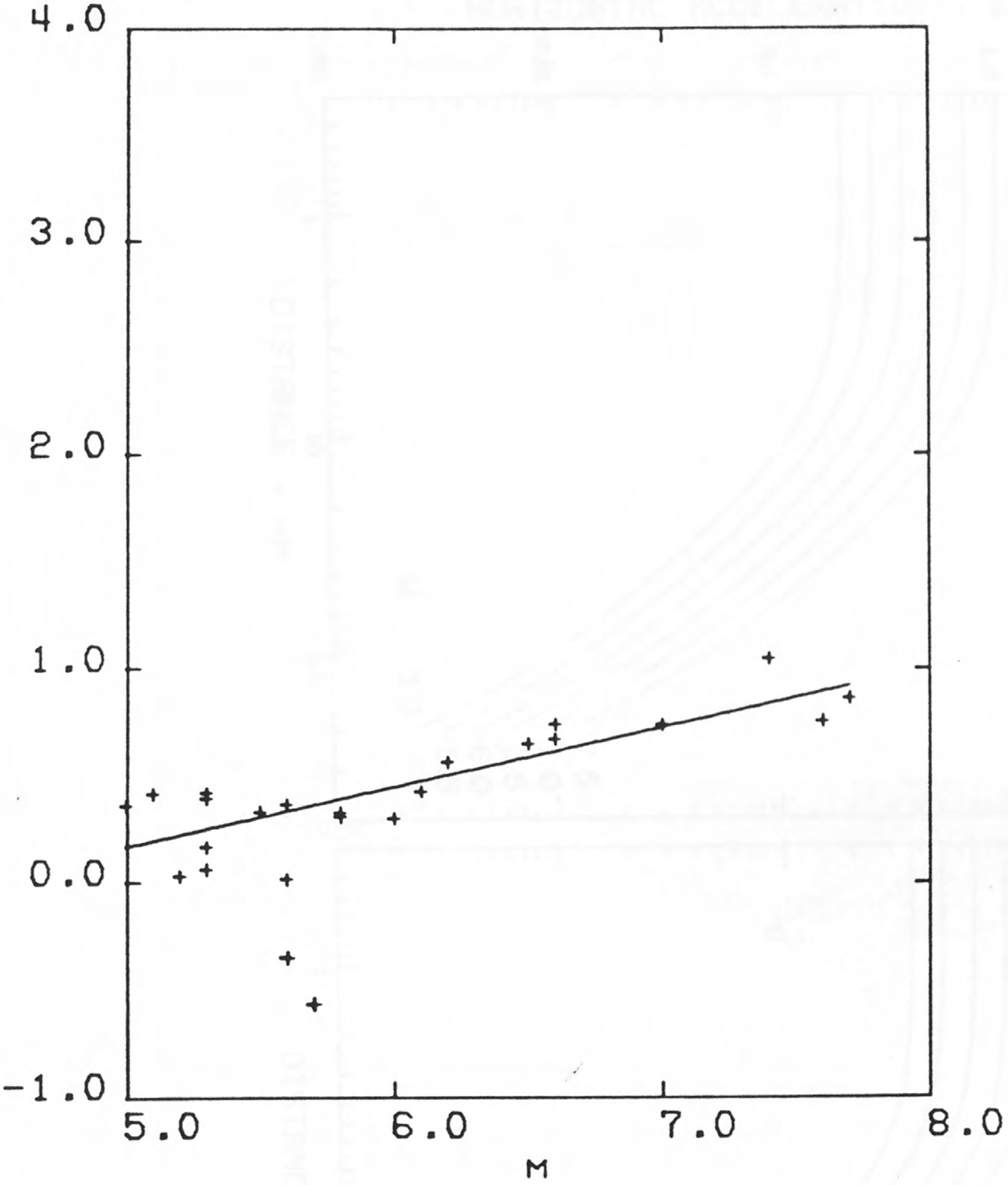

Figure 2. Values of $\underline{a}_i$ for peak horizontal acceleration from the regression analysis of equation (1) plotted against moment magnitude.

