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The implications of recent ground motion observations for theoretical predictions for Eastern North America

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ABSTRACT

Theoretical predictions of ENA ground motion parameters based on a stochastic model (Boore and Atkinson, 1987; Atkinson and Boore, 1990) are evaluated in light of recent data, including data from the 1988 Saguenay, Quebec earthquake. Data are consistent with the theoretical model on average, although high-frequency ground motions from the Saguenay earthquake are underpredicted. A more general two-corner model of the source is proposed, which would define the source spectrum of any earthquake by both moment and Nuttli magnitude.

INTRODUCTION

The Nov. 25, 1988 Saguenay, Quebec earthquake produced high-frequency ground motions that were significantly greater than those predicted by recent ground motion relations for eastern North America (ENA)(Boore and Atkinson, 1987; Toro and McGuire, 1987; Atkinson and Boore, 1990). The ENA ground motion relations were based on a simple theoretical model. High-frequency radiation was treated as finite-duration bandlimited white noise, whose amplitude spectrum was given by a seismological source model; the source model was a simple bilinear shape, defined solely by the moment magnitude of the earthquake and stress parameter (Brune model with 100 bar stress drop).

The model had been validated, to some extent, by comparisons with small to moderate ENA earthquakes, but the Saguenay earthquake (moment magnitude 6) was seen as a test of its applicability to larger events. (Note: The 1985 Nahanni earthquakes were also considered a test for larger events (Wetmiller et al., 1988), but were not as widely recorded and extensively studied.) The fact that the stochastic model did a poor job of predicting the Saguenay ground motions has raised important questions concerning the validity of the underlying seismological model. Before jumping to conclusions based on a single earthquake, it is worthwhile to step back and consider the

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implications of the new data in the broader context of the data set as a whole.

The purpose of this paper is to review the theoretical predictions of the ENA ground motion model in light of all the currently available data. The predictions are represented by the equations of Atkinson and Boore (1990) for the random horizontal component of pseudo-relative velocity (PSRV), for 5% critical damping, on ENA rock sites. The data are ENA PSRV observations (horizontal component or equivalent), for frequencies of 1 to 10 Hz (see Atkinson, 1991a for detailed tables and plots). Data were included only if they were recorded at rock sites in ENA, and the seismic moment had been reliably determined.

The Nahanni earthquakes are considered a valid inclusion in this data set because they exhibit the dominant characteristics of ENA events (Wetmiller et al., 1988): the events occurred in a region of low seismicity and high horizontal compressive stress, thrust mechanisms are dominant, surface ruptures are lacking despite shallow focal depths, and the rocks in the focal region have high seismic velocities.

COMPARISON OF OBSERVATIONS WITH PREDICTIONS

The predictions are evaluated by examining residuals, defined as the log (to the base 10) of the ratio of observations to predictions. Figure 1 plots residuals calculated for the Atkinson and Boore equations, as a function of magnitude and distance, for frequencies of 1 and 5 Hz (points which plot above the zero line represent observations larger than predicted, while points below the zero line are observations that were smaller than predicted). Frequencies of 2 and 10 Hz were also examined, but are not plotted. The Atkinson and Boore equations were derived for magnitudes 4.5 to 7.5 at distances of 10 to 500 km, so these comparisons actually stretch the range of validity of the equations considerably.

At 1 Hz, the residuals show a marked increase with R, and a decrease with M. For frequencies of 2 Hz and greater, the equations predict the data quite well for magnitudes as small as 3.6, to a log distance of 2.8 (R = 630 km), with the exception of the Saguenay ground motions (all the M 6.0 data). The Saguenay motions are much larger than predicted (by almost a factor of 10) for frequencies of 5 to 10 Hz, and show an unusually large degree of scatter. Somerville et al. (1990) interpret the Saguenay observations in terms of wave propagation effects. They argue that strong postcritical reflections produce large ground motion amplitudes in the 60 to 200 km distance range, due to the focal depth and crustal structure. However the analyses of Atkinson and Boore (1991) suggest that the large amplitudes persist over a much larger distance range.

The mean residual at all frequencies is somewhat greater than 0 (equivalent to a factor of about 1.25). The standard deviation of residuals is larger than typically observed in the west (e.g. about 0.35, as compared to typical western values of about 0.25 (Joyner and Boore, 1982)). The positive mean residuals and large standard deviations are at least partly due to the influence of the Saguenay data, but may also be attributed to the fact that the predictive equations were not derived from the data set.

