

# On the Calibration of the Specific Barrier Model to Eastern North America Earthquakes

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## Summary

*The paucity of high-quality strong motion data for moderate and large earthquakes in Eastern North America (ENA) makes it difficult to reliably estimate strong ground motions for future earthquake events in the region. The stochastic modeling approach, which utilizes a seismological model to describe the spectral amplitudes of the ground motion and their relationship with the earthquake size, is arguably the only viable method of ground motion prediction in ENA. The source model used in the present study is the "specific barrier model" proposed and developed by Papageorgiou and Aki (1983a, 1983b, 1985) and Papageorgiou (1988). This paper presents results of the calibration of the "specific barrier model" using the available strong motion database of ENA earthquakes.*

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## Introduction

Prediction of seismic hazard in tectonic regions of moderate-to-low seismicity, such as Eastern North America (ENA), is a difficult task due to the paucity of available data for such regions. The "stochastic modeling approach" has been extensively used in the past for the prediction of strong ground motion in ENA. Various earthquake source models such as the " $\omega^2$  model" (Brune 1970, Frankel et al., 1996) have been employed for this purpose (Atkinson and Boore 1998). A more physically realistic source model is the "specific barrier model" proposed and developed by Papageorgiou and Aki (1983a, 1983b, 1985) and Papageorgiou (1988). This model may be used for "far-field" as well as for "near- source" strong motion prediction.

This paper presents results of the calibration of the "specific barrier model" using the available strong motion database of ENA earthquakes. Estimates of "global" and "local" stress drops believed to be representative of earthquake sources in ENA are presented and a "scaling law" (i.e., the variation of source spectrum scales with respect to the earthquake size) for the source spectra of ENA earthquakes is proposed.

## Spectral Response Data

The strong motion database utilized in this study for the calibration of the "specific barrier model" comprises the pseudo-spectral acceleration data recorded on rock used by Atkinson and Boore (Tables 1 and 2 in Atkinson and Boore, 1998) for the evaluation of earthquake source models for ENA, with the exception of four historical ENA events. The remaining events are shown in Table 1. Events of magnitude greater than 5.8 occurred in other intraplate regions that are believed to be tectonically similar to ENA (Atkinson and Boore, 1998). Only PSV (= pseudo-velocity response)

data associated with frequencies of oscillation equal to 1, 2, 5 and 10 Hz were used because they were available.

Furthermore, four different variations of the datasets were considered for the calibration of the model for comparison purposes:

Dataset 1 (AB98): all the events included in Table 1 of Atkinson and Boore (1998).

Dataset 2: the dataset shown in Table 1.

Dataset 3: the dataset shown in Table 1 excluding the 1988 Saguenay mainshock.

Dataset 4: data for the Saguenay earthquake only.

**Table 1. Seismic events from which response spectral data has been utilized in calibrating the "specific barrier model" to ENA earthquakes.  $N$  indicates the number of records for which spectral response data at frequencies 1, 2, 5 and 10 Hz is used.**

Date	Event	$M_w$	$N$
05/17/76	Gazli, USSR	6.8	2
09/16/78	Tabas-e-Golshan, Iran	7.4	4
01/19/82	Gaza, NH	4.3	6
10/07/83	Newcomb, NY	5.0	16
01/31/85	Painesville, OH	4.8	9
12/23/85	Nahanni, NT, CA	6.8	6
07/12/86	St. Marys, OH	4.5	5
11/23/88	Saguenay (fs), QC, CA	4.2	11
11/25/88	Saguenay (ms), QC, CA	5.8	28
10/19/90	Mont Laurier, QC, CA	4.5	17
06/15/91	Georgia, USSR	6.2	2

## Seismological Model

Central to the stochastic modeling approach is the spectral scaling of the seismic radiation of the seismological model implemented for the prediction of ground motion (Boore 1983, Boore and Atkinson, 1987). Use of random vibration theory allows for the prediction of extreme ground motion parameters such as the peak response of a harmonic oscillator (Cartwright and Longuet-Higgins, 1956, Boore 1983).

The "specific barrier model" is adopted as source model. Once the moment magnitude, average shear velocity of the medium and the rupture velocity are given, the "specific barrier model" is uniquely determined by two parameters: the "global" and "local" stress drops  $\Delta\sigma_G$  and  $\Delta\sigma_L$ , respectively (Papageorgiou 1988). The ratio of rupture velocity to shear velocity is set equal to 0.8.

Other elements of our seismological model such as path and site effects were considered according to Atkinson and Boore (1995). However, since various investigators have accounted for path effects in different ways, it was decided to implement and test some of these descriptions. An attempt is made to discriminate among these various ways to account for path effects by evaluating the quality of fit of their predictions to the available data. Therefore, three variations of the seismological model mentioned before were used. Model I accounts for the attenuation of high-frequency waves by a low-pass exponential filter  $P(f) = e^{-\pi\kappa f}$  ( $\kappa$ -filter) with  $\kappa = 0.01$  in accordance with Frankel et al., (1996). Model II accounts for the attenuation of high-frequency waves by a Butterworth low-pass filter  $P(f) = [1 + (f / f_{max})^8]^{-1/2}$  with  $f_{max} = 50$  Hz ( $f_{max}$ -filter). Model III makes use of the abovementioned  $f_{max}$  filter and utilizes Boore and Atkinson's geometrical spreading factor (Boore and Atkinson 1987), which changes from  $1/r$  to  $1/(r r_x)^{1/2}$  at distance  $r_x$  in order to account for the observed transition of body waves to surface waves at around  $r_x = 100$  km in ENA.