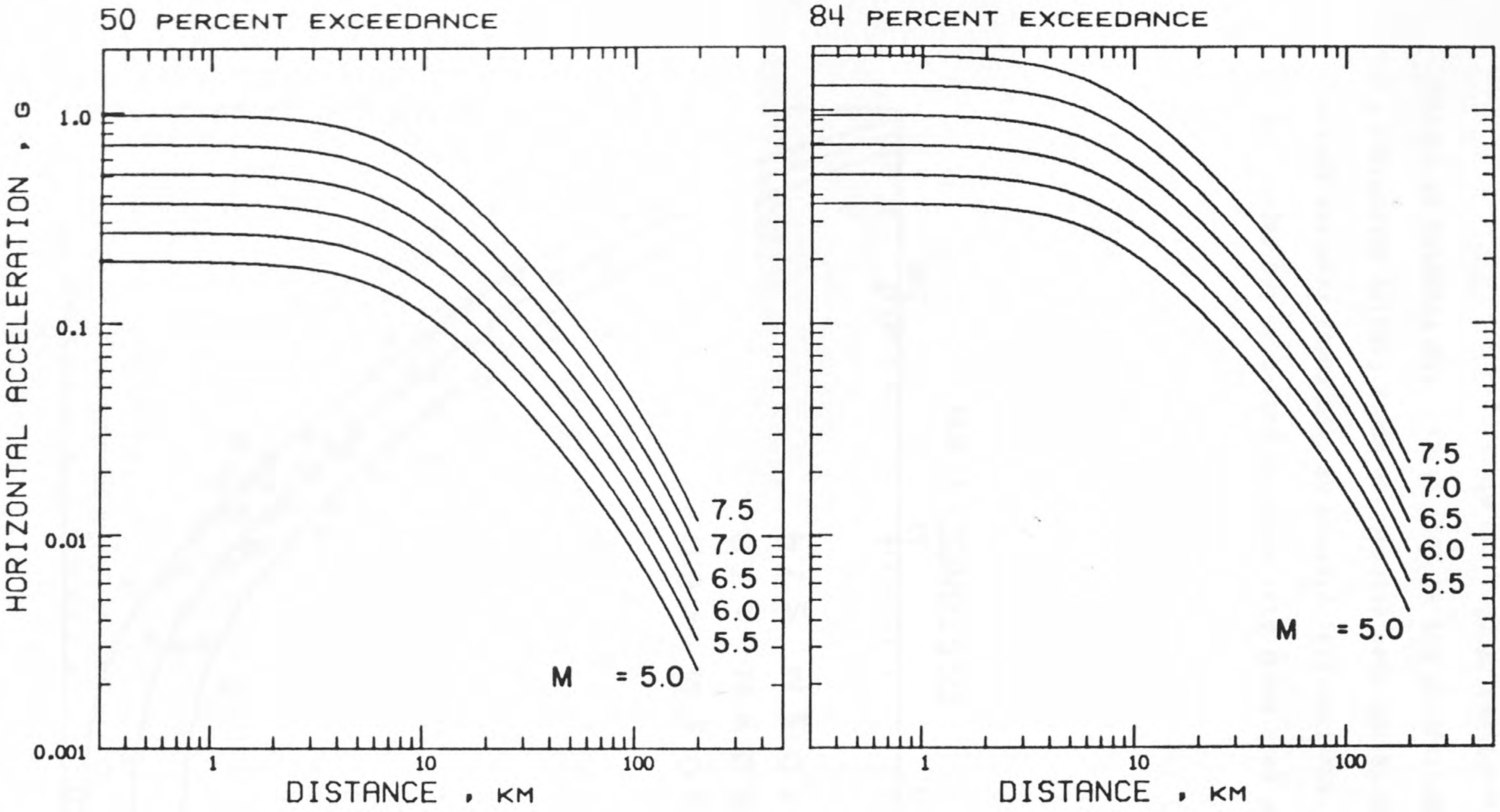

Figure 3. Predicted values of peak horizontal acceleration for 50 and 84 percent exceedance probability as functions of distance and moment magnitude.

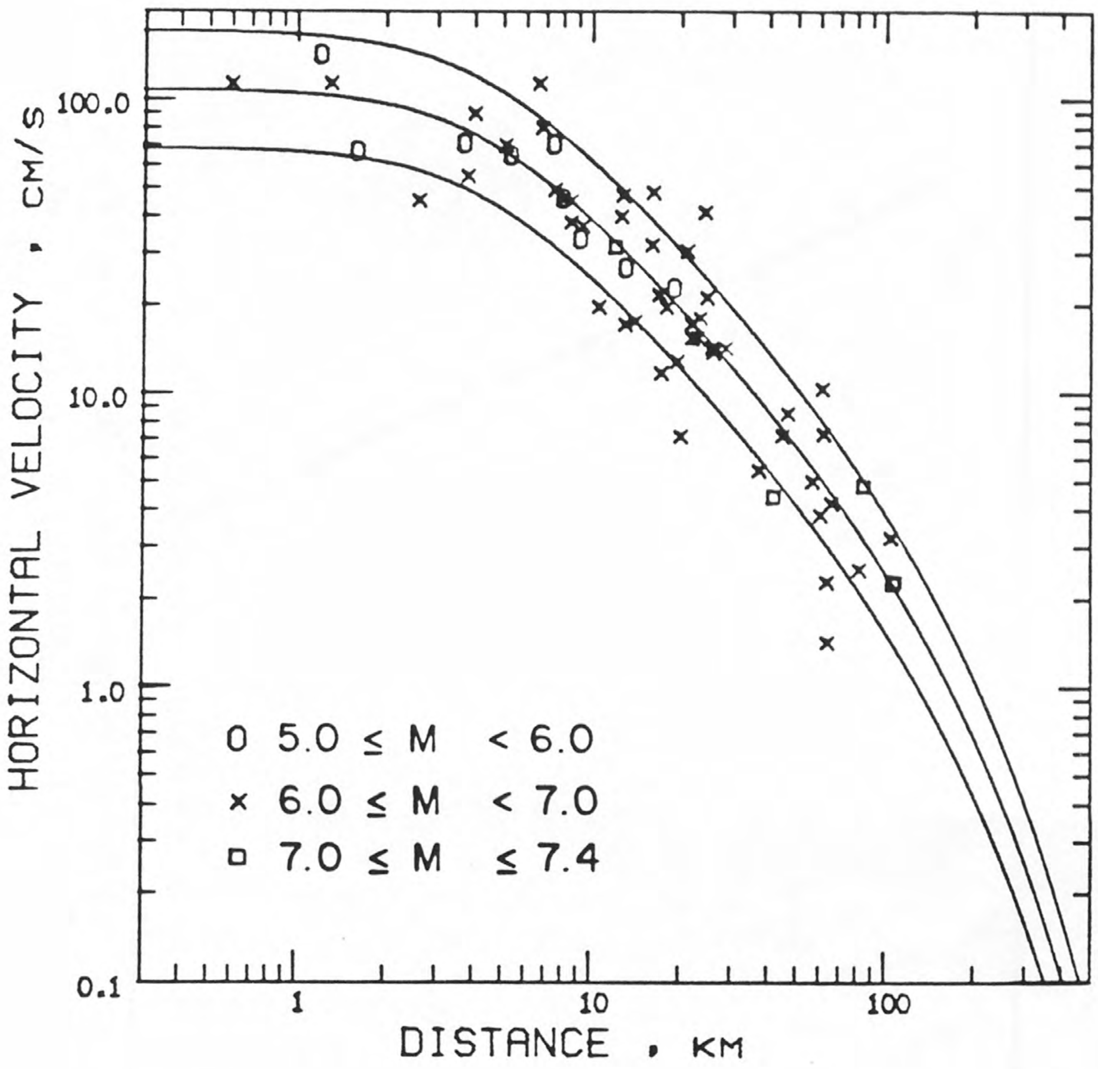

Figure 4. Residuals of peak horizontal velocity data from the regression analysis of equation (1), plotted as departures from the center curve, which is the mean attenuation curve finally determined for a moment magnitude of 6.5 at soil sties. The flanking of curves represent departures of plus and minus σ_s.

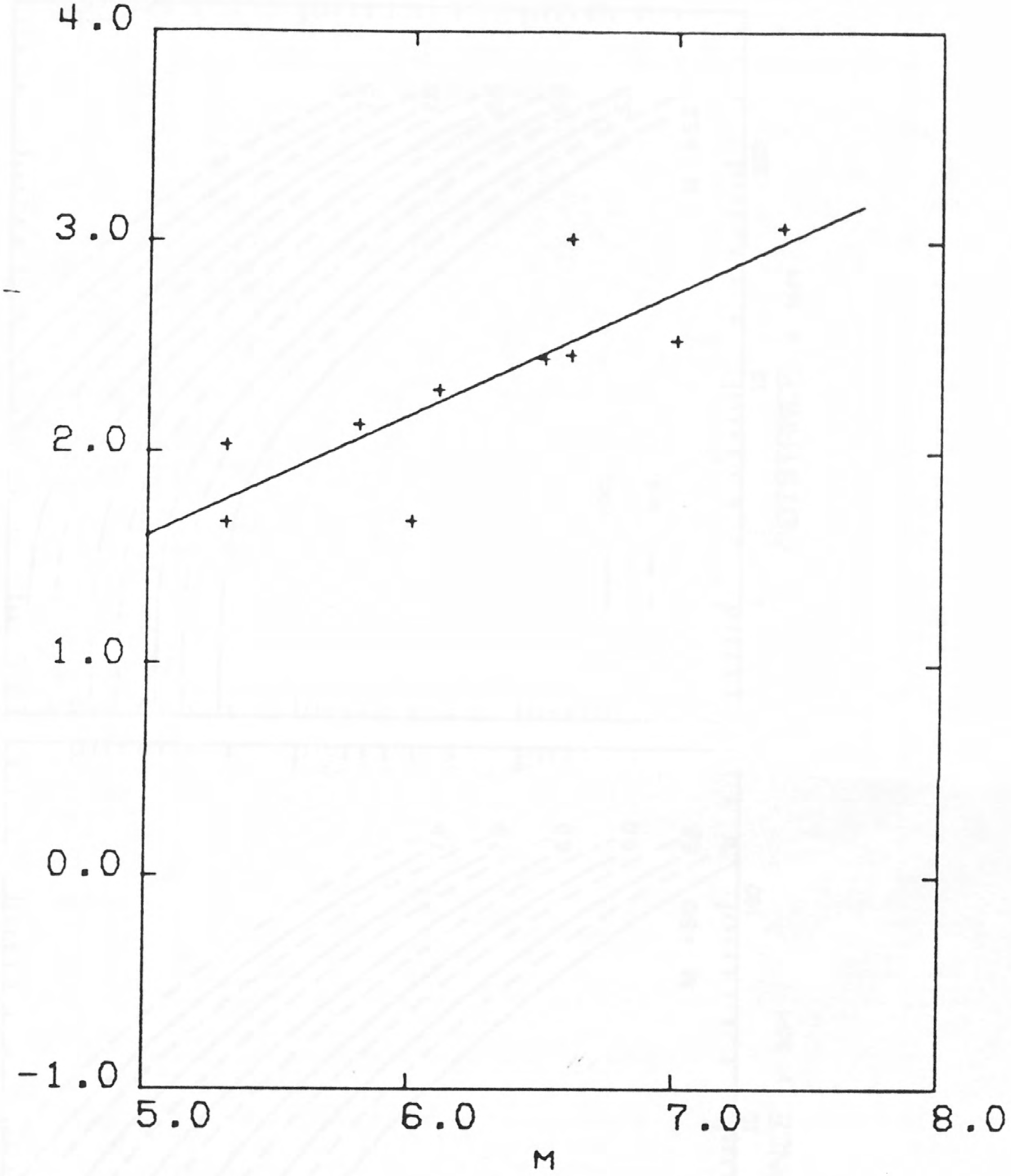

Figure 5. Values of $\underline{a}_i$ for peak horizontal velocity from the regression analysis of equation (1) plotted against moment magnitude.

