Updated ground motion relations for earthquakes in eastern North America

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Non-technical Summary: Ground motion relations describe the amplitude and frequency content of motions as functions of magnitude and distance. They have a direct bearing on seismic design. In order to adequately assess the seismic hazard in eastern North America, improved ground motion relations must be developed to describe the expected amplitudes for future moderate-to-large earthquakes in the region. Time histories of ground motion are also required for engineering analyses of the response of structures to earthquakes. This project is updating a widely-used regional model for ground motion using new data and analysis. The outcome of the research will be improved prediction of the expected ground motions, and reduced uncertainties in seismic hazard estimates, for the central and eastern United States.

Introduction

The prediction of ground-motion amplitudes for future earthquakes, as a function of magnitude and distance, is an important problem in earthquake engineering. Ground motion relations have more impact on seismic hazard analysis than any other input parameter, and are thus the major source of uncertainty in seismic hazard estimates. It has been established that ground-motion amplitudes at distances ranging from several km to several hundreds of km can be accurately estimated, on average, if the underlying model parameters are known. Ground motions can be modeled, with comparable accuracy, using stochastic modeling techniques, ray theory, or some combination of the two; examples for eastern North America (ENA) are provided by Ou and Herrmann (1990), EPRI (1993), Atkinson and Somerville (1994), Atkinson and Boore (1995, 1997), and Toro et al. (1997). The techniques differ in the way in which the source, propagation and site processes are modeled, but all will predict similar motions for the ENA crustal structure, given the same understanding of the underlying processes. Thus the accurate specification of these processes for future earthquakes is critical for the development of reliable ground-motion relations for ENA.

The reason that the development of ground-motion relations in ENA has remained controversial is that strong ground-motion data are too sparse to allow ground-motion relations to be derived directly from empirical data, necessitating considerable reliance on models of ground-motion processes. This is an important distinction between ENA and California. In California, strictly empirical approaches are routinely employed to develop ground-motion relations for engineering applications (see Abrahamson and Shedlock (1997) and papers referenced therein). Questions concerning the underlying parameters for ground motion models thus have limited consequences for earthquake engineering, in the California case. For ENA, by contrast, these issues have significant engineering implications.

There are several alternative ENA ground-motion relations that have been widely used over the last decade. These include the relations of Atkinson and Boore (1995), Frankel et al. (1996) and Toro et al. (1997). All of these relations were developed based on a stochastic point-source model of the underlying ground motion processes. (Note: New relations using alternatives to the stochastic method have recently been developed by Campbell (2003) and Somerville et al. (2003).) In the stochastic model, ground motion is treated as bandlimited

Gaussian noise, whose amplitude spectrum is shaped by a seismological model of the source, propagation and site processes. These relations have made a valuable contribution to our evolving understanding of ENA ground motion and hazard, but they are now outdated in two very significant respects:

1. The current ENA ground motion relations all assume a point-source representation of the earthquake source. Recent work shows that finite-fault effects are important in controlling the amplitudes, frequency content and near-source scaling of ground motions. A generic finite-fault model has been developed (Beresnev and Atkinson, 1997, 1999, 2001; Motazedian and Atkinson, 2003) and can be applied to the development of improved ENA ground motion relations. In this project, we are extending the generic ENA ground motion relations by explicitly considering finite-fault effects. Comparisons of finite-fault and point-source motions are also being made.
2. All of the current ENA ground motion relations use the attenuation model developed by Atkinson and Mereu (1992). This model was based on the analysis of about 1000 seismographic recordings of earthquakes in southeastern Canada and the northeastern United States, to determine overall geometric spreading and anelastic attenuation (Q model). The data were recorded from 1980-1990 on vertical-component short-period instruments (covering the 1 – 15 Hz frequency band). Since 1990, many 3-component broadband instruments have been installed. There is now a much more powerful database available for attenuation analyses. We have re-examined these widely-quoted attenuation results using modern broadband data, specifically including horizontal-component data, recorded in the eastern United States and Canada.

