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A Comparison of Methods of Estimating the Attenuation of Earthquake Strong Ground Motion

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SYNOPSIS Strong ground-motion attenuation relations take on a variety of forms, depending upon the parameters used to express the relations and upon the geographic area for which the equations are developed. In general the strong ground-motion parameters, namely acceleration, velocity, displacement and response spectra ordinates, are taken to be proportional to the distance from the earthquake source to the site, to the magnitude or some measure of the strength of the earthquake source, and to loss factors resulting from transmission of energy through the inelastic earth. In certain areas of the world, where strong-motion data are abundant, empirical relations can be developed to express these relations. In other areas of the world, where strong-motion data are few or are entirely lacking, more attention must be given to theoretical considerations. In this paper we give case histories of two such types of regions, namely western North America with an abundance of data and eastern North America with a paucity of data.

THEORETICAL CONSIDERATIONS

The attenuation of earthquake strong ground motion is defined here to include the following topics: 1) the decrease in amplitude of strong ground-motion parameters (peak acceleration, velocity and displacement) with distance from the earthquake, 2) the dependence of the relation described in 1) upon the magnitude of the earthquake (or on some other parameter related to magnitude), and 3) the dependence of the relation described in 1) upon the rupture process of the earthquake. Site effects at the point where the ground motion is estimated will only sometimes be included in the relation.

Most so-called "strong ground-motion attenuation curves" present peak ground acceleration as a function of epicentral distance, hypocentral distance, or distance from the nearest point of the fault rupture surface. They are based upon empirical data obtained from accelerograms. Sometimes the data are fitted by a simple linear relation between the logarithm of the peak acceleration and the logarithm of the distance, but more often the logarithm of the acceleration is assumed to be proportional to r^{-n}, for losses due to elastic transmission of energy, and also proportional to exp $(-kr)$, for losses due to anelastic effects, where r is a distance term and k is the coefficient of anelastic attenuation. Empirical curves of this type are constructed as a function of earthquake magnitude, and a set of curves is obtained which covers the range of magnitudes for which there is observational data.

Numerous investigators have developed curves of the type described above, which differ among themselves for a variety of reasons. At relatively small distances the choice of epicentral distance, hypocentral distance, or closest distance to the fault for the term r in r^{-n} can have a big influence on the curve. Sometimes a term such as $(r - h)^{-n}$ is used, where r is epicentral distance and h is average focal depth. The effect of this is to make the peak acceleration nearly constant when r is less than h.

The definition of "peak" ground acceleration also can influence the curves. Some investigators take the peak value to be the largest of the values recorded on the three accelerograms. Others, more commonly, use the largest of the values seen on the two horizontal component accelerograms. Still others use the arithmetic average of the maximum values recorded on the two horizontal component accelerograms. Less frequently, the vector sum of the maxima on the two horizontal component accelerograms is used. Differences in the definition of "peak" acceleration can result in numerical differences of as much as 50%.

Even more important is the choice of magnitudes used to set the level of, or scale, the attenuation curves. The local magnitude, M_L, often is employed in California and the adjacent area of the western United States. Body-wave magnitude, m_b, or surface-wave magnitude, M_S, frequently are used in other areas of the world. M_w, the moment magnitude, which is related empirically to the seismic moment of the earthquake, recently has been used for scaling purposes. Unfortunately, some investigators do not distinguish between magnitude scales, and use a quantity called "magnitude" or "Richter magnitude" which may be an unspecified mixture of the various kinds of magnitudes.

The coefficient of anelastic attenuation, k, is frequency dependent. Therefore, for peak motions, its value changes both with epicentral distance and with earthquake magnitude. Usually the change in k with distance is ignored, and often the change with magnitude also is overlooked, resulting in a constant value for k.

Observational data show that the anelastic attenuation factor, k, also depends strongly on the geology of the earth's crust. In general, k is substantially smaller in geologically old and stable regions, such as shields or ancient platforms, than in young tectonic regions where most of the earthquakes occur. The effect of differences in k values can be dramatic, resulting in differences in damage areas of ten or more times for earthquakes of the same magnitude. Examples of this phenomenon frequently are seen in North America, where earthquakes east of the Rocky Mountains have the lesser attenuation and the larger damage area.

