AN ALTERNATIVE APPROACH TO MODELING EARTHQUAKE GROUND MOTION ATTENUATION IN THE WESTERN UNITED STATES

by

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SUMMARY

This paper summarizes a study in which published ground motion attenuation relationships for the western United States were evaluated based on their ability to match recorded motions of the region. Results show, that depending upon how important variables are considered, the variation in predicted results for the group of equations vary by as much as one order of magnitude. To model this variation, a procedure was developed which consisted of taking a weighted average of all applicable relationships for a particular mode of ground motion, i.e., peak ground acceleration, velocity and displacement. Weighting factors were computed for each attenuation equation based on how well the equation fit available data in limited ranges of magnitude. The present analyses, completed under a U.S. Geological Survey-sponsored project, were part of an overall Bayesian seismic risk analysis of California. The primary documentation for this work is contained in Reference 1.

INTRODUCTION

The intensity of ground motion felt at a site during an earthquake is a function of many variables: earthquake size, type, and depth, distance and intervening geology between source and site, near-surface site conditions, depth of sediments, instrument location and orientation, radiation patterns and focusing effects, and topography. Current attenuation relationships vary in form and in values predicted depending upon how the above variables are considered. In the present study, 22 different attenuation relationships for peak ground acceleration, 12 relationships for peak ground velocity, and 8 relationships for peak ground displacement were identified. All 42 relationships utilized, to some extent, California strong motion data; all have been developed by prominent researchers. Large variations are still observed however, even under supposedly similar conditions.

Numerous definitions of the distance between source and site exist; each reflects a different interpretation of where the source should be located. For example, present definitions include distance to the hypocenter, epicenter, energy center and causative fault. Of the four distances, probably the best or most commonly known are hypocentral and epicentral distance. The determination of these require no special studies. These distances, however, have the disadvantage in that they may sometimes be inappropriate. For example, in the case of a long fault rupture, there is the possibility of having the epicenter located at one end of the fault while having the recording station located at the other end. The 1966 Parkfield earthquake is an example of such a situation. Distance to the energy center also

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[I] Section Manager, J.H. Wiggins Company, Redondo Beach, California becomes inappropriate when long fault ruptures occur. A measure of the distance to the causative fault is an attempt to model and reflect the above mechanism. This measure assumes that radiation from the fault occurs uniformly.

Whether site conditions are considered or not leads to another source of variation. Most investigators agree that site conditions do play an important role in determining the level of ground motion experienced at a site. To what extent site conditions affect ground motions, however, is not agreed upon. Most of those who incorporate site factors do distinguish between soil and rock. However, whether shallow soil layers over rock amplify or deamplify motions is not agreed upon. The different rock classes vary from the hard basement complex to the softer sedimentary rock. The soil class encompasses a much wider range of definitions. For example, soil varies depending upon the depth over rock. Different degrees of hardness are also incorporated. In some cases, the fundamental period or the average shear-wave velocity of the site is used to determine the soil or site factor. In summary, there appears likely to be little common basis from which to compare these relationships, at least with respect to site conditions.

Additional factors contributing to large variations include whether the data are adjusted to account for instrument orientation, whether both horizontal components of a record are utilized, what magnitude is used (e.g., M_L, M_S, M_b), what data the investigator chooses to incorporate, what definition of the parameter in question is used, and perhaps the most significant factor, what functional form between all of these parameters does the investigator assume. The function form is an important factor because it reflects the investigator's interpretation of how all the different parameters are related. As will subsequently be seen, this information can be used effectively with available data in arriving at a better estimate of peak ground motion for a particular site.

APPROACH

In an attempt to incorporate the variation in these relationships, a procedure was developed whereby "average" relationships for different modes of ground motion (e.g., peak[1] ground acceleration, peak ground velocity, peak ground displacement) were derived from a weighted-average of all available attenuation relationships. This procedure should be distinguished from one which relies on a linear regression of earthquake data.

In the present study, weighting factors for an equation were determined by how well the equation fit existing data in selected magnitude ranges. The goodness-of-fit was quantitatively defined by the error (or residual), sum of the squares (ξ). That is,

$$\xi = \sum_{i=1}^{n} \log^2\{X_i/\hat{X}_i\} \qquad (1)$$

where X_i denotes an observed value of peak ground motion (i.e., that recorded by an accelerograph instrument), $\hat{X}_i$ denotes a value of peak ground motion

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[1] "Peak" herein is defined to mean the maximum value observed on a record or integrated and "balanced" record.

computed from an attenuation equation, and n represents the number of observations in the $\{X_i\}$ set. As can be seen, the smaller values of ξ imply lower relative errors. A typical $\{X_i\}$ set would include the California Institute of Technology (1973, 1974, 1975) data base where magnitudes and distances are given.