Progress to Date

A. Regression analysis of recent broadband seismographic data

A database of 1700 digital seismograms from 186 earthquakes of magnitude mN2.5 to 5.6 that occurred in southeastern Canada and the northeastern United States from 1990-2003 was compiled. Maximum-likelihood regression analysis of the database was performed to determine a model for the attenuation of Fourier spectral amplitudes for the shear-window, for the vertical and horizontal component of motion, for frequencies from 0.2 to 20 Hz. Fourier amplitudes follow a hinged trilinear attenuation model. Fourier spectral amplitudes decay as $R^{-1.3}$ (where R is hypocentral distance) within 70 km of the source. There is a transition zone from 70 km to 140 km as the direct waves are joined by strong post-critical reflections, where the attenuation is described as $R^{+0.2}$; spectral amplitudes actually increase with distance in this range for low frequencies. Beyond 140 km, the attenuation is well described by $R^{-0.5}$, corresponding to geometric spreading in two dimensions. The associated model for the regional Quality factor for frequencies greater than 1 Hz can be expressed as $Q = 893\ f^{032}$. Q can be better modeled over a wider frequency range (0.2 to 20 Hz) by a polynomial expression: $\log Q = 3.052 - 0.393 \log f + 0.945 (\log f)^2 - 0.327 (\log f)^3$. The polynomial expression accommodates the observation that Q values are at a minimum (about 1000) near 1 Hz, and rise at both lower and higher frequencies. Correction factors for the spectral amplitude model that describe the effects of focal depth on the amplitudes and their attenuation are developed using the subset of events with known focal depth. The attenuation model is similar to that determined from an earlier study with more limited data (Atkinson and Mereu, 1992) but the enlarged database indicates more rapid near-source amplitude decay and higher Q.

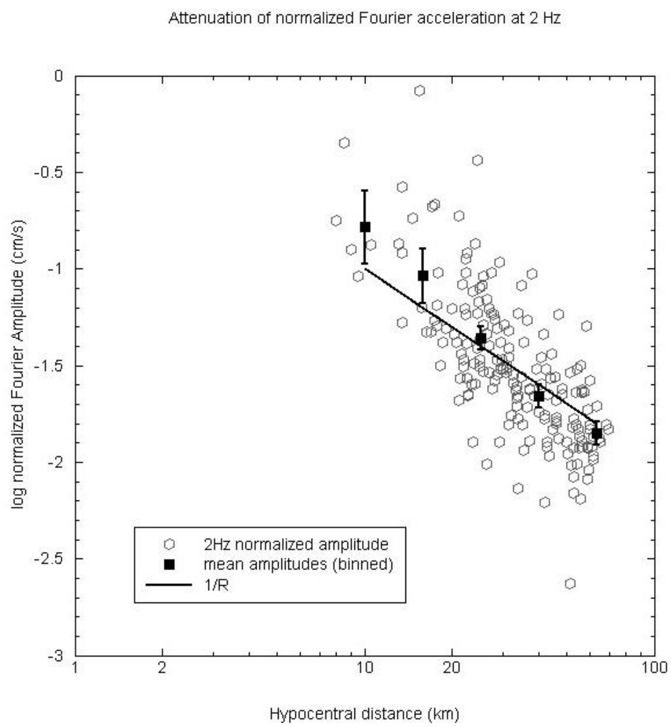

Figure 1 *– Attenuation of normalized 2-Hz Fourier spectral amplitudes, for all events having at least 3 observations within 70 km of the earthquake source. Normalization is done by subtracting an initial estimate of the earthquake's source amplitude from each observation. Error bars are 90% confidence limits on mean amplitudes in distance bins.*

The conclusion that an attenuation slope steeper than 1.0 is required for $R \le 70$ km is an important new finding. The shape of the near-source attenuation can be illustrated by using just earthquakes that were recorded within 70 km on at least three stations; there are 270 data points in this subset. I assume that the source spectra for each earthquake in this subset, at low-to-intermediate frequencies, can be estimated by correcting all observed spectra for geometric spreading by multiplying by R (thus I am not preconditioning the result in any way by assuming a steeper attenuation). At frequencies ≤ 2 Hz, anelastic attenuation effects for observations within 70 km are negligible (<10%). The source spectra for each earthquake is estimated by averaging (log average) the attenuation-corrected spectra over all stations that recorded the event (hence the requirement that each event be recorded at at least three stations). I then subtract the log source spectrum for the event from each of its observed log spectra, to obtain spectral amplitudes that have been normalized to a common source level (log amplitude = 0 at R= 1km). The normalized spectral amplitudes are thus defined as:

$$\log An_{ij}(f) = \log A_{ij}(f) - (1/N) \sum_{i=1}^{N} (\log A_{ij}(f) + \log R_{ij}) \quad (1)$$

where An_{ij} is the normalized amplitude for earthquake i at station j, A_{ij} is the observed amplitude of earthquake i at hypocentral distance R_{ij}, and the sum is over the N stations that recorded earthquake i. Figure 1 plots the log normalized spectral amplitudes at a frequency of 2 Hz, along with the mean and 90% confidence limits of these data grouped into distance bins that are 0.2 log units in width. It is clear on Figure 1 that the attenuation is significantly steeper than that defined by 1/R. Regression of the normalized log amplitudes of Figure 1 indicates a slope of 1.41, with 95% confidence limits of 0.19 on the slope coefficient. Thus we can be 95% confident that the true slope is steeper than 1.2.

