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Ground Motion Relations for Use in Eastern Hazard Analyses

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ABSTRACT

A key input to seismic hazard analyses are ground motion relations giving peak acceleration, velocity and response spectra as functions of earthquake magnitude and distance. There are two types of uncertainty in these relations, both of which are important to seismic hazard evaluation: epistemic (modeling) uncertainty and aleatoric uncertainty (randomness). This paper describes the uncertainty in eastern ground motion relations.

INTRODUCTION

Ground-motion relations describing peak ground motions and response spectra as functions of earthquake magnitude and distance are of paramount importance in the assessment of earthquake hazard to engineered structures. In the past decade, ground-motion relations for eastern North America (ENA) have been based largely on a stochastic model (eg. Atkinson, 1984; Boore and Atkinson, 1987; Toro and McGuire, 1987; Atkinson and Boore, 1990; EPRI, 1993; Atkinson and Boore, 1995), supplemented by a combination of empirical and theoretical approaches. Ground motions are modeled as finite-duration bandlimited Gaussian noise, whose amplitude spectrum is given by a seismological model of source and propagations processes. The model has been widely applied because the necessary input parameters can be drawn from the broad eastern seismological database; the much more limited strong-motion dataset can then be used solely to validate the model. The model has been calibrated to observations in both California (Boore, 1983) and ENA (Atkinson and Somerville, 1994; Atkinson and Boore, 1995). There is a general consensus among ground motion experts that the stochastic model is a valid and robust approach to developing ENA ground motion relations. However significant differences of opinion remain concerning the appropriate values of various input parameters to the model.

Recently, new ground motion relations have been proposed by the Electric Power Research Institute (EPRI, 1993), and by Atkinson and Boore (1995). The EPRI research emphasized modeling of regional variations in wave propagation effects over the eastern United States, and their impacts on uncertainty. The Atkinson and Boore research emphasized the use of empirical data to constrain the stochastic model parameters and validate

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predictions; the data included observations from the Eastern Canada Telemetred Network, strong-motion stations, and historical earthquakes. Because of their emphasis on empirical validation in general, and the use of eastern Canadian ground-motion data in particular, the Atkinson and Boore (1995) relations are most applicable to seismic hazard mapping in eastern Canada.

A key question concerning use of these new ground-motion relations in seismic hazard analysis concerns their uncertainty. There are two types of uncertainty in ground motion relations, both of which have important implications for hazard evaluation (see Adams et al., this volume): epistemic (or modeling) uncertainty and aleatoric uncertainty (or randomness). In this paper the uncertainty in the Atkinson and Boore (1995) relations, as applied in seismic hazard computations, will be evaluated. The aleatoric uncertainty estimates are based on analysis of empirical ground motion data. The epistemic uncertainty is estimated based on a recent series of workshops in which the range of professional opinion was sampled.

BEST-ESTIMATE RELATIONS AND THEIR ALEATORIC UNCERTAINTY

I treat the Atkinson-Boore 1995 (AB95) relations as 'best-estimate' ground motion relations for hard-rock sites in ENA. The AB95 paper tabulates median response spectral and peak ground motion parameters for a range of moment magnitudes (**M**) and distances and shows simple quadratic equations that approximate the simulated ground motion amplitudes for seismic hazard calculations. Table 1 lists the coefficients of the AB95 quadratic equations.

Random variations in source and propagation parameters will cause observed ground motion amplitudes to scatter widely about the median relations. Individual ground motion observations may differ by factors of three or more from the predictions of the median relation, even if the median itself is perfectly accurate. This scatter acts to increase the expected value of the ground motion amplitude for any specified probability level, due to the nature of the distributions. Random scatter is described by the standard deviation of residuals, where a residual is the difference (in log units) between an observed ground-motion value and the value predicted by the ground-motion relations.

The degree of random scatter associated with the ground-motion relations depends partly on the choice of magnitude scale (Atkinson, 1995). Moment magnitude or high-frequency magnitude (Atkinson and Hanks, 1995) are the best magnitudes for predicting ground motion amplitudes, but m_N is still the preferred scale of the Geological Survey of Canada (GSC) for characterizing the magnitude-recurrence parameters. Based on the data comparisons of Atkinson and Boore (1995), the standard deviation of ground motion residuals for m_N-based seismic hazard computations should be approximately 0.30 log (base 10) units. This means that 68% of observations will be within a factor of two of the median.

