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Predicting Earthquake Ground Motion in North America

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ABSTRACT

Predicting ground-motions for engineering purposes in all of North America requires multiple sets of equations, derived in different ways. For earthquakes in the tectonically-active western part of North America equations can be largely or entirely based on recorded ground motions. For earthquakes in most of North America, however, recorded data are not adequate for direct predictions of ground motions and prediction equations must be based on a combination of empirical data and simulated ground motions. This article reviews the ground-motion prediction equations developed by Gail Atkinson and myself for crustal and subduction-zone earthquakes in western North America and intraplate earthquakes in the rest of the continent.

Introduction

Predictions of earthquake ground motions in North America requires multiple sets of equations because of differences in source and path properties. In practice, equations for predicting ground motions for earthquakes in three distinct tectonic regimes have been used in North America: the intraplate (essentially, east of the Rocky Mountains), subduction zone, and the rest (western North America excluding the subduction zones extending northward from northern California). The subduction earthquakes are further divided into earthquakes along the interface of the subducting slab and earthquakes within the slab. For each type of earthquake a number of different ground-motion prediction equations (GrMPEs) are used in practice. These include GrMPEs published by my colleague Gail Atkinson and myself. This paper summarizes those papers.

GrMPEs and Hazard Maps

The distance and magnitude ranges for which ground motions need to be predicted in North America are governed by the earthquake size and locations that might affect a site. These can be extremely variable over the continent, leading to the need for GrMPEs to be applicable over a wide range of magnitudes, distances, and source type. As an illustration, I show below a deaggregation for the 2% in 50 years seismic hazard for New York, New York, for 1 sec spectral acceleration.

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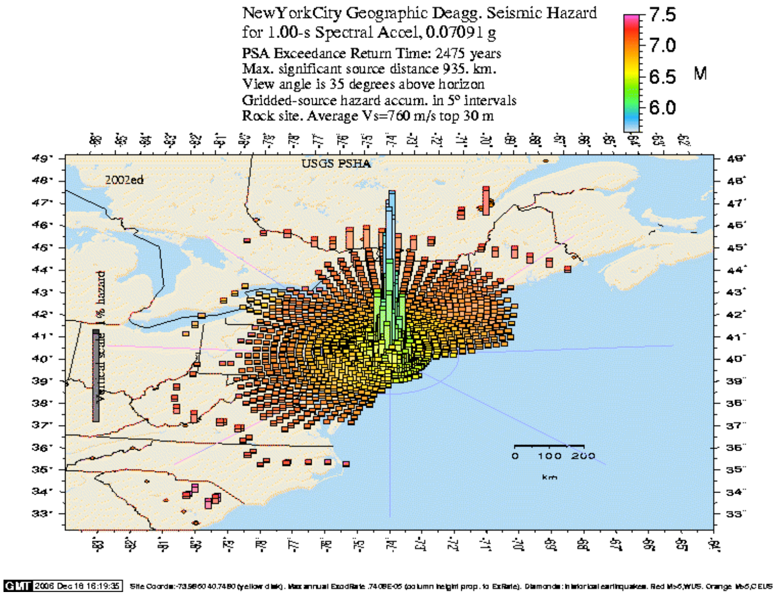

Figure 1. Deaggregation for New York, New York (see text).

In this figure and subsequent figures, the relative contribution to the hazard is given by the height of each bar; the magnitude for each bar location is given by the colors (the maps are from the interactive deaggregation link for the 2002 U. S. Geological Survey National Seismic Hazard Maps, reached from http://earthquake.usgs.gov/research/hazmaps/products_data/index.php). Figure 1 indicates that the 1-sec seismic hazard at New York is dominated by nearby local sources with magnitudes less than 6. In contrast, consider the deaggregation for Oberlin, Ohio:

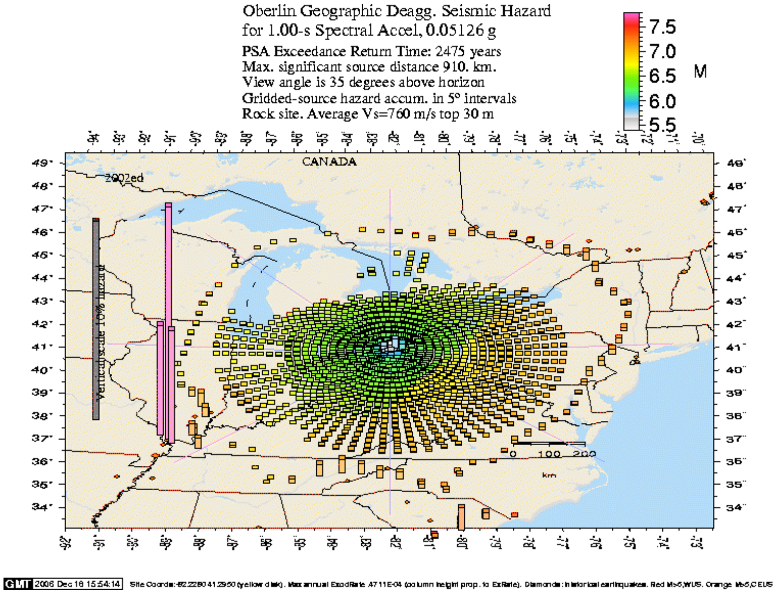

Figure 2. Deaggregation for Oberlin, Ohio.

Here the hazard is dominated by earthquakes whose magnitudes are in excess of 7, located along the New Madrid seismic zone, hundreds of kilometers from Oberlin, Ohio. When well-defined active faults are near a site, then obviously the hazard will be dominated by earthquakes on those faults. A good example is shown in Figure 3, for San Francisco, California.

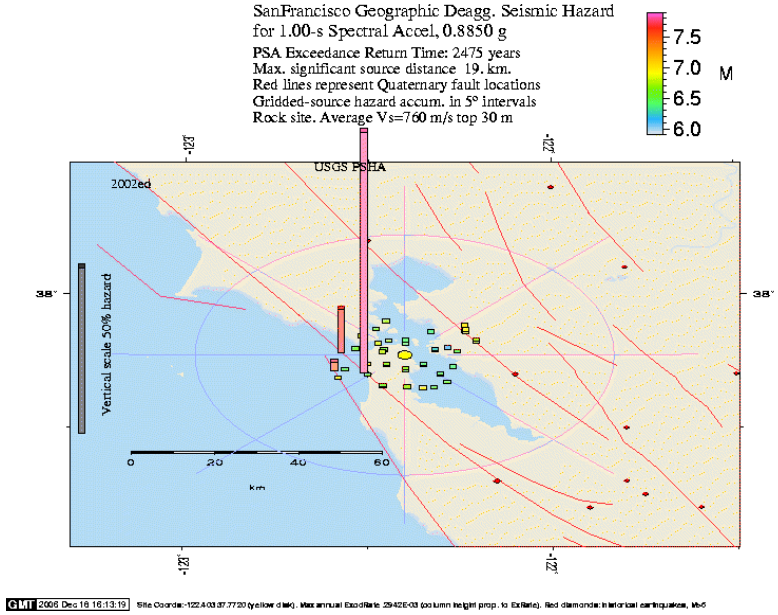

Figure 3. Deaggregation for San Francisco, California.