The quality factor  $Q(f)$  is in all models expressed using an empirical functional form proposed by Boore (1985), which was fitted to match Atkinson and Boore's  $Q(f) = 680 f^{-0.36}$  (Atkinson and Boore, 1995) at intermediate and high frequencies. Site amplification factor was assumed equal to unity in all models, which is a reasonable assumption for "very hard rock" in ENA (Boore and Joyner, 1997).

## Results

Calibration of the seismological model to spectral response data and calibration of the "specific barrier model" to inferred source spectra were performed using a "weighted" nonlinear least squares regression based on the modified Levenberg-Marquardt algorithm (VNI 1991).

Fitting of Model I to the datasets in Table 2 using both the "global" and "local" stress drop parameters of the "specific barrier model" as "free" inversion parameters resulted in "global" stress drops ranging from 30 to 50 bar. A "global" stress drop value of  $\Delta\sigma_G = 45$  bar was then assumed, which is consistent with Haddon's estimate of the source area of the 1988 Saguenay mainshock event (Haddon 1995) and with empirical relationships between moment magnitude and fault area proposed by Wells and Coppersmith (1994).

In order to infer a similarly representative value of the "local" stress drop,  $\Delta\sigma_G$  was set equal to 45 bar and then inversions of Models I, II and III were carried out using the spectral response datasets indicated in Table 2 and treating  $\Delta\sigma_L$  as the only inversion parameter. Results are given in Table 2, where  ${}^i\Delta\sigma_L$  and  ${}^i\sigma$  correspond to seismological models  $i = I, II$  and  $III$  and  ${}^i\sigma$  denotes the non-weighted standard deviation of the residual between the logarithm of measured values and the logarithm of predicted values (referred to in what follow simply as "the standard deviation").

Table 2 suggests that, except for Dataset 4, all the other datasets give a very stable value for  $\Delta\sigma_L$ . Judging from the standard deviations, Model III clearly has the largest residuals, hence Models I and II are preferred. It is observed that the inversions cannot clearly discriminate between Models I and

II (i.e., whether a high-frequency  $f_{max}$ -filter or a  $\kappa$ -filter is preferable). This is very likely related to the fact that the available data cover a rather narrow (ENA events) frequency range (1 to 10 Hz).

The standard deviation resulting from inversions using Dataset 2 is significantly reduced from that for Dataset 1, which means that exclusion of the data of the four historical events was warranted.

**Table 2. Results of the calibration of the "specific barrier model" using spectral response data.  $I\sigma_{400}$  is the standard deviation of model I with  $\Delta\sigma_L = 400$  bar.**

No.	Dataset	$I\Delta\sigma_L$	$I\sigma$	$II\Delta\sigma_L$	$II\sigma$	$III\Delta\sigma_L$	$III\sigma$	$I\sigma_{400}$
1	AB98, Table 2	185	0.37	153	0.36	224	0.38	0.36
2	Table 1	213	0.32	171	0.32	224	0.36	0.31
3	Table 1 (except *)	183	0.25	151	0.25	197	0.27	0.30
4	Saguenay data*	935	0.28	682	0.27	987	0.33	0.32

Similar scrutiny of results for Datasets 2 and 3 shows that exclusion of the Saguenay data improves the fit even further. Finally, the very high "local" stress drop values for Dataset 4 as compared to the other datasets indicate high amplitudes of ground motion for this event, as compared to what is expected on the average from other events with the same seismic moment (see section entitled **Spectral Response Data**).

However, data for events of  $M_w = 5.0$  or smaller in Table 1 include 64 records, while data for larger events include 42 records, 28 of which are provided for by the Saguenay event. The non-weighted standard deviation is therefore greatly affected. Besides, the Saguenay event is one of the largest recorded earthquakes in ENA over the last 50 years and researchers have debated over whether it was a "typical" ENA event or not (Haddon 1997). Discussion of this issue is out of the scope of this paper, but a note is made about the difference between the stress drop results for Datasets 2 and 3.

## Discussion and Conclusions

Estimates of values of the "local" stress drop obtained from the inversions using the spectral response data of Datasets 1, 2 and 3 are equal to approximately 50% of the values corresponding to a "local" stress drop of 400 bars (see last column in Table 2). However, the corresponding difference between standard deviations is not large, as observed when comparing values of  $I\sigma$  and  $I\sigma_{400}$  (Table 2), especially for Datasets 1 and 2, which include the Saguenay data.