EPISTEMIC UNCERTAINTY IN BEST-ESTIMATE RELATIONS

In addition to random uncertainty in ground motions, there is epistemic or modeling uncertainty regarding the 'true' median ground motion relations. This uncertainty is due to imperfect knowledge concerning the parameters and models that govern the generation and propagation of ground motion. Epistemic uncertainty is accounted for in a hazard analysis by defining upper and lower sets of ground motion relations to bracket the best-estimate, with weights expressing the likelihood that each set represents the 'true' median. The amount of 'spread' between the high and low relations affects the 'spread' between the median and 84th percentile seismic hazard curves: uncertainty in the true level of the median ground motion relations leads to uncertainty in the true value of the 1/500 per annum ground motion spectrum. We may therefore wish to be, say, 84% certain that the 'true' 1/500 motions are less than our design-basis values.

A useful quantification of this epistemic uncertainty occurred during a recent series of workshops convened by the Senior Seismic Hazard Analysis Committee (SSHAC) of the U.S. National Academy of Science, sponsored by the Dept. of Energy, the Electric Power Research Institute, and Lawrence Livermore Lab. In the first stage of the exercise, four ground motion modelers (Atkinson, Campbell, Silva, Somerville) were asked to provide estimates and documentation of ENA hard-rock motions for specified magnitudes (m_N) and distances; these proponents used four different methods (stochastic with empirical inputs; empirical; stochastic with wave-propagation modeling; advanced numerical modeling, respectively). In the second stage, a larger group of ground-motion experts was then asked to evaluate each of the proponents' techniques and make estimates of the true median and its epistemic uncertainty. In Figure 1, the medians and uncertainty bars (±1 standard deviation) resulting from this second-stage process are shown for 1-Hz spectral acceleration, for an event of m_N=5.5, at closest fault distances of 5, 20, 70 and 200 km. Also shown are judgmental upper and lower limits on the ground motions, which I have drawn as a synopsis of these results. My limits are drawn to enclose all median estimates, and nearly all of the second-stage uncertainty bars. In drawing these limits I also considered the larger spread in the first-stage proponent median estimates (not shown) as indicative of the underlying uncertainties. This figure represents the current professional consensus as to ground motion levels and their epistemic uncertainty.

Based on SSHAC figures such as Figure 1, I have defined upper and lower ground motion limits (representing, very approximately, ±1 standard deviation) for response spectral ordinates (5% damped, hard-rock sites, random horizontal component) at periods of 0.1 and 1.0 seconds. These are shown in Figure 2 for **M** 5 and 7 (m_N 5.5 and 7). The plotted limits include the epistemic uncertainty in the conversion from m_N to **M**.

Figure 2 also shows upper and lower ground motion relations derived to represent the epistemic uncertainty expressed in the SSHAC meetings. These relations were derived as follows:

(i) use the same functional form as for the AB95 best-estimate relations of Table 1.

(ii) fix coefficient c_4 to have the same value as in AB95; this is the simplest interpretation of the information on Figure 2.

(iii) fix coefficient c_3 to have the same value as in AB95; the SSHAC estimates do not provide sufficient information to place any additional constraints on this parameter.

(iv) use the SSHAC limits at R=20 km as the most reliable basis from which to set the source levels of the relations; for any **M**, the desired source level for the quadratic equation (ie. $c_1 + c_2 (M-6) + c_3 (M-6)^2$) is then given by log $PSA_{(R=20)}$ + log (20). The R=20 km values were considered more reliable than the R=5 km values due to differences and ambiguities in the interpretation of the distance definition in the near-source region. The SSHAC limits at R=20 km, together with the above constraints on c_3 and c_4, allow c_1 and c_2 to be determined.

Table 1 lists the coefficients of the lower and upper relations derived from this process. The SSHAC estimates were available for periods of 0.1 and 1.0 seconds. From these two periods, I concluded that the only significant difference in the upper and lower equations, compared to the AB95 median equations, is in the c_1 coefficient (ie. the overall level); the c_2 coefficients (ie. the magnitude scaling) for the upper and lower limits are not significantly different from that used by AB95. Differences between the AB95 and the high and low c_1 values, at periods of 0.1 and 1.0 seconds, were interpolated on the log period scale to obtain the corresponding differences for other periods. For PGA, I assumed the deviation from the AB95 c_1 coefficient matched that for PSA at T=0.1 sec. For PGV, I assumed the c_1 deviation matched that for PSA at T=0.5 sec.

WEIGHTING OF GROUND MOTION RELATIONS FOR HAZARD ANALYSIS

Table 1 provides the best-estimate ground motion relations and their upper and lower bounds (±1 standard deviation). To use these three sets of relations in a hazard analysis, we must weight them. It can be seen from Table 2 that the AB95 relation is near the middle of the range between the high and low relations for periods of 0.2 to 0.3 seconds (eg. % distance from low to AB95 is about 50%, as would be expected if AB95 represents the median). For these periods, it is appropriate to determine the weights based on a discrete three-point normal distribution, with the three points representing -1 sigma (standard deviation), the median, and +1 sigma. The weights given to the low, median and high relations should accordingly be 0.28, 0.44 and 0.28, respectively.

For cases where the AB95 relation is close to the high or low limit, AB95 clearly does not represent the median of a normal distribution of the epistemic uncertainty. To account for the shift of the AB95 relations away from this median, we can downweight the relations at the nearby limit, and increase the weight for the further limit. This has the effect of moving weight closer to the middle of the uncertainty distribution. For periods of 0.1 and 1.0 seconds, the spacing between the nearest limit and the AB95 relation is only 25% of the total space between the high and low limits (rather than the ideal 50% corresponding to the median). Examination of the appropriate weights of a three-point normal distribution for this case suggests halving the weight given to the nearby limit, and putting this extra weight at the further limit. For T=0.5 seconds, the same reasoning is used to suggest downweighting the nearby limit by applying a factor of 2/3. Table 2 lists the suggested weights according to this reasoning. I have assumed that PGA behaves like PSA at T=0.1 sec, while PGV behaves like PSA at T=0.5 sec. The weights of Table 2 contain an element of judgement as to the best way of approximating the distribution of uncertainty indicated by the three sets of relations. The aim is to put an appropriate amount of weight near the centre of the ground motion limits indicated by the SSHAC exercise, while at the same time preserving the concept of the AB95 relations as the 'best-estimate' of the true median.

CONCLUSION

Median ground motion relations for use in seismic hazard analysis in ENA are given in Table 1, along with upper and lower bound relations expressing the epistemic or modeling uncertainty in the relations. Hazard analyses should weight these three sets of relations according to Table 2. The random scatter (standard deviation) about the ground motion relations, for analyses using m_N-based seismicity parameters (converted to **M** in the hazard analysis program, in order to compute motions from the **M**-based ground-motion relations) is approximately 0.30 log units.