Empirical data and relations of the type described above are lacking for most parts of the world, either because of a lack of accelerographs to provide the data or because of infrequent occurrence of earthquakes, particularly those of large magnitude. However, the geotechnical engineer often is called upon to provide estimates of strong ground motion at a particular site in regions where there are little or no empirical data. For such a case, there are a number of approaches that have been taken.

The first approach makes use of earthquake intensity data. Isoseismal maps for specific earthquakes usually are available, and these can be used to determine the attenuation of intensity with epicentral distance. The epicentral intensity can be taken as a measure of earthquake strength. Therefore the intensity attenuation curves can be scaled by the epicentral intensity value. Empirical relations then are used to convert calculated site intensities to peak ground acceleration and/or velocity values. A problem with this approach is that the correlation between peak ground-motion values and earthquake intensity is not simple, but depends both on epicentral distance and earthquake magnitude.

A second approach assumes that the strong ground motion at small epicentral distances is the same for all earthquakes of the same magnitude. Then it only is necessary to attenuate the close-in values to the desired distance, using appropriate k values, which can readily be obtained from microseismic studies. Evidence exists which indicates that this is a satisfactory approach for all except the large earthquakes, those of m_b or M_L no greater than 6. However, the near-field strong ground motion, along with the fault rupture dimensions, can differ for large earthquakes of the same magnitude according to their geographic location.

A third approach makes use of seismographic data to establish relations between the various types of magnitudes and certain physical characteristics of the earthquake source. From such relations equations can be developed from elastic wave theory for scaling relations for the strong ground-motion parameters, namely peak acceleration, velocity and displacement, as a function of one of the types of magnitude. Microseismic data can be used to determine the functional relation, or shape, of the attenuation curves. Available strong-motion data, usually for small magnitude earthquakes, can be used to set the level of the curves. This method appears to work well for eastern North American earthquakes, although there are no existing data to compare against the theoretical values for large magnitude earthquakes.

Almost as important as the strong-motion attenuation curves themselves are the estimates of uncertainty to be attached to them. Most often a curve is fitted to the arithmetic mean of the logarithm of a peak ground-motion parameter, such as acceleration, and departures from the mean curve are treated as random variables. Then a 1σ (one standard deviation) or 2σ value is calculated. Because variations from the mean curve often are larger at small distances (distances less than the focal depth or the fault rupture length), sometimes 1σ values are estimated separately for small and larger distances.

Although it is possible to mathematically model the complex rupture process and produce synthetic strong-motion records that resemble the actual recorded ones, it is not possible to construct such a mathematical-physical model that can be used to predict the strong ground motion that will result from future earthquakes, because certain features of the model will vary from one earthquake to another. This especially is true of peak acceleration, which is dominated by high frequency waves, and thus depends on the fine details of the rupturing process.

Attenuation of response spectra also is of concern to geotechnical engineers. For this problem the dependence of the coefficient of anelastic attenuation on wave frequency must be considered. In general, this dependence can be approximated by relations of the form

$$Q(f) = Q_o\,(f/f_o)^n \quad \text{and} \quad k = \pi f/Q(f)V(f) \tag{1}$$

where Q is the specific quality factor, f_o is a reference frequency and V is the group velocity of waves at frequency f. The quantity n can be taken as a constant over a limited range of frequencies. Combination of the two equations leads to