The attenuation model is used to play back attenuation effects to determine the apparent source spectrum for each earthquake in the database and hence determine moment magnitude (**M)** and Brune stress drop. The events have moment magnitude in the range from 2.5 to 5. Stress drop increases with moment magnitude for events of **M**<4.3, then appears to attain a relatively constant level in the range from 100 to 200 bars for the larger events, as previously noted by Atkinson (1993).

The results of this task further our understanding of attenuation in the region through analysis of an enlarged ground-motion database. In particular, the inclusion of the 3-component broadband data gathered over the last decade allows extension of attenuation models to both horizontal and vertical components over a broad frequency range (0.2 to 20 Hz). These attenuation models, and constraints obtained on source parameters, are the most important input information into the generation of updated ground motion relations. This work will be published soon (Atkinson, 2004).

B. Empirical Green's Function Analysis

We have made detailed comparisons of source spectra obtained by correcting observations for regional attenuation and site parameters (referred to as the 'Direct Method') to those obtained using the Empirical Green's function (EGF) approach. This work is important because source spectra obtained by the Direct Method, based on regional seismograms, are considered controversial. It has been suggested that the apparent source spectra may be dominated by propagation effects and may not accurately represent the amplitude and frequency content of the source radiation (eg. Haddon, 1996). If this were true, it would limit the usefulness of such apparent spectra in predicting ground motions from future earthquakes; the predictions would only be reliable for the magnitude and distance ranges represented in the empirical database (as used in the regressions for source parameters). To address this criticism, Direct Method source spectra were being compared to those obtained using the well-known EGF approach. In the EGF approach, the Fourier spectrum of a target event is divided by the Fourier spectrum of a small EGF event, located at the same location, and with the same focal mechanism (and recorded at the same station). The attenuation and site terms cancel in the spectral division, yielding the ratio of the source spectrum of the target event to that of the EGF event. If the EGF event is sufficiently small (at least 1 to 2 magnitude units smaller than the target event, in general), then its displacement spectrum will be flat over the frequency band of interest. In this case, we have obtained the shape of the source spectrum of the target event, free of path and site contamination. We need only adjust it by a constant factor representing the displacement level of the EGF event, in order to obtain the amplitude spectrum of the target event. The beauty of the EGF approach is that allows the source spectrum to be easily separated from path and site effects. The drawback is that it is limited to cases where suitable EGF events can be found.

In this project, we implemented comparisons of the Direct and EGF approach in the Charlevoix seismic zone, and for the 2002 Au Sable Forks, NY earthquake. In each case, we use the EGF approach to determine the source spectrum for the target event. The EGF source spectrum is then compared to that determined by correcting the observed Fourier spectra for attenuation and site effects, using the results from the regression analyses. From these comparisons, we conclude that both the Direct and EGF methods yield the same result in terms of the source spectrum. The work on this aspect of the study for the Charlevoix seismic zone was published in 2001 (Sonley and Atkinson, 2001), while the work on the Au Sable Forks earthquake was published in 2003 (Atkinson and Sonley, 2003).

C. Development of ENA Ground Motion Relations

The results of the first two tasks are currently being used in the development of updated ground motion relations for ENA. This work continues the long-standing collaboration of Atkinson and Boore in this area of research. We are re-examining each of the input parameters used in our 1995 ground motion relations (Atkinson and Boore, 1995), beginning with the source representation. The finite-fault effects of the source may be represented either by a revised two-corner model, or more directly through the use of a stochastic finite-fault model. We are implementing both approaches for comparison purposes. Advantages of using the stochastic finite-fault model are that it is more transparent, flexible, and allows quantification of variability due to directivity. The new information on propagation, including the extension of attenuation results to lower frequencies, has been formulated as a revised propagation model. Information on regional crustal velocity profiles has been used to model the amplification effects due to propagation through the crustal velocity gradient (for ENA rock sites these effects are small but not negligible). Uncertainty in each of the model parameters is being quantified in order to allow quantification of uncertainty in the derived ground motion relations.

Stochastic simulations, including finite-fault effects, are being used to develop new ground motion relations for ENA. Relations will be developed for response spectra (several damping values) and peak ground motion parameters, including both peak ground acceleration and peak ground velocity. Peak ground velocity is significant due to its current use in assessing instrumental intensity for use in rapid Shake Maps (eg. Wald et al., 1999). Uncertainty in the median relations due to uncertainty in the input parameters will be assessed.

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