Bulletin of the Seismological Society of America, Vol. 98, No. 4, pp. 2094–2097, August 2008, doi: 10.1785/0120070279

Comment on "Empirical-Stochastic Ground-Motion Prediction for Eastern North America" by Behrooz Tavakoli and Shahram Pezeshk

by Kenneth W. Campbell

Tavakoli and Pezeshk (2005) conclude that the use of a point-source single-corner source spectrum by Campbell (2003, 2004) causes his eastern North America (ENA) hybrid empirical ground-motion model to underestimate ground-motion amplitudes from near-source large-magnitude earthquakes. This conclusion was based on published studies that found that the use of a double-corner source spectrum, together with a focal depth that increases with magnitude, was required to match a dataset of strong-motion recordings from moderate-to-large earthquakes in California (Atkinson and Silva, 1997, 2000). Tavakoli and Pezeshk also note that Atkinson and Boore (1995, 1997) propose the use of a double-corner source spectrum to model the source spectra of large earthquakes in ENA. These studies lead Tavakoli and Pezeshk to suggest that using a double-corner source spectrum with Campbell's (2003) hybrid empirical method (HEM) constitutes an improvement in the method.

One of the attributes of the HEM is that the regional adjustment factors that are used to modify the ground-motion estimates in the host region are not sensitive to the exact form of the source spectra or to the absolute amplitudes and functional relationships of the seismological parameters that are used to define the seismological models in the host and target regions. Instead, these adjustment factors are sensitive only to the differences in the seismological models between these regions. This means that the seismological models do not need to produce correct absolute ground-motion amplitudes, as assumed by Tavakoli and Pezeshk; they only need to provide an accurate ratio of ground-motion amplitudes. Accurate ratios will be obtained if the source spectra and the other seismological parameters in each region have the same functional relationships regardless of what form these relationships might take. For example, using a constant stress drop in each region will produce the same regional adjustment factors as using a stress drop that decreases (or increases) with magnitude as long as their ratios are the same over the magnitude range of interest. The reason that Tavakoli and Pezeshk obtained different results than Campbell (2003, 2004) was because the alternative double-corner source models and related seismological parameters that they used for ENA and western North America (WNA) did not produce the same ground-motion ratios as the single-corner source models and related seismological parameters used by Campbell. The issue is whether the regional differences in seismological models proposed by Tavakoli and Pezeshk are scientifically justified or whether they represent an artifact of how the seismological models were developed. Campbell (2007) reviewed this issue and concluded that the differences between the ENA and WNA source models used by Tavakoli and Pezeshk do not appear to be fully justified and, in at least one case, are the result of an error. A summary of Campbell's results as they relate to the assumptions made by Tavakoli and Pezeshk is presented in the next paragraph of this Comment.

Tavakoli and Pezeshk selected the double-corner source spectrum of Atkinson and Silva (1997, 2000) together with a magnitude-dependent stress drop as the cornerstone of their WNA seismological model. Atkinson and Silva made two modifications to the standard Brune (1970, 1971) point-source spectrum in order to better match California strong-motion data: (1) they used a double-corner rather than a single-corner spectral shape and (2) they allowed the hypocentral depth of the equivalent point source to increase with magnitude. Neither of these changes significantly affected simulated ground motions at small magnitudes, for which the single-corner and the double-corner source models were found to give similar results. The modifications were only needed to match the finite-source effects of the large-magnitude earthquakes (Atkinson and Silva, 1997, 2000). Tavakoli and Pezeshk adopted the double-corner source model of Atkinson (1993) and Atkinson and Boore (1995) together with a constant stress drop as the cornerstone of their ENA seismological model. They assumed that the hypocentral depth of the equivalent point source had the same dependence on magnitude as in WNA. However, this ENA double-corner spectrum has a different shape than the Atkinson and Silva WNA double-corner source spectrum even after accounting for regional differences in stress drop. All of the other seismological parameters are the same as those proposed by Campbell (2003, 2004). Therefore, the cause of the difference in the ratios of the simulated ENA-to-WNA ground-motion amplitudes (i.e., the regional adjustment factors) between the Tavakoli–Pezeshk and Campbell models can be attributed to two assumptions made by Tavakoli and Pezeshk: (1) that non-stress-drop-related source spectral shapes are different between ENA and WNA and (2) that stress drop is independent of magnitude in ENA but magnitude dependent in WNA. Next, I explore the scientific bases for these double-corner source spectral models.