$$k(f) = \pi f_o^{\,n}\, f^{1-n}/Q_o V(f) \tag{2}$$

For neotectonic areas, such as coastal California and Japan, the value of n has been found, from microseismic data, to lie in the range of 0.7 to 1.0 for frequencies of 1 to 25 Hz. If n = 1.0, the equation (2) predicts that the value of k will be independent of wave frequency. This leads to the conclusion that the shape of the response spectrum will not change as the distance increases, with only the level of the spectrum decreasing. Comparison of the response spectra of the same earthquake calculated from accelerograms at different distances for California earthquakes show that this conditio is approximately satisfied. As a consequence, methods of analysis that assume an invariant shape for response spectra of California earthquakes can be justified. However, in regions such as eastern North America, or in similar geologic regions such as the shield areas of southern India, eastern South America, and most of Afric and Australia, the value of n for frequencies of 1 to 25 Hz is approximately 0.2 to 0.4. This implies that k increases as the wave frequency increases, resulting in a change of shape of the response spectrum with distance, with the high frequencies being attenuated at a more rapid rate than the lower frequencies.

The nature of the two basic types of attenuation, elasti (principally geometrical spreading of the wavefronts) an anelastic, is such that the former dominates at the smaller distances and the latter becomes relatively more important at the larger distances. The definition of "smaller" and "larger" in this case is not unique, because it depends on the value of k, which is regionally dependent and also frequency dependent.

CASE HISTORIES

In order to clarify the discussion to this point, examples of strong ground-motion attenuation relations fo North America will be given. No attempt is made to discuss all the proposed relations. Rather, emphasis will be given to recent work that, for the most part, is published in the seismological literature.

Joyner and Boore Relations (1981)

Joyner and Boore used a large collection of strong-moti data (primarily of California earthquakes) to establish empirical attenuation relations for peak horizontal acceleration and peak horizontal velocity. Their derived equations are:

$$\log A = -1.02 + 0.249\underline{M} - \log r - 0.00255r + 0.26P$$
$$\text{where } r = (d^2 + 7.3^2)^{\frac{1}{2}} \quad \text{and} \quad 5.0 \le \underline{M} \le 7.7 \qquad ($$

$$\log V = -0.67 + 0.489\underline{M} - \log r - 0.00256r + .17S + .2$$

$$\text{where } r = (d^2 + 4.0^2)^{\frac{1}{2}} \quad \text{and} \quad 5.3 \quad \underline{M} \quad 7.4 \tag{5}$$

In these equations A is peak horizontal (larger of the maximum values on the two horizontal components) acceleration in g, V is peak horizontal velocity in cm/sec, $\underline{M}$ is moment magnitude, d is the closest distance, in km, to the surface projection of fault rupture, S takes on the value of zero at rock sites and one at soil sites, and P is zero for 50 percentile values and one for 84 percentile values. The numerical values appearing in the equations were obtained by multiple linear regression analysis.

From their analysis of the peak acceleration data Joyner and Boore found that the characteristics of the recording site (soil or rock) had no statistical significance, i.e. site conditions have no significant influence on recorded peak accelerations. However, they found a site effect for peak horizontal velocity, with soil sites having peak values approximately 1.5 times larger than rock sites.

Joyner and Boore used the quantity P as a measure of the scatter in the peak acceleration data. A value of P equal to zero gives the 50 percentile value of peak ground motion, and a value of P equal to 1 gives the 84 percentile value.

Campbell Relations (1981a)

Campbell was concerned with near-source attenuation (≤ 50 km) of peak horizontal acceleration. He also applied regression analysis to a set of worldwide data, mostly from plate-margin earthquakes. He found that his data were adequately represented by the relation

$$\mathrm{PGA} = a \exp(bM) \cdot [R + C(M)]^{-d} \tag{6}$$

where PGA is the arithmetic mean of the maximum acceleration on the two horizontal accelerograms in g, and R is distance in kilometers from the fault rupture zone. M is defined to be "Richter magnitude", taken as M_L for $M_L \leq 6$ and as M_S for $M_S \geq 6$. This assumes that the M_L and M_S values are coincident at a numerical value of 6.

Values of the coefficients a, b, C and d were determined in two ways. In the so-called unconstrained model in which only regression analysis was employed, a = 0.0159, b = 0.868, d = 1.09 and C(M) = 0.0606 exp(0.700M). In the constrained model, for which the peak acceleration is assumed to be constant or independent of M at the fault rupture surface and in which d is assumed to be 1.75, in order to match the far-field data, a = 0.0185, b = 1.28 and C(M) = 0.147 exp(0.732M). Unlike Joyner and Boore (1981), Campbell found that at small distances the shape of the attenuation curves is a function of M.