The latter observation suggests that it may be enlightening to derive regression equations from the data set, and compare these to the equations based on the theoretical model. Regression analyses based on these data are described by Atkinson (1991a). The data-based regression equations produce residuals which show no persistent trends with magnitude or distance, except for the Saguenay data, which systematically exceed the overall best-fit equations at high frequencies. In other words, the equations which best fit the data set as a whole cannot fit the Saguenay observations. The equations based entirely on the data do not differ greatly from the theoretical equations, as illustrated in Figure 2. The agreement is rather remarkable considering the very different nature of the derivation methods (empirical versus theoretical).

DISCUSSION

The Atkinson and Boore (1990) equations appear to be conservative with respect to empirical results, even though the Saguenay ground motions are an important part of the empirical data set. However the scatter of the empirical relations is large, with standard deviations of the residuals being about 0.35 log units. This is greater than typical western values of 0.25 (Joyner and Boore, 1982), and may have important implications for seismic hazard evaluations.

The fact that the high-frequency ground motions are overpredicted at Nahanni and underpredicted at Saguenay raises the question as to whether the Nahanni motions are perhaps lower than 'average' due to differences in tectonic setting and stress drop between the Nahanni region and ENA. To address this possibility, Figure 3 compares the amplitude levels of the Nahanni source acceleration spectra, at frequencies above the corner frequency, to the levels for other intraplate events. The data sources and their interpretation are described by Boore and Atkinson (1989).

To show the implications of the data points for source scaling, lines have been drawn corresponding to stress parameter values of 10 and 100 bars in the simple bilinear (Brune) source model. The data suggest that, with the exception of the Saguenay mainshock, stress parameters for intraplate events scatter over the range 25 to 150 bars and have little systematic dependence on moment for M 3.5 to 7. The Nahanni mainshock appears to be consistent with other intraplate events, whereas the Saguenay mainshock does not. This discrepancy cannot be explained solely by focal depth, since the Saguenay foreshock and aftershock do not appear to have anomalous high-frequency amplitudes (all three Saguenay events occurred at depths of 25 to 30 km).

The high stress parameter implied by Figure 3 for the Saguenay mainshock (about 800 bars) does not adequately describe the nature of the discrepancy. Recall that while the model underpredicts the Saguenay earthquake's high-frequency amplitudes, it overpredicts its low-frequency amplitudes (the cross-over point is around 1 Hz). It is the nature of the simple model which fails in this case, rather than the value of the stress parameter.

The discrepancies between theoretical and empirical ground motion predictions can be used to suggest possible refinements to the underlying seismological source model. As suggested by Atkinson (1991a), the shape of the source spectrum can be revised to produce qualitative agreement between theory and observations by the introduction of a second corner frequency. However, a simple two-corner model would still underpredict high-frequency amplitudes of the Saguenay mainshock (and overpredict Nahanni), unless additional parameters are used to more closely reflect specific earthquake characteristics. In order to significantly improve the fit of the theoretical model to any particular earthquake, it appears necessary to introduce modifications to account for earthquake-specific source complexities, or distinctive source characteristics of local tectonic settings.

A simple way to accomplish this is to describe the earthquake by both its moment magnitude, M, and Nuttli magnitude, MN. Atkinson (1991b) describes a scheme for defining the source spectrum, in which the low frequency portion of the spectrum, including the lower corner frequency, is specified by the moment magnitude. The location of the higher corner frequency, and the level of the high-frequency portion of the spectrum, is specified by MN. This new shape is still simple enough to be used in developing predictive equations, but better reflects inter-earthquake variability in the high-frequency level of the spectrum.

The new source spectral model has been tested against the observations of the Saguenay earthquake (Atkinson, 1991b). The fit to the data is much improved, but still not completely satisfactory at high frequencies. In particular, PSRV is underpredicted by a factor of 1.5 to 2 at frequencies of 5 to 10 Hz. (At frequencies of 2 Hz and less, the agreement is good.) Possibly, the refinement of using a high-frequency spectral level tied to MN does not entirely predict the actual high-frequency spectral level. Alternatively, the underprediction may be attributable to wave propagation effects within the relatively small distance range examined, as suggested by Somerville et al. (1990). To examine these possibilities, the model needs to be evaluated and refined based on systematic analysis of a larger data set. Research to accomplish this goal is currently in progress. With proper modeling of the underlying source spectrum and salient propagation effects, ground motion relations can be given a sounder theoretical underpinning. This should ultimately lead to better agreement with ground motion data.