Because of the limited number of strong-motion recordings in ENA, Atkinson (1993) used a diverse set of data to derive the double-corner source spectrum used by Atkinson and Boore (1995) and Tavakoli and Pezeshk. The main database was a set of 1500 digital seismograms ($2.5 \leq \mathbf{M} < 6.0$)

recorded by the Eastern Canada Telemetered Network (ECTN). This database was supplemented with moment magnitudes from other sources for the limited number of $\mathbf{M} > 4.5$ earthquakes. One-Hertz source spectral amplitudes for the larger earthquakes were taken from northeastern North American regional seismograms compiled by Street and Turcotte (1977) and from worldwide intraplate teleseismic seismograms compiled by Boatwright and Choy (1992). High-frequency source spectral levels ($4 \leq \mathbf{M} < 7$) were inferred from a relationship between high-frequency spectral level and felt area derived from ENA seismograms and observations of modified Mercalli intensity (MMI). The 1988 Nahanni, Canada, earthquake ($\mathbf{M}$ 6.8) and its aftershocks comprised the only set of large-magnitude strong-motion recordings in her study. However, because the Nahanni events occurred along the eastern margin of the Rocky Mountains, some seismologists question whether they occurred in an ENA tectonic environment, a WNA tectonic environment, or a transition between WNA and ENA tectonic conditions. The relationship between the lower source-corner frequency (f_a) and magnitude was derived from the worldwide intraplate data of Boatwright and Choy (1992) and from corner frequencies inferred from source durations by Somerville *et al.* (1987). The relationship between the higher source-corner frequency (f_b) and magnitude was derived from ECTN data and, according to Atkinson, was poorly constrained. The so-called sag in the double-corner source spectrum observed at intermediate frequencies was also poorly constrained by these data. One of the conclusions of the study was that most $\mathbf{M} > 4$ events have high-frequency spectral levels that are consistent with a constant stress drop of approximately 150 bars. Although there is nothing seismologically wrong with the use of such a diverse dataset (in fact, it is quite clever), it is nevertheless possible that this diversity could unintentionally lead to inconsistent results, especially at large magnitudes. As a result, one needs to be careful when comparing Atkinson's results to the California source models of Atkinson and Silva (1997, 2000) that have been constrained by strong-motion data from large-magnitude earthquakes. This caveat, together with the lack of adequate empirical constraints of both the high-frequency corner and the intermediate-frequency spectral sag, and the questionable validity of the Nahanni earthquakes as occurring in a true ENA tectonic environment, results in a source spectral shape that is less well constrained than its WNA counterpart, especially for near-source large-magnitude earthquakes.

Chen and Atkinson (2002) offer additional insight regarding the potential regional differences in source spectral shapes. They compared the apparent source radiation from earthquakes in Japan, Mexico, Turkey, California, British Columbia (western Canada), and ENA and found that in all of these regions, the apparent source spectra for small-to-moderate earthquakes ($\mathbf{M} < 6$) showed good agreement with a point-source, single-corner, ω^{-2} (Brune) source spectrum with an approximate stress drop of 100 bars. They also concluded that a two-corner source model was a better match to the spectra of large-magnitude ($\mathbf{M} \geq 6$) earthquakes. For small-to-moderate events, the single-corner and double-corner source models were nearly identical and suggested a general similarity between the different tectonic regions studied. Although minor discrepancies appear in some cases, Chen and Atkinson did not find any noticeable regional characteristics or depth effects associated with the apparent source spectra. They concluded that earthquakes of a given moment magnitude appear to have similar source spectral levels and shapes over different tectonic regions where a mixture of tectonic styles may be present within a region. This conclusion would appear to support a general similarity in source spectral shapes between WNA and ENA, at least within observational uncertainty.

Other investigators have also proposed that source spectral shapes in ENA and WNA might be similar or dependent only on differences in stress drop. Atkinson and Silva (1997) found that their empirical source spectrum for small-magnitude earthquakes in California was similar to that found for ENA by Atkinson and Boore (1995, 1997) at low frequencies when differences in crustal properties were taken into account, implying that the two regions have similar source spectra at these frequencies. They also found that the observed corner frequencies, f_a and f_b, of the double-corner source spectra in each region were virtually identical, but that the $f_b - \mathbf{M}$ relationship used in ENA predicted higher values of f_b in order to better match the large ENA spectral levels at high frequencies. These investigators suggested that the enhanced high-frequency amplitudes in ENA are consistent with known differences in stress drop between the two regions, although the double-corner source models do not explicitly include stress drop as a parameter. Therefore, the study of Atkinson and Silva also suggests that differences in source spectra, aside from those caused by differences in stress drop, might not be important in the development of regional adjustment factors between WNA and ENA.

Atkinson (2001) went one step further and gave evidence to suggest that there is little, if any, difference in the apparent source radