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 are widely used today. 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 (2002) and Somerville et al. (2002); these are still in the review and evaluation stage.) In this 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 and calibrated against all well-recorded earthquakes in both eastern and western North America (Beresnev and Atkinson, 1997, 1999, 2001), and can now 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.
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 are re-examining 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

This is the first year of the two-year research program. The progress to date has focused on the use of new empirical data to further constrain our estimates of source, path and site effects for the eastern and central U.S. We are using new broadband data collected over the last few years in small to moderate earthquakes in ENA, including data from the 20 April, 2002 **M** 5.0 Au Sable Forks, NY earthquake. These data allow attenuation and source issues to be addressed over a much broader bandwidth than previous data analyses (such as Atkinson and Mereu, 1992), and widen the scope to three components of motion. To date, we have obtained and processed hundreds of broadband records from moderate ENA events, correcting them for instrument response to compile a new three-component broadband database of Fourier and response spectra amplitudes, for all events of M > 3. Figure 1 shows a sample of the response spectral database for ENA events of **M** 5.0 (±0.2), including the recent Au Sable Forks event, in comparison to a number of proposed ENA ground motion relations.

At present, regression analyses are being performed on the Fourier spectral amplitudes, using the maximum likelihood method, to develop an equation for the decay of spectral amplitudes as a function of magnitude, distance and frequency. The long-period Fourier displacement level for each event will be used to calculate its moment magnitude, enabling comparisons of moment and catalog magnitudes. The behaviour of the Fourier spectral amplitudes and their attenuation with distance is a critical input to the development of ground motion relations.

In previous studies (Atkinson and Mereu, 1992; Atkinson and Boore, 1995), it has been determined that the geometric attenuation can be described by a "hinged-trilinear" form. This is explained by the presence of strong postcritical reflections from the Moho discontinuity that cause "flattening" of the attenuation curve, leading to almost no apparent geometric spreading between approximately 70 and 130 km (Somerville and Yoshimura, 1990; Atkinson and Mereu, 1992). We constrain the attenuation by using this previously-determined geometrical spreading function, then check the adequacy of the model through analysis of regression residuals. The analysis of residuals (where the residuals are defined as the ratio of observed to model amplitudes) is a useful tool to check model validity, and evaluate uncertainties in regression coefficients.

In summary, then, regression of the broadband database is in an advanced stage, and will be used to improve our knowledge of source and attenuation in ENA over a broad frequency range. This information is important for modeling ground motions from future large earthquakes, particularly at intermediate frequencies, which have not been well represented in previous databases.

B. Empirical Green's Function Analysis

We are making 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 is 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 are 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 to date, we have implemented comparisons of the Direct and EGF approach in the Charlevoix seismic zone, and for the recent 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 has already been published (Sonley and Atkinson, 2002), while the work on the Au Sable Forks earthquake has recently been submitted for publication to Seism. Res. L. (Atkinson and Sonley, 2002).

C. Development of ENA Ground Motion Relations

The results of the first two tasks will be exploited in the development of updated ground motion relations for ENA. This task will be conducted in the second year of this project. This work will continue the long-standing collaboration of Atkinson and Boore in this area of research. We will re-examine 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 favoring the direct use of the stochastic finite-fault model, as it is more transparent, flexible, and would allow quantification of variability due to directivity. The new information on propagation, including the extension of attenuation results to lower frequencies, will be formulated as a revised propagation model. Information on regional crustal velocity profiles will be 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). Soil response for typical generic profiles will also be defined. Uncertainty in each of these model parameters will be quantified in order to allow quantification of uncertainty in the derived ground motion relations.

Stochastic simulations, including finite-fault effects, will be 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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Figure 1: Comparison of ground motions from ENA earthquakes of **M** 5.0 ± 0.2 with several ENA ground-motion relations for rock site conditions. Relations are horizontal-component pseudo-acceleration, 5% damped, according to Atkinson and Boore, 1995 (AB95), Toro et al., 1997 (T97), Campbell, 2002 (C2002) and Somerville et al., 2002 (S2002).