Equation (1), when integrated over all i (i.e. observations), is a statistical indicator of the relative error of a relationship. Dividing SSE by the number of degrees of freedom results in the error mean square. This sum of the squares approach is consistent with the least-squares technique of fitting data.

If we denote the error, sum of the squares, computed for equation i by ξ_i, then a weighted-average value of ground motion, $\overline{X}$, can be computed for a particular magnitude and distance using the following equation,

$$\log\{\overline{X}(m,R)\} = \frac{\xi_1^{-1}\log\{X_1(m,R)\} + \xi_2^{-1}\log\{X_2(m,R)\} + \ldots + \xi_i^{-1}\log\{X_i(m,R)\} + \ldots + \xi_t^{-1}\log\{X_t(m,R)\}}{\frac{1}{\xi_1} + \frac{1}{\xi_2} + \ldots + \frac{1}{\xi_i} + \ldots + \frac{1}{\xi_t}} \qquad (2)$$

where t represents the total number of attenuation equations, and $X_i(m,R)$ represents the value of ground motion computed from equation i based on m and R. When $\overline{X}(m,R)$ is computed for a number of different m and R, a graphical presentation of these weighted average curves can be made.

This weighted-average procedure is expected to produce a more realistic estimate of ground motion as a function of magnitude and distance for the following reasons: (1) the effects of data bias are minimized by segregating the data by magnitude ranges (e.g., 6.0-6.9) and performing the analysis independently for each range, and (2) when the data are sparse or of low quality, the judgment of recognized experts on how motion should attenuate (i.e., the attenuation relationships) is used to interpolate or extrapolate trends. In addition, because the analysis is performed independently for each magnitude range, there is no need to filter the effects of any single earthquake or site.

DATA BASE

The data base for this study consisted of 669 separate basement and ground-level strong motion earthquake accelerogram records.

In order to avoid statistical bias due to a particular data base, an attempt was made to incorporate as much of the original data used by the investigators as possible. Data from the following sources were used:

1. Volume II, Corrected Accelerograms, and Integrated Velocity and Displacement (California Institute of Technology, 1973, 1974, 1975).
2. Strong-Motion Earthquake Accelerograms-Digitization and Analysis, 1971 Records (U.S. Geological Survey, 1976).
3. Ground Motion Values for Use in the Seismic Design of the Trans-Alaska Pipeline System (Page et al, U.S. Geological Survey, 1972).

4. Construction of Strong Motion Response Spectra from Magnitude and Distance Data (J.H. Wiggins, 1964).
5. Intensity of Earthquake Ground Shaking near the Causative Fault (G.W. Housner, 1965).
6. Earthquake Magnitude, Intensity, Energy, and Acceleration (B. Gutenberg and C.F. Richter, 1956).

Duplicate records were eliminated on the basis of date, location and magnitude.

RESULTS

Twenty-two different attenuation relationships for peak ground acceleration, 12 relationships for peak ground velocity, and 8 relationships for peak ground displacement were identified in this study.

Error, sum of the squares, ξ were computed for each attenuation curve using Eq. 1. This was done for five separate magnitude ranges: 4.0-4.9; 5.0-5.9; 6.0-6.9; and 7.0-7.9. In addition, if an investigator had several curves, reflecting different site conditions for example, weighting factors were computed for each. Only the best curve (i.e., greatest weighting factor), however, was selected for use in the weighted-average analysis.