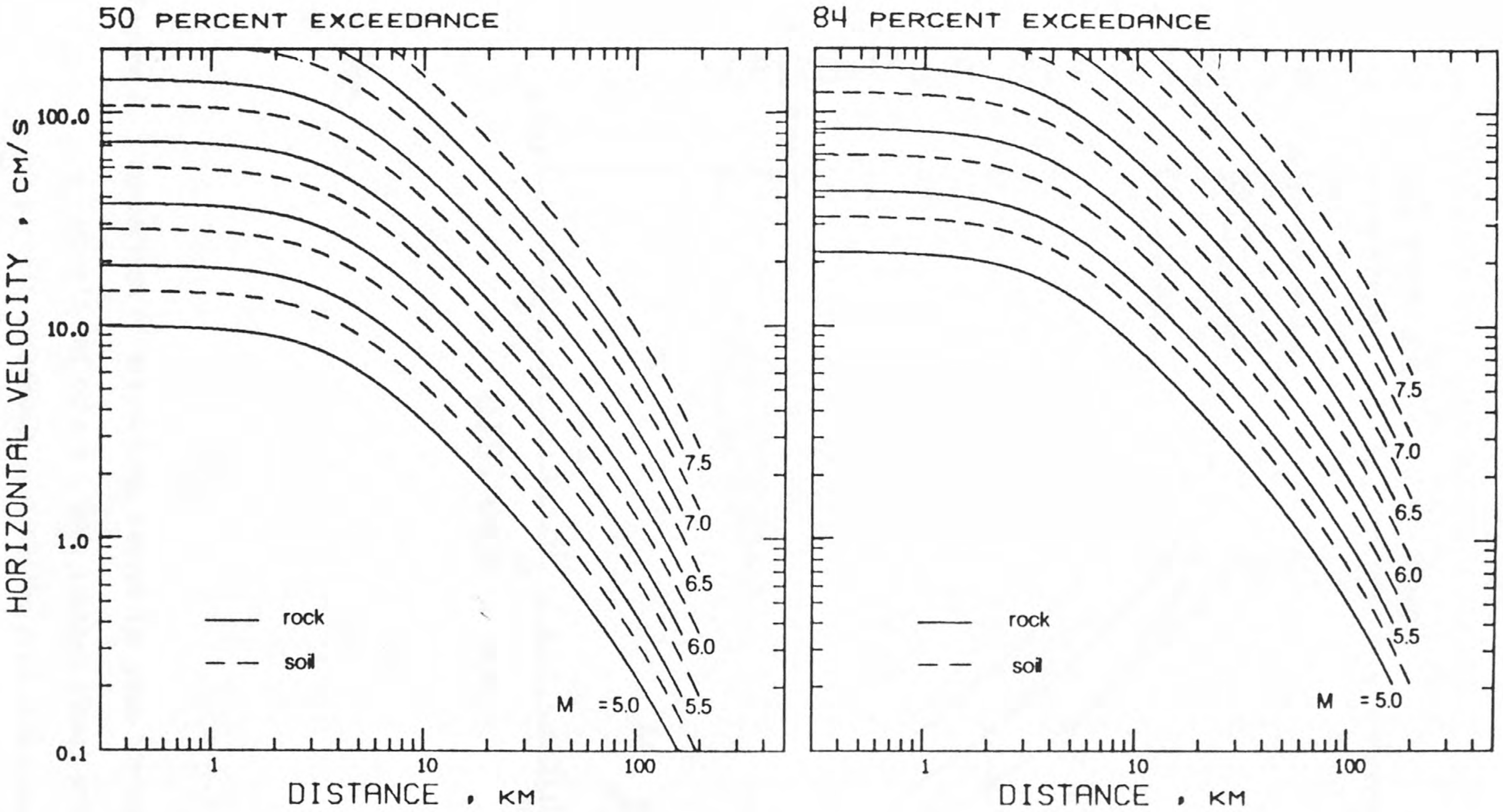

Figure 6. Predicted values of peak horizontal velocity for 50 and 84 percent exceedance probability as functions of distance, moment magnitude and site conditions.