ACKNOWLEDGMENTS

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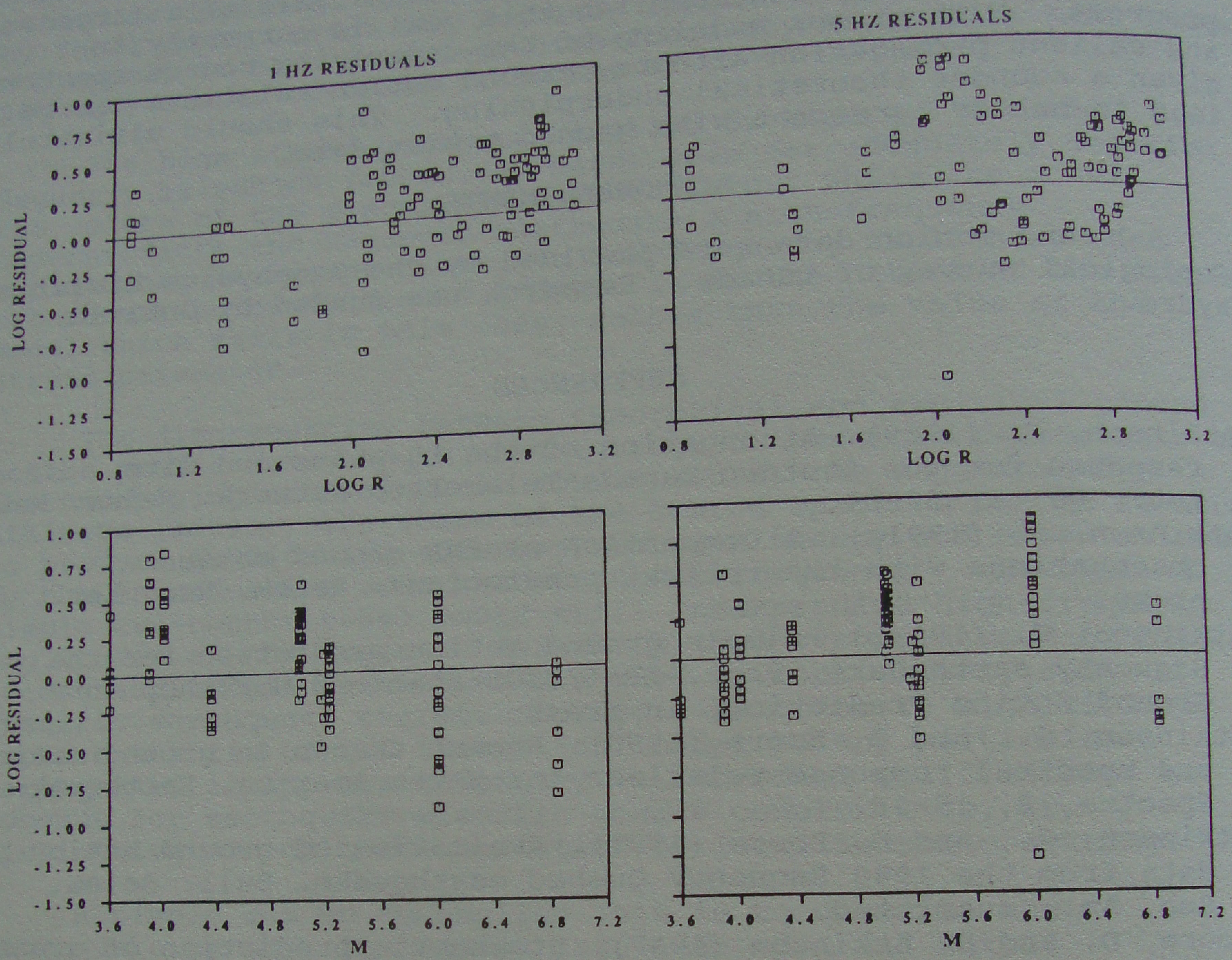

Figure 1. Residuals from comparison of PSRV data with theoretical predictions, as a function of distance and magnitude.