Fig. 1 displays the weighted-average curves for peak ground acceleration plotted against the data for the four magnitude ranges. The magnitudes in each figure reflect mean values for data in that range. As is evident from the figure, the magnitude 6.0 to 6.9 range dominates the picture, accounting for approximately 50 percent of the total number of data points. The 1971 San Fernando earthquake accounts for most of the near source data (i.e., epicentral distances between 30 to 150 kilometers), while the 1968 Borrego Mountain earthquake contributes most of the far field data (i.e., epicentral distances greater than 150 kilometers) for this magnitude range. The peak ground motions for these larger magnitudes (including the 7.0 to 7.9 range) tend to follow well behaved trends, i.e., the scatter in the data rarely exceeds one order of magnitude. In contrast, for the smaller magnitudes, this spread often exceeds two orders of magnitude. A closer examination of the effect of focusing on these smaller magnitude-closer distant events may provide an explanation for this large variation. For example, for a moderately large earthquake of Richter magnitude 6.4, the October 15, 1979 Imperial Valley earthquake produced horizontal accelerations as large as 0.8g (Ref. 8). In addition, a vertical acceleration of 1.74g was recorded. Incorporating a focusing effect parameter into the development of future attenuation equations may serve to reduce the scatter in some of this data.

The weighted-average curves for peak ground acceleration, velocity and displacement are displayed in Fig. 2. With the exception of the 3.5 and 8.5 curves, the magnitudes assigned to each curve represent the mean magnitude for the corresponding ranges stated previously. The 3.5 and 8.5 curves were extrapolated by using the weighting factors determined for the 4.5 and 7.5 (7.6 for acceleration) curves, respectively.

The curves in Fig. 2 can be approximated by the following equations.

$$\log A = 1.83 + 0.37M - 1.44 \log R \qquad \sigma_{\log A} = 0.28 \qquad 3(a)$$

$$\log V = 0.054 + 0.45M - 1.19 \log R \qquad \sigma_{\log V} = 0.24 \qquad 3(b)$$

$$\log D = -1.15 + 0.51M - 0.97 \log R \qquad \sigma_{\log D} = 0.33 \qquad 3(c)$$

where A is peak ground acceleration (cm/sec^2), V is peak ground velocity (cm/sec), D is peak ground displacement (cms), M is Richter magnitude, and R is hypocentral distance (kms). The corresponding standard deviations are computed based on the larger magnitude events ($M>6.0$).

CONCLUSIONS

A large number of different ground motion attenuation relationships were identified for peak ground acceleration, velocity and displacement. Depending upon what data were incorporated or how important variables were considered, the variation in computed results was as large as one order of magnitude. Individual relationships were ranked based on how well each fit existing data in selected magnitude ranges. This information was used to develop composite relationships which reflected weighted-averages of all individual relationships. Results showed that these composite curves differed from those developed exclusively from the data in that lower ground motions were predicted for larger magnitudes. Because these curves were developed independently for each magnitude range, they tended to follow more closely actual data trends.