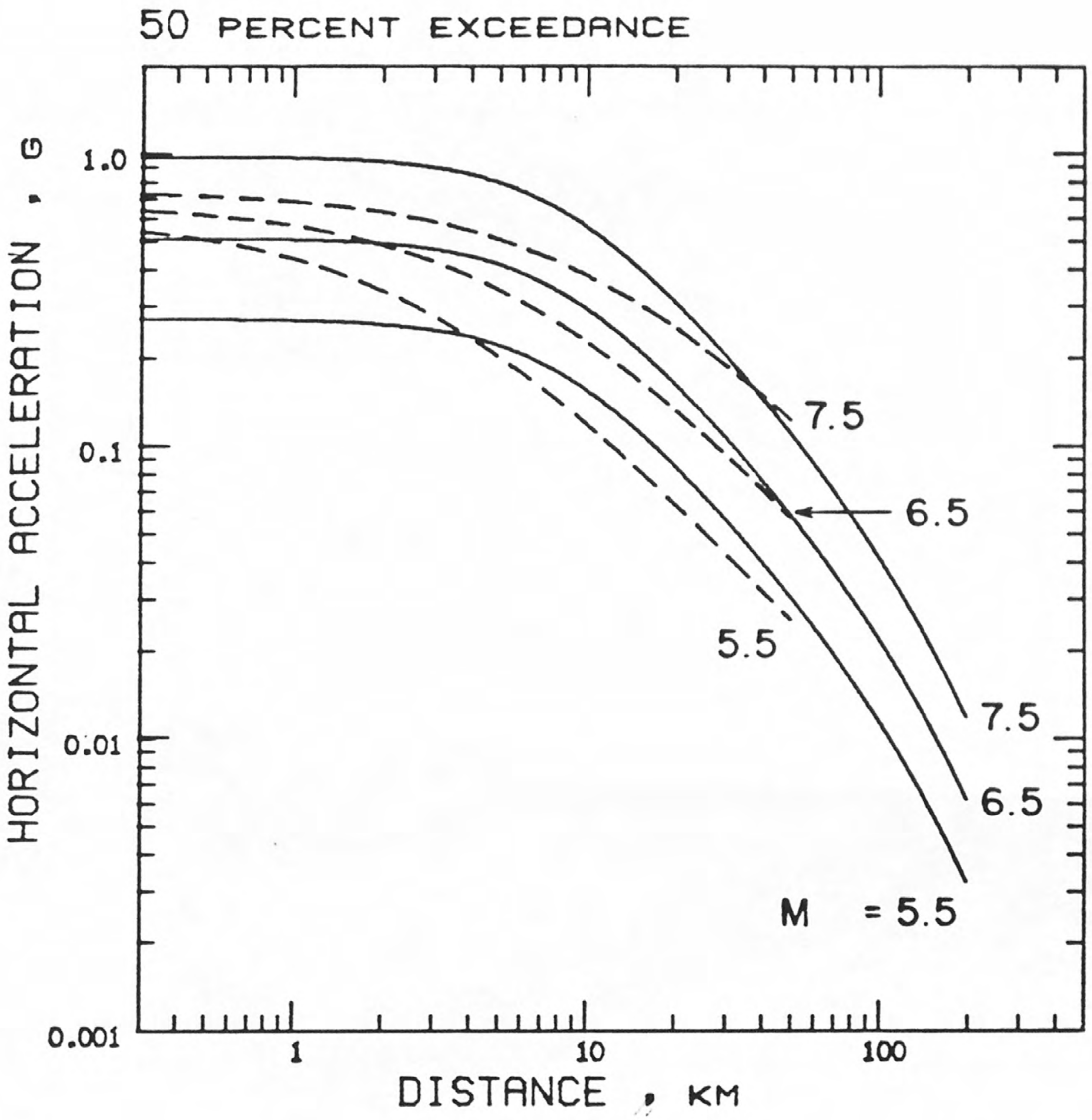

Figure 7. Comparison of attenuation curves for peak horizontal acceleration by Campbell and others (1980) (dashed lines) with the curves for 50 percent exceedance probability from this report (solid lines).