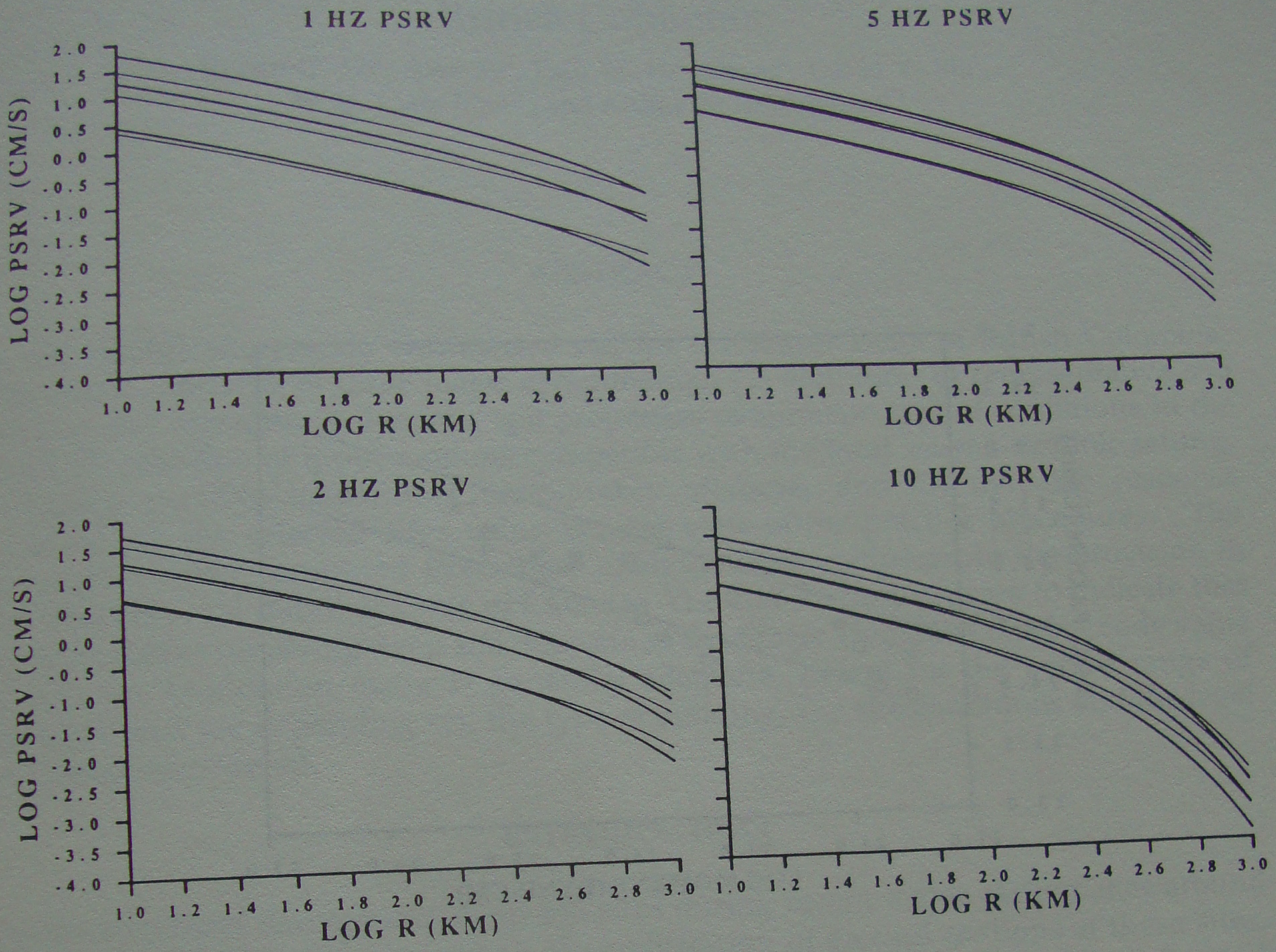

Figure 2. Comparison of theoretical ground motion equations of Atkinson and Boore (1990) (heavy lines) with empirical equations from regression of data.

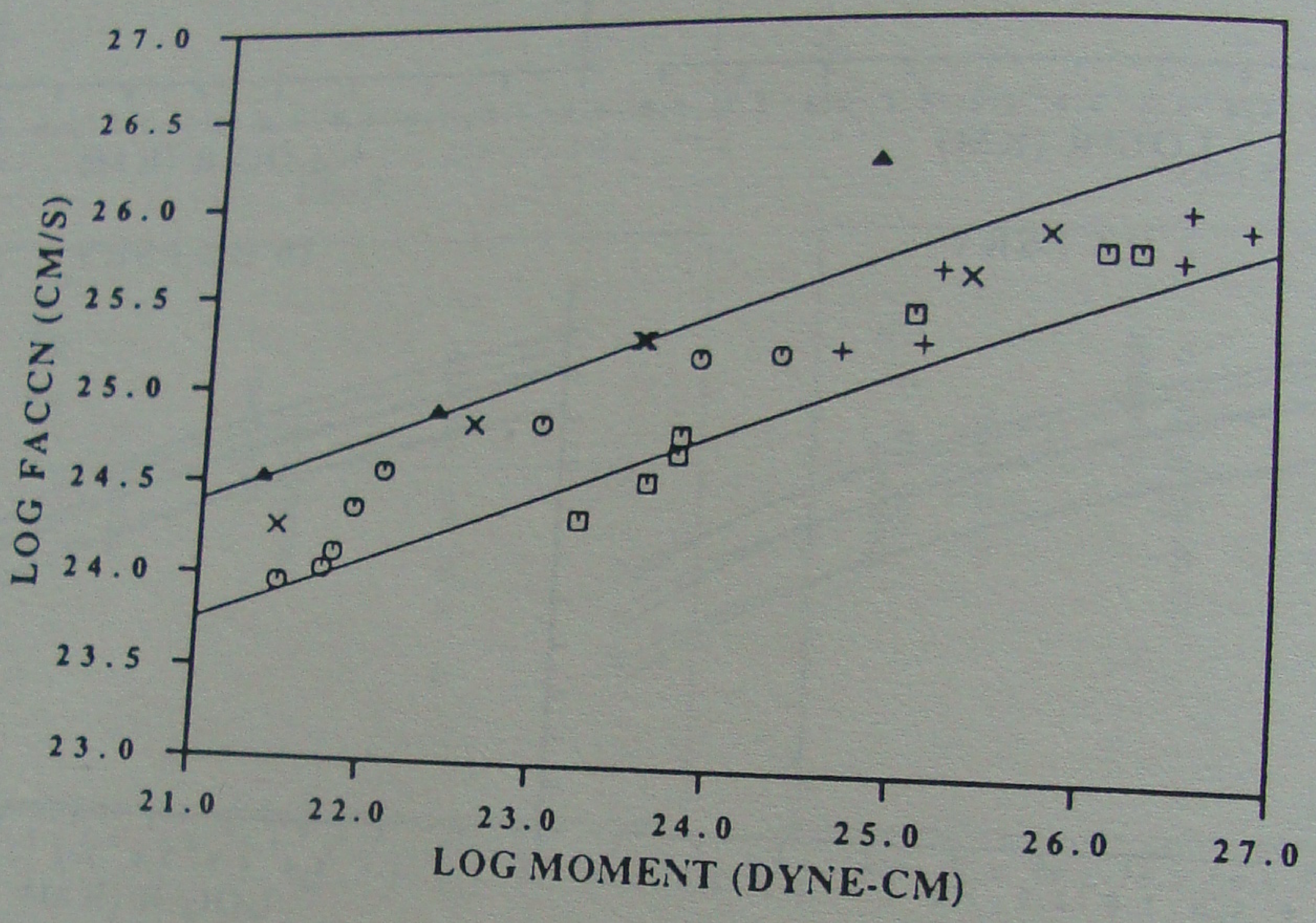

Figure 3. High-frequency acceleration spectral levels for intraplate earthquakes. Mainshocks of all but the Nahanni, Miramichi and Saguenay earthquakes are shown as x's (ENA data) or crosses (intraplate data of Boatwright and Choy); the Nahanni, Miramichi and Saguenay data are given by solid squares, circles, and triangles, respectively.