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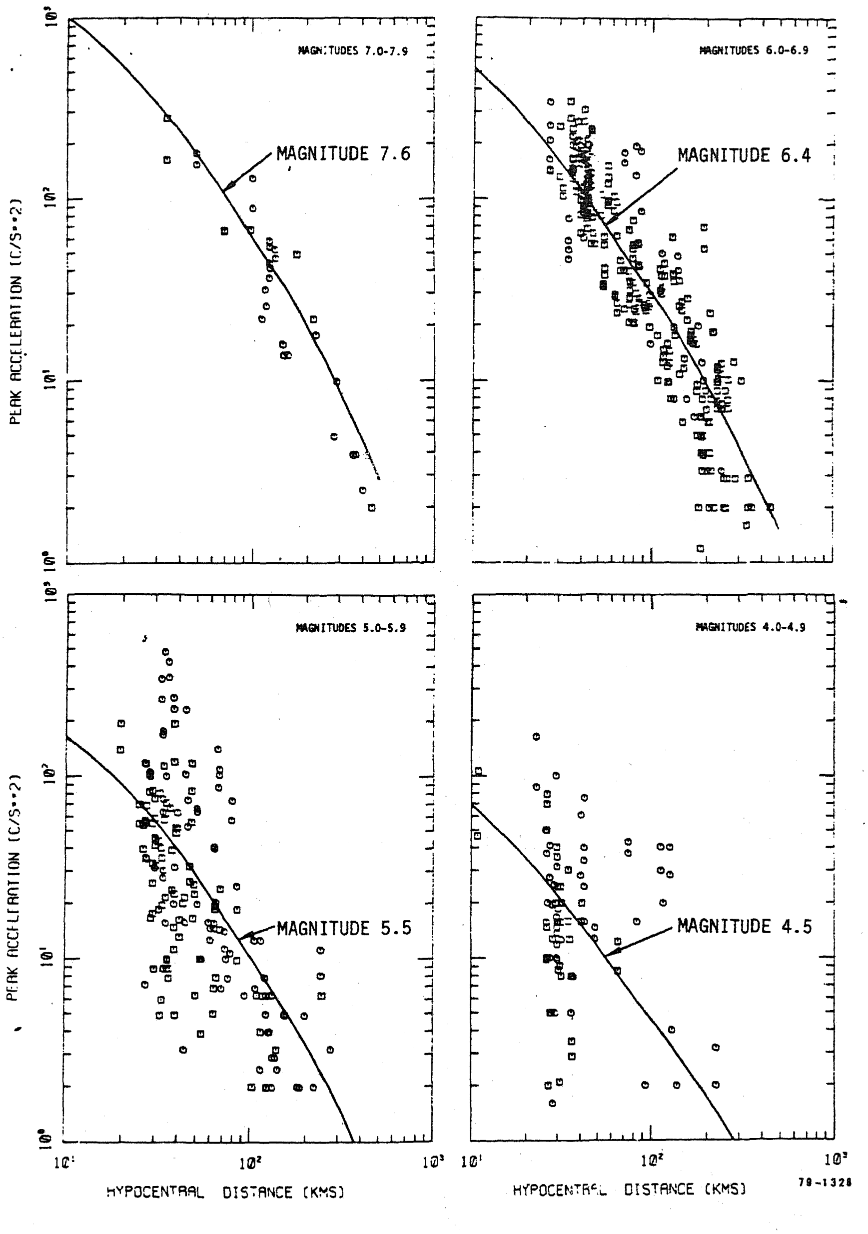
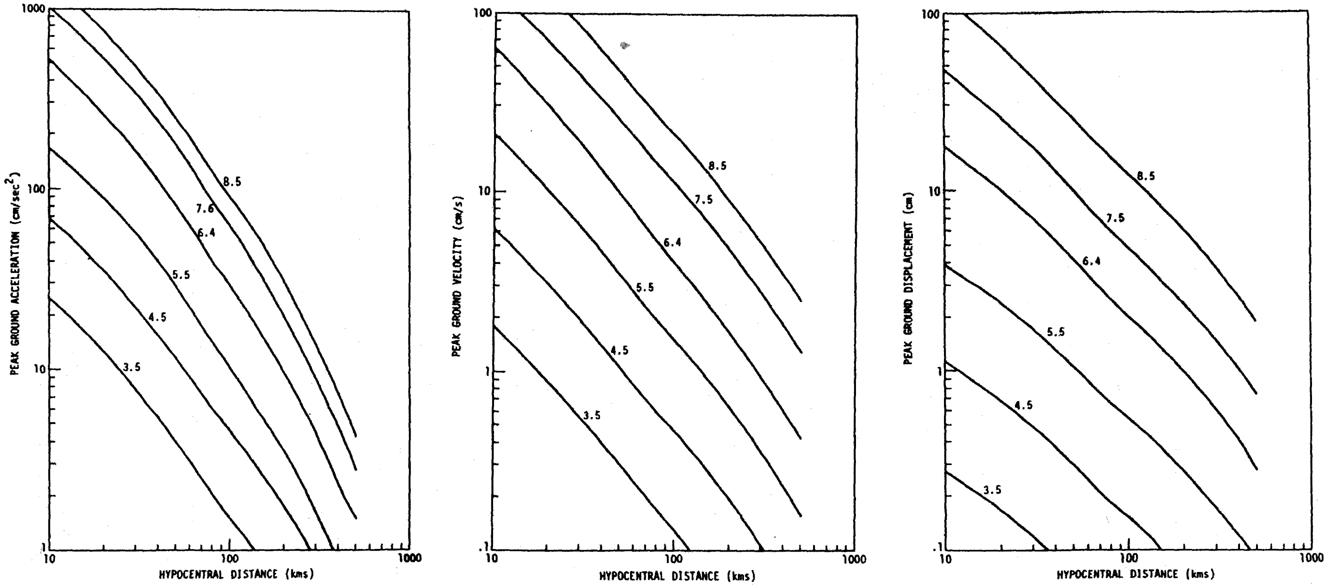


Figure 1. Weighted-Average Attenuation Curves for Peak Ground Acceleration Plotted Against Data Base.



(a) Peak Ground Acceleration

(b) Peak Ground Velocity

(c) Peak Ground Displacement

Figure 2. Weighted-Average Attenuation Curves