Campbell found that the larger of the peak horizontal accelerations on the two components, as used by Joyner and Boore (1981), is 13% bigger than the quantity which he used, namely the arithmetic mean of the maximum values on the two horizontal components. His values of a, b, d and C given above correspond to the median value of peak ground acceleration. The 84 percentile value can be obtained by multiplying the median value by a factor of 1.45 for the unconstrained model, and by a factor of 1.47 for the constrained model.

Like Joyner and Boore (1981), Campbell found that site conditions did not affect peak ground acceleration except for the cases of a thin soil layer over rock or steep topography, both of which tended to increase the recorded acceleration values.

Bolt and Abrahamson Relation (1982)

Bolt and Abrahamson assumed a relation between peak horizontal ground acceleration, y, distance from the wave source, x, for a given magnitude as

$$y = a\left[(x + d)^2 + 1\right]^c \exp\left[-b(x + d)\right] \tag{7}$$

where the parameters a,b,c and d were determined by regression. Bolt and Abrahamson's data consisted of 183 peak acceleration values for 24 shallow earthquakes in western North America. They used the larger of the maximum acceleration on the two horizontal components in their analysis. They also used moment magnitude, $\underline{M}$. The range of $\underline{M}$ was 5.0 to 7.7, with most earthquakes having values between 5.5 and 6.5.

For the group of data of $6.0 \leq \underline{M} \leq 7.7$, they found by nonlinear least squares analysis that

$$y = 1.6\left[(x + 8.5)^2 + 1\right]^{-0.19} \exp\left[-0.026(x + 8.5)\right] \tag{8}$$

where y is in g's and x in kilometers. The value of the standard error for one observation was 0.09g.

When a similar analysis was applied to the data for the ranges $5.0 \leq \underline{M} \leq 6.0$, $6.0 \leq \underline{M} \leq 7.0$ and $7.0 \leq \underline{M} \leq 7.7$, the peak accelerations were found to be nearly constant for distances of less than 10 km, and to show little dependence on magnitude. At larger distances the attenuation curves scale according to $\underline{M}$ in a manner somewhat similar to that found by Joyner and Boore (1981) and Campbell (1981a).

Eastern North America Relations Based on Intensity Data

As noted earlier, eastern North America is noteworthy for the paucity of strong-motion data. Therefore other information, such as intensity attenuation, must be used. The basic procedure relates epicentral intensity, I_o, site intensity, I_s, and epicentral distance, R, to each other by means of observational data. There are a large enough number of earthquakes to provide data of this kind. A problem develops, however, when I_s is converted to a, v or d, because then data must be used from areas where adequate strong-motion records exist, and intensity attenuation in those areas is much greater than in eastern North America.

The Lawrence Livermore National Laboratory (LLNL) Engineering Geoscience Group (1983) developed a number of approaches to the problems considered above. For a (arithmetic mean of peak acceleration on the two horizontal components, in cm/sec^2), they obtained four alternate relations

$$\ln a = 1.31 + 1.2\, m_b - 1.02 \ln R \tag{9}$$

$$\ln a = 3.16 + 1.24\, m_b - 1.24 \ln (R + 25) \tag{10}$$

$$\ln a = 1.47 + 1.1\, m_b - 0.88 \ln R - 0.0017\, R \tag{11}$$

$$\ln a = 0.77 + 1.13\, m_b - 0.74 \ln R - 0.007\, R \tag{12}$$

where R is epicentral distance, in kilometers.

Eq. (9) is based on an empirical relation by Nuttli and Herrmann (1978) between I_s, I_o and R, an empirical relation between I_o and m_b, and a slightly modified version of an empirical relation between a, m_b, R and I_s by Murphy and O'Brien (1977). Eq. (10) is based on the work of Battis (1981), who assumed that peak ground motion at

R = 10 km is the same throughout the world for earthquakes of identical I_0 value and, in addition, that the a value at the limit of perceptibility by humans is everywhere 6 cm/sec^2. Eq. (11) is based on intensity attenuation studies done by Weston Geophysical Corporation, Inc. (1981) for New England earthquakes. Eq. (12) was developed by the LLNL Engineering Geosciences Group (1983), using a magnitude-weighted model of Bernreuter (1981) to relate m_b, a and I_s.

The LLNL Engineering Geosciences Group (1983) gave two equations for v (arithmetic mean of peak velocity on the two horizontal components, in cm/sec). They are

$$\ln v = -6.72 + 2.3\ m_b - \ln R \tag{13}$$

$$\ln v = 0.924 + 0.95\ m_b - .0023R - .765 \ln R + .923\ E_1 + E_2 \tag{14}$$

where E_1 and E_2 are random errors with mean equal to zero which represent error terms in the fit of site intensity versus source intensity and distance, and the fit of site intensity versus magnitude and distance, respectively. The first of the equations is developed from work of Nuttli and Herrmann (1978) and the second from the work of Weston Geophysical Corporation, Inc. (1981).

Direct Models for Eastern North America

Direct models are based on the assumption that earthquakes anywhere in the world of the same "source strength" have the same near-field motion, so that differences in far-field motion result only from differences in anelastic attenuation. Nuttli (1979) used the near-field a and v values for the 1971 San Fernando, California earthquake to set the level of the attenuation curves, and then used a scaling law to relate near-field a and v values to m_b for central United States earthquakes. His results were given as a series of curves, rather than in equation form.

Campbell (1981b) presented curves for peak horizontal acceleration for central United States earthquakes of $m_b = 5.0$ and 6.5. The LLNL Engineering Geosciences Group (1983) extended his work to obtain

$$\ln a = 3.99 + 0.59\ m_b - 0.833 \ln r - 0.003\ r \tag{15}$$

where $r^2 = (d^2 + 5.3^2)^{\frac{1}{2}}$, and d is shortest distance between the site and the surface projection of the fault rupture plane. As the fault rupture plane usually is not known in eastern North America, d is taken equal to R.

Semi-Theoretical Models (Herrmann and Nuttli, 1984)

The semi-theoretical method uses relations between m_b and far-field ground motion to determine the attenuation of the peak ground-motion curves, and theoretical considerations along with observational data of the spectra of seismic waves from mid-plate earthquakes to determine the magnitude scaling relations for a_h, v_h and d_h. The levels of the curves for an $m_b = 5.0$ earthquake are determined from the existing strong-motion data for the eastern United States. The resulting equations are

$$\log a_h = .57 + .50\ m_b - .83 \log (R^2+h^2)^{\frac{1}{2}} - .00102R \tag{16}$$

$$\log v_h = -3.6 + 1.0\ m_b - .83 \log(R^2+h^2)^{\frac{1}{2}} - .0005R \tag{17}$$

$$\log d_h = -6.81 + 1.5 m_b - .83 \log(R^2+h^2)^{\frac{1}{2}} - .00026R \tag{18}$$

where a_h, v_h and d_h are the arithmetic means of the peak values on the two horizontal components, in cm/sec^2 cm/sec and cm, respectively, R is epicentral distance an h is focal depth, both in kilometers. These equations apply for $m_b \gtrsim 4.5$ and should be used with caution for $m_b \gtrsim 6.5$.

CONCLUSIONS

In areas where there are abundant strong-motion data, such as western North America, attenuation relations ca be obtained readily by fitting curves to the empirical data. However, most parts of the world do not have an abundance of strong-motion data. For them, the various methods used in eastern North America provide alternati means of obtaining attenuation relations. It is gratifying that disparate methods based on intensity data, o combining near-field western data with far-field easter attenuation characteristics, and on semi-theoretical modeling give essentially the same attenuation relation for eastern North America.

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