Taking into consideration the abovementioned limitations of the available spectral response data, the following values for the two key scaling parameters of the "specific barrier model" are tentatively proposed:  $\Delta\sigma_G = 45$  bar and  $\Delta\sigma_L = 330$  bar. Figure 1 shows the scaling laws of a few source models that have been proposed for ENA earthquakes (Atkinson and Boore 1998), including the "specific barrier model" for  $\Delta\sigma_G = 45$  bar and  $\Delta\sigma_L = 330$  bar.

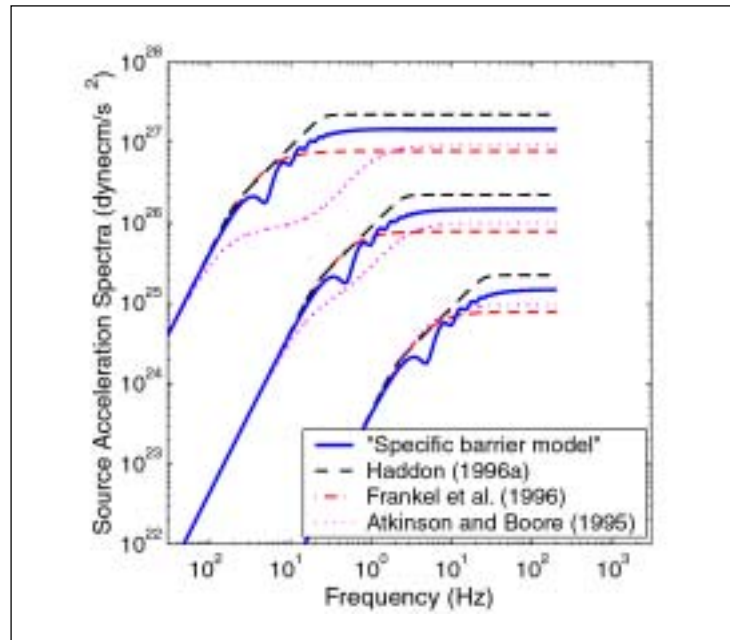


Figure 1. Acceleration source spectra for a few source models proposed for earthquakes in Eastern North America. The "specific barrier model" shown uses  $\Delta\sigma_G = 45$  bar and  $\Delta\sigma_L = 330$  bar.

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## References

- Atkinson GM, Boore DM (1995): Ground-motion relations for Eastern North America. *Bulletin of the Seismological Society of America*, **85** (1), 17-30.
- Atkinson GM, Boore DM (1998): Evaluation of models for earthquake source spectra in Eastern North America. *Bulletin of the Seismological Society of America*, **88** (4), 917-934.
- Boore DM (1983): Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. *Bulletin of the Seismological Society of America*, **73** (6A), 1865-1894.
- Boore DM (1985): The prediction of strong ground motion. *Proceedings of NATO Advanced Studies Institute on Strong Ground Motion Seismology*, Ankara, Turkey.
- Boore DM, Atkinson GM (1987): Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in Eastern North America. *Bulletin of the Seismological Society of America*, **77** (2), 440-467.

- Boore DM, Joyner WB (1997): Site amplifications for generic rock sites. *Bulletin of the Seismological Society of America*, **87** (2), 327-341.
- Brune JN (1970): Tectonic stress and the spectra of seismic shear waves from earthquakes. *Journal of Geophysical Research*, **75**, 4997-5009.
- Cartwright DE, Longuet-Higgins MS (1956): The statistical distribution of the maxima of a random function. *Proceedings of the Royal Statistical Society*, **237**, 212-232.
- Frankel A, Mueller C, Barnhard T, Perkins D, Leyendecker EV, Dickman N, Hanson S, Hopper M (1996): National seismic-hazard maps: Documentation. *Open-File Report 96-532*, U.S. Geological Survey, Reston, VA.
- Haddon RAW (1995): Modeling of source rupture characteristics for the Saguenay earthquake of November 1988. *Bulletin of the Seismological Society of America*, **85** (2), 525-551.
- Haddon RAW (1997): Reply to comment by G. M. Atkinson, et al., on "Earthquake source spectra in Eastern North America". *Bulletin of the Seismological Society of America*, **87** (6), 1703-1708.
- Kanamori H, Anderson DL (1975): Theoretical basis of some empirical relations in seismology. *Bulletin of the Seismological Society of America*, **65** (5), 1073-1095.
- Papageorgiou AS (1988): On two characteristic frequencies of acceleration spectra: patch corner frequency and  $f_{\max}$ . *Bulletin of the Seismological Society of America*, **78** (2), 509-529.
- Papageorgiou AS, Aki K (1983a): A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion. I. Description of the model. *Bulletin of the Seismological Society of America*, **73** (3), 693-722.
- Papageorgiou AS, Aki K (1983b): A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion. Part II. Applications of the model. *Bulletin of the Seismological Society of America*, **73** (4), 953-978.
- Papageorgiou AS, Aki K (1985): Scaling law of far-field spectra based on observed parameters of the specific barrier model. *Pure and Applied Geophysics*, **123** (3), 354-374.
- VNI (1991): *IMSL Stat/Library User's Manual - Version 2.0*. Visual Numerics, Inc., Houston, TX.
- Wells DL, Coppersmith KJ (1994): New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement. *Bulletin of the Seismological Society of America*, **84** (4), 974-1002.