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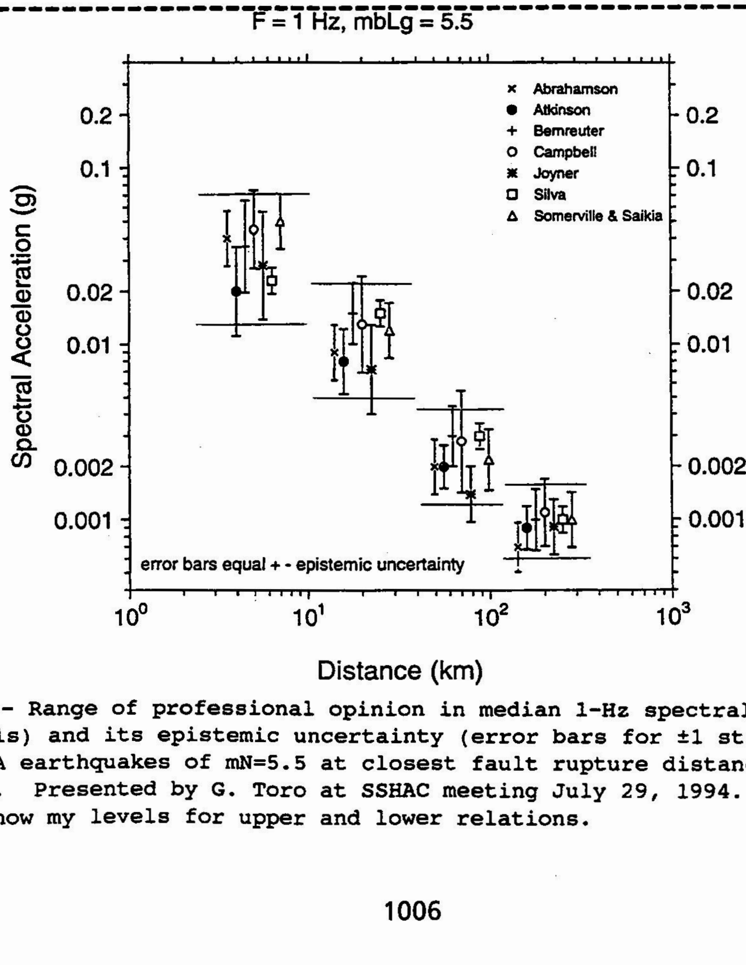

FIGURE 1 - Range of professional opinion in median 1-Hz spectral acceleration (symbols) and its epistemic uncertainty (error bars for ±1 standard deviation), for ENA earthquakes of mN=5.5 at closest fault rupture distances of 5, 20, 70 and 200 km. Presented by G. Toro at SSHAC meeting July 29, 1994. Large horizontal bars show my levels for upper and lower relations.