Here the hazard comes almost entirely from earthquakes on the nearby San Andreas fault. As a final example, consider the hazard for Portland, Oregon:

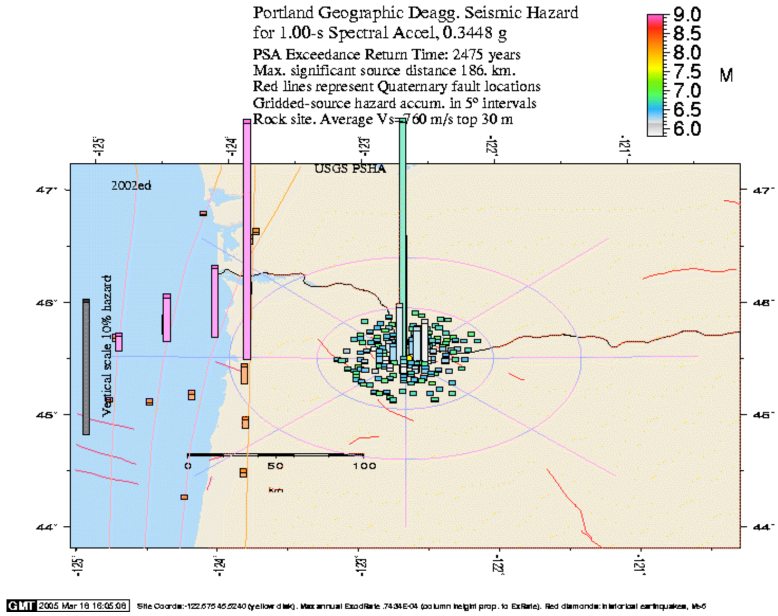

Figure 4. Deaggregation for Portland, Oregon.

Here there are two main contributors to the hazard: moderate size, nearby earthquakes, and great earthquakes on the subduction zone to the west.

The Atkinson-Boore Ground-Motion Prediction Equations for North America

Recognizing that different sets of prediction equations are need for the situations arising in hazard calculations in North America, Gail Atkinson and I have published three sets of prediction equations; two of these have been updated recently. Ideally, predictions would be based on recordings of ground motions for the distances and magnitudes of most concern. For many situations, however, the available data are not adequate for this task. For example, the following figures show the distribution of recordings in magnitude—distance space used for the three sets of ground-motion predictions: Figure 5 for Boore and Atkinson's (2006) equations as part of the PEER NGA project to revise a number of widely-used equations for tectonically active regions, for crustal earthquakes (a revision of the Boore et al.,1997, equations) and Atkinson and Boore's (2006) equations for eastern North America (a revision of Atkinson and Boore, 1995); Figure 6 for Atkinson and Boore's (2003) equations for subduction-zone earthquakes.

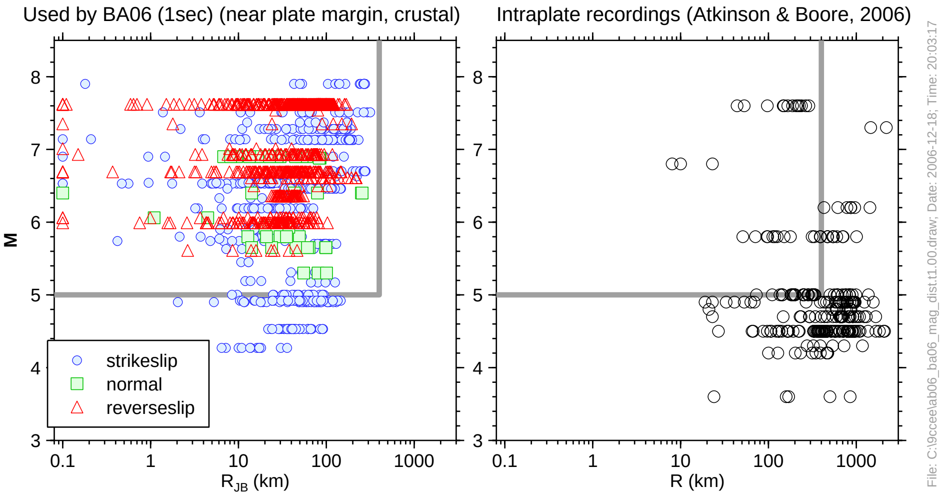

Figure 5. M and R distribution of recordings used by Boore and Atkinson (2006) and by Atkinson and Boore (2006) for predicting 1 sec spectral accelerations. The box outline in gray is an approximation of the region of most engineering interest.

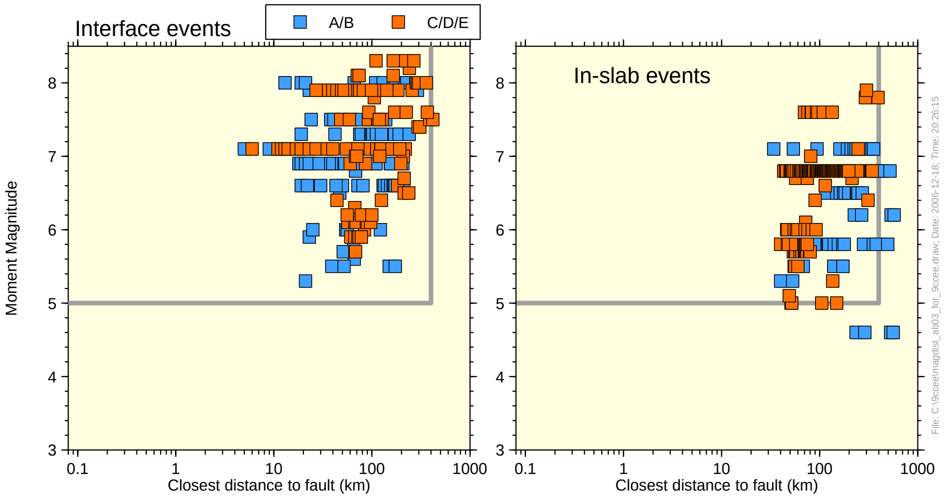

Figure 6. M and R distribution of recordings used by Atkinson and Boore (2003) for predicting 1 sec spectral accelerations for subduction-zone earthquakes. The box outline in gray is an approximation of the region of most engineering interest.

Crustal Earthquakes in Tectonically-Active Regions.

To the extent that ground motions produced by crustal earthquakes in tectonically active regions are similar to those from crustal earthquakes in western North America, the left side of Figure 5 indicates that empirically-based GrMPEs can be derived (even then, however, there remain some critical regions in M—R space for which data are sparse). Based on this, Boore and Atkinson (2006) and four other developer teams have recently derived GrMPEs for crustal earthquakes in tectonically active regions (the work was the main task of the large multiyear Pacific Earthquake Engineering Research Center Next Generation Attenuation project (PEER NGA)). The Boore and Atkinson (2006) (BA06) work was an update of the Boore et al. (1997) (BJF97) equations (see Boore, 2005, for an erratum). The following plot compares predictions from the old and new equations, for T = 1 sec.

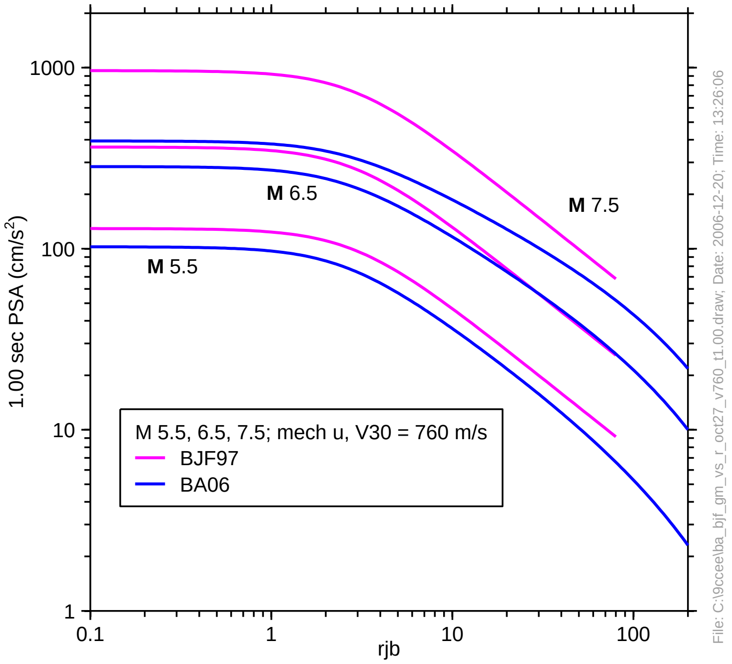

Figure 7. Predictions of 1 sec, 5%-damped spectral acceleration for crustal earthquakes in tectonically active regions, for V30 = 760 m/sec (NEHRP BC boundary) and mechanism unspecified. Predictions are shown for the old and the new equations.

The motions from the BJF97 and the BA06 equations are similar for magnitudes and distances for which data are relatively abundant. On the other hand, there is a large discrepancy for **M** 7.5 at distances less than about 80 km, with the new equations predicting much lower ground motions (in general the new PEER NGA equations predict lower motions than the previous equations). Why is there such a large discrepancy between the BA06 and the BJF97 predictions? One reason is that the BJF97 equations assumed a magnitude-independent shape of the curves. This meant that the distance between the curves was the same at all distances. The larger magnitude data were sparse at close distances, and thus the more distant data controlled the magnitude scaling at close distances. The other main reason is simply that more data from large earthquakes at distances less than 80 km are now available (see Figure 5). The magnitude scaling at a reference distance of 5 km is shown in the next figure. The symbols in that figure represent an average of all data for a given earthquake, reduced to the reference distance and to a reference value of 760 m/sec for V30. These data were used to derive the magnitude scaling for the BA06 equations (the determination was first done without consideration of fault type, and then with the magnitude dependence fixed by that regression, a second regression determined the effect of mechanism). Also shown in the figure is the magnitude scaling for the BJF97 equations (arbitrarily adjusted vertically by eye to go through the middle of the data). It is clear that the BJF97 equations overpredict the large event motions, and the magnitude saturation seems to be well supported by the data. BA06 also show that similar magnitude saturation is obtained if the data from the 1999 Chi-Chi mainshock are excluded (no aftershock records from any earthquake were using in developing BA06).

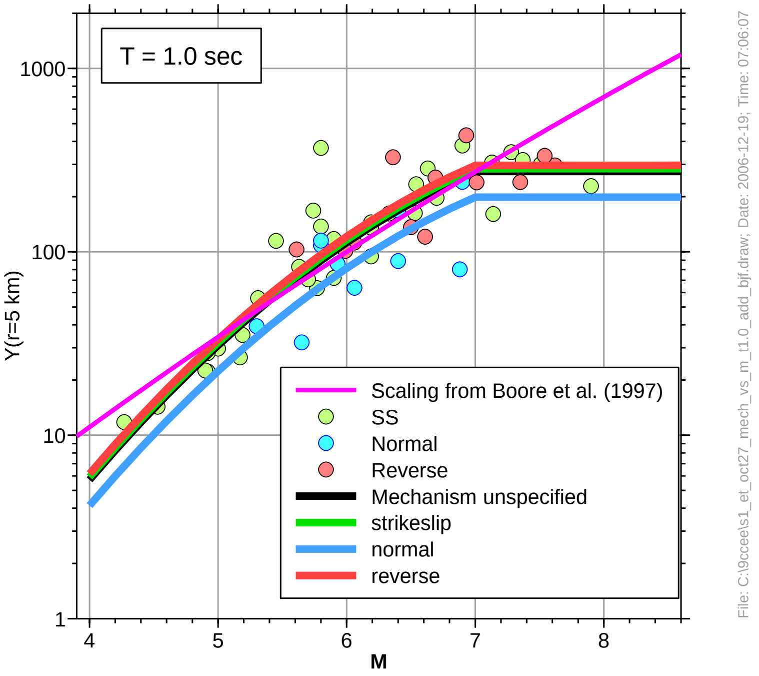

Figure 8. Magnitude scaling of data used by BA06, for T = 1 sec. Each symbol is the average of motions reduced to a reference distance of 5 km.

Subduction Zone Earthquakes.

Figure 9 contains a comparison of data from earthquakes along the interface of a subduction zone and earthquakes within the subducting slab. As Atkinson and Boore (2003) (AB03) discuss, earthquakes contributing to seismic hazard are generally larger for those occurring at the interface of the subducting slab than those within the slab. But ground motions from in-slab events tends to be larger at close distances than the motions from interface earthquakes (compare the left and right plots of Figure 9). The motions from in-slab events decay more rapidly than the interface event motions.

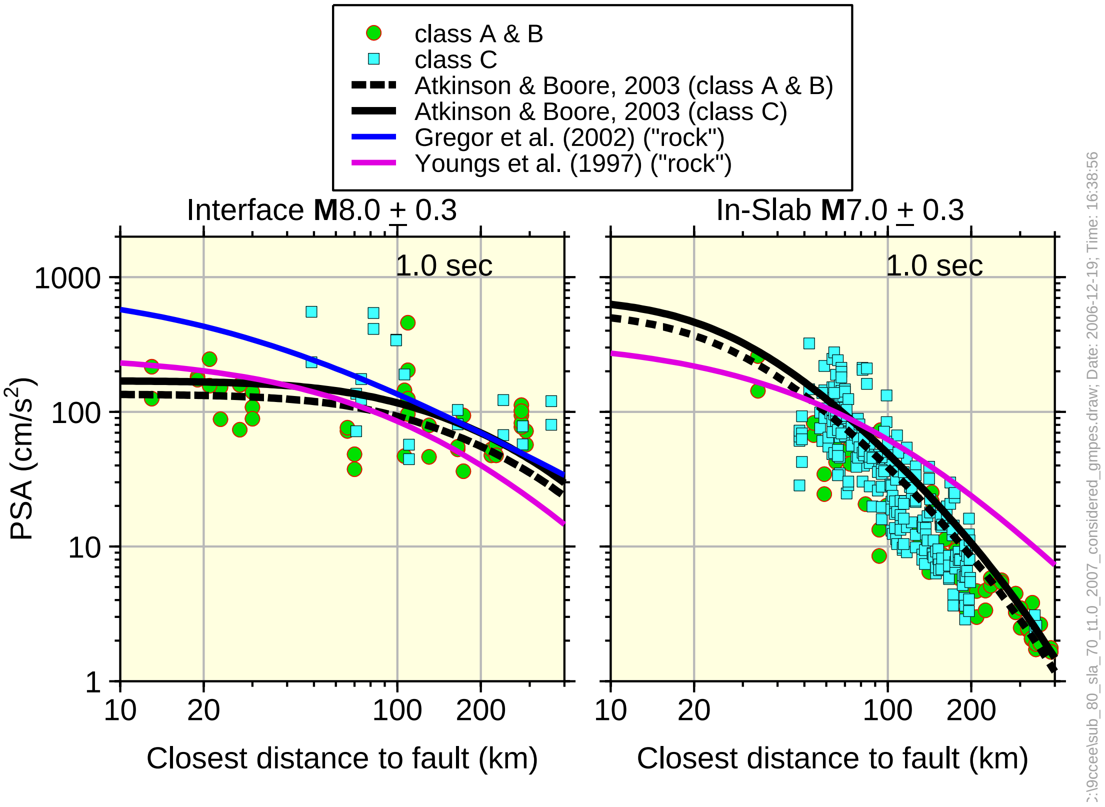

Figure 9. Subduction zone ground motion data and ground-motion predictions.

AB03 used the distribution of recordings shown in Figure 6 to develop empirical ground-motion prediction equations. Their predictions are also included in Figure 6, along with those from two other authors (Young et al., 1997, and Gregor et al., 2002). The Youngs et al equations are empirically based, but they did not have as much data as did AB03. Note in particular that Youngs et al. assumed that the distance decay is the same for both classes of events, but the data clearly indicate otherwise. The Gregor et al. predictions are based on theoretical simulations. Although I believe that data should trump theory, it is also important to realize that none of the large-magnitude interface-event data are from the Cascadia subduction zone. For this reason it might be worthwhile combining observed and simulated data in an update of AB03.

The differences in decay rate, amplitudes at near-to-intermediate source distances, recurrence rates, and magnitude distributions lead to important differences in seismic hazard for the two types of events.

Intraplate Earthquakes

It is clear from Figure 5 that adequate data are not available for deriving GrMPEs in eastern North America. For this reason, GrMPEs in eastern North America are usually based on theoretical simulations of ground motions, with parameters such as the manner in which waves of different frequency decay with distance controlled, when possible, by recordings of smaller earthquakes. Using this procedure, Atkinson and Boore (1995) (AB95) published equations and tables of ground motions for eastern North America; these equations were recently updated by Atkinson and Boore (2006) (AB06). The simulation parameters are based on empirical information on source and attenuation parameters; they are validated using the limited ENA ground-motion data. The figure below compares ground motions from the AB95 and AB06 equations.

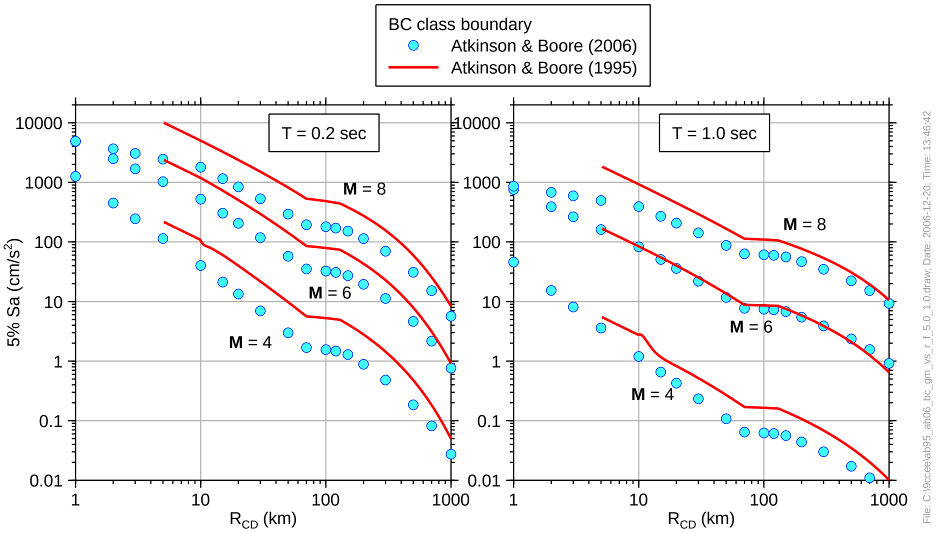

Figure 10. 0.2 and 1 sec spectral accelerations from the GrMPEs of Atkinson and Boore (1995) and Atkinson and Boore (2006), for a BC-boundary site class (V_{30} = 760 m/sec).

The procedures for simulating the motions were different, with AB95 using point-source stochastic simulations with a double-corner-frequency model in an attempt to mimic the effect of finite faulting. AB06 used a stochastic finite-fault model, and the source parameters were slightly different. The difference in models can account for some of the difference at close distance, but most of the difference has a simpler explanation: the geometrical spreading out to 70 km was described by $1/R$ in AB95 and $1/R^{1.3}$ in AB06. The latter geometrical spreading is taken from Atkinson (2004). The following figure shows the distribution of data used in her analysis.