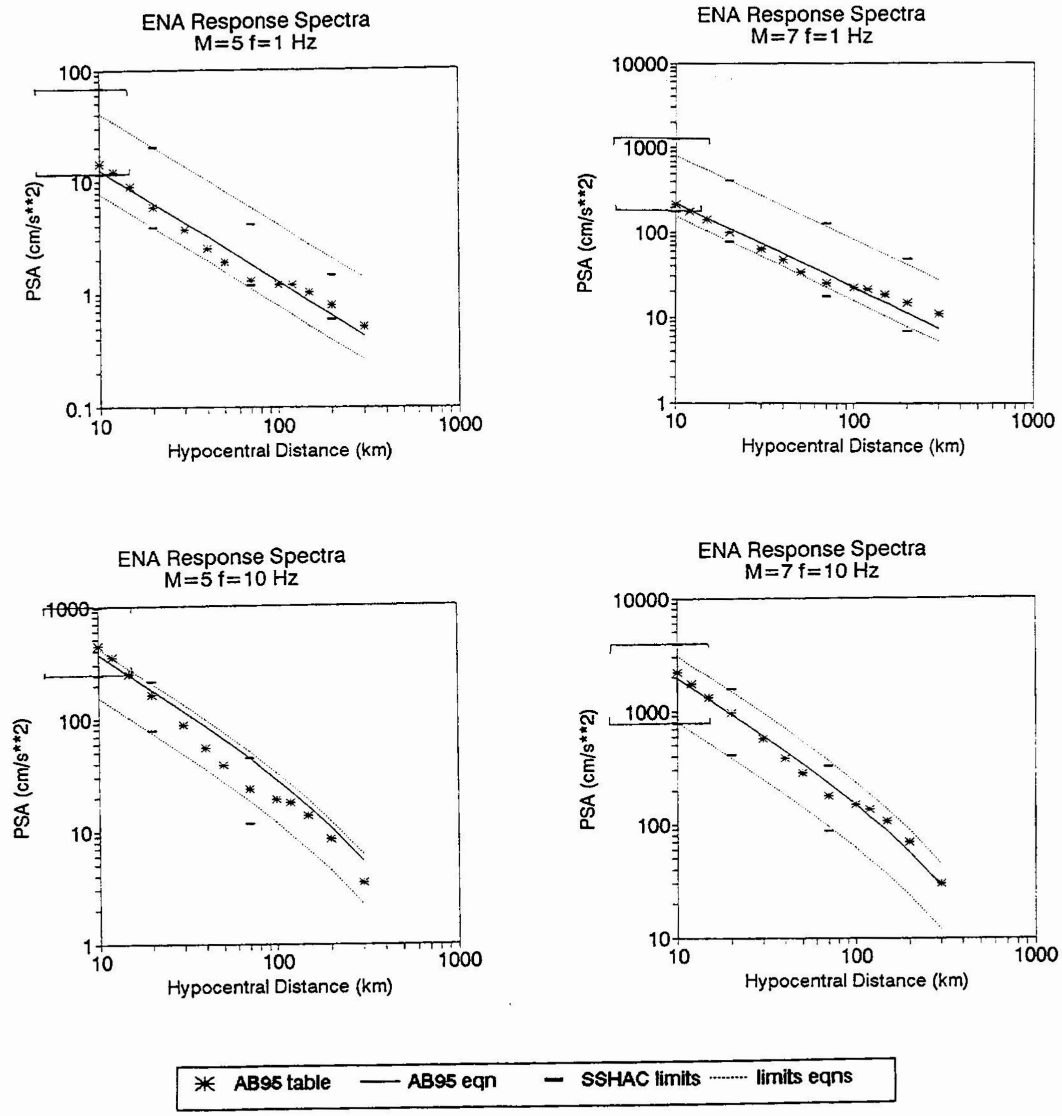

FIGURE 2 - ENA ground motion relations for hazard analyses. Asterisks are simulated values of Atkinson and Boore (1995). Solid lines are quadratic equations of Table 1 that approximate the AB95 simulations. Dotted lines are the equations for the lower and upper relations of Table 1, which approximate the SSHAC uncertainty bounds (horizontal bars). Long horizontal bars for R = 10 km SSHAC limits indicate ambiguity in interpretation of distance measure.

TABLE 1 - Regression Coefficients for Quadratic Equation AB95

T (sec)	c_1 (Best Estimate)	c_2 (Best Estimate)	c_3 (Best Estimate)	c_4 (Best Estimate)	Lower c_1	Upper c_1
0.1	3.99	0.360	-0.0527	0.00121	3.61	4.12
0.2	3.75	0.418	-0.0644	0.000457	3.43	4.00
0.3	3.54	0.475	-0.0717	0.000106	3.26	3.88
0.5	3.26	0.550	-0.0640	0.0000	3.02	3.68
1.0	2.77	0.620	-0.0409	0.0000	2.59	3.31
PGA	3.79	0.298	-0.0536	0.00135	3.41	3.92
PGV	2.04	0.422	-0.0373	0.0000	1.80	2.46

Notes: Equation gives PSA, PGA in cm/s^2, PGV in cm/s, where PSA is the pseudo-acceleration for the random horizontal component, for a single degree-of-freedom, 5% damped oscillator of period T.

$$\log PSA = c_1 + c_2(M-6) + c_3(M-6)^2 - \log R - c_4 R + c_5 S$$

where R is hypocentral distance in km. S=0 for hard rock sites, S=1 for soil sites. Values of the soil-response coefficient c_5, as a function of period, depend on the reference ground condition (eg. 'Class B' c_5 values are given in Adams et al., 1995, GSC Open-file report; 'deep soil' c_5 values are given in Atkinson and Boore, 1995).

First four table columns give coefficients for best-estimate (Atkinson and Boore, 1995) relations. Last two columns give c_1 coefficients for upper and lower bound ground motion relations (coefficients c_2, c_3, c_4 are the same as for the best-estimate case).

TABLE 2 - Weights Suggested for Ground Motion Relations

Period (sec)	Spacing*	Lower	AB95	Upper
0.1	75	0.42	0.44	0.14
0.2	56	0.28	0.44	0.28
0.3	45	0.28	0.44	0.28
0.5	36	0.19	0.44	0.37
1.0	25	0.14	0.44	0.42
PGA	75	0.42	0.44	0.14
PGV	36	0.19	0.44	0.37

Notes: *Spacing is the relative distance (from 0% to 100%) from the lower ground motion curve to the AB95 ground motion curve. If the AB95 relations represented the median of professional opinions, then a spacing of 50 would result.