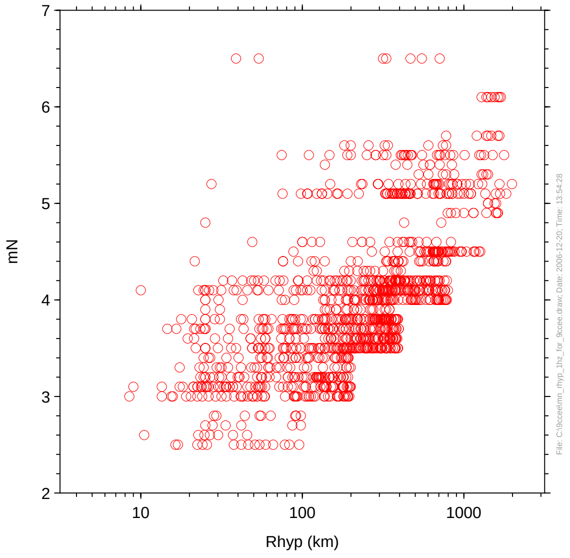

Figure 11. Distribution of data for distance dependence of ground motion in ENA.

I repeated her analysis, using a different method for removing the source-to-source differences (necessary because data from a wide range of magnitudes was used). I found that if anything, the ground motions decay somewhat more rapidly than $1/R^{1.3}$. A $1/R^{1.3}$ spreading has also been found for southeastern Australia (T. Allen, personal communication, 2006). Because most other authors of GrMPEs for ENA assume $1/R$ geometrical spreading within 70 km, the AB06 predicted ground motions will be systematically lower than others, if the same source parameters are used.

Conclusions

Because of the variability in seismicity and crustal structure in North America, no single set of equations can be used to predict ground motions. Instead, equations are developed for various source/path situations. Most commonly, these equations are developed for earthquakes in relatively stable intraplate regions, for earthquakes in subduction zones, and for earthquakes located along and near active non-subduction plate boundaries. Many such sets of equations have been published. In this article I have discussed briefly those by myself and my collaborator, Gail Atkinson.

Acknowledgments

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References

Atkinson, G. M., 2004. Empirical attenuation of ground-motion spectral amplitudes in southeastern Canada and the northeastern United States, *Bull. Seism. Soc. Am.* 94, 1079—1095.

Atkinson, G. M., and D. M. Boore, 1995. Ground motion relations for eastern North America, *Bull. Seism. Soc. Am.* 85, 17-30.

Atkinson, G. M., and D. M. Boore, 2003. Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions, *Bull. Seism. Soc. Am.* 93,1703-1729.

Atkinson, G. M., and D. M. Boore, 2006. Earthquake ground-motion prediction equations for eastern North America, *Bull. Seism. Soc. Am.* 96, (in press).

Boore, D. M., 2005. ERRATUM: Seismological Research Letters, Vol. 68, No. 1, pp. 128-153, January/February 1997, Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work, D. M. Boore, W. B. Joyner, and T. E. Fumal, *Seism. Res. Letters* 76, 368-369.

Boore, D. M., and G. M. Atkinson, 2006. Boore-Atkinson provisional NGA empirical ground-motion model for the average horizontal component of PGA, PGV and SA at spectral periods of 0.05, 0.1, 0.2, 0.3, 0.5, 1, 2, 3, 4, and 5 seconds, report to the PEER-Lifelines Next Generation Project [Revised 27 October 2006] [http://peer.berkeley.edu/lifelines/nga_docs/nov_13_06/Boore-Atkinson-NGA_11-13-06.html].

Boore, D. M., W. B. Joyner, and T. E. Fumal, 1997. Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work, *Seism. Res. Letters* 68, 128-153.

Gregor, N. J., W. J. Silva, I. G. Wong, and R. R. Youngs, 2002. Ground-motion attenuation relationships for Cascadia subduction zone megathrust earthquakes based on a stochastic finite-fault model, *Bull. Seism. Soc. Am.* 92, 1923-1932.

Youngs, R., S. Chiou, W. Silva, and J. Humphrey, 1997. Strong ground motion attenuation relationships for subduction zone earthquakes, *Seism. Res. Letters* 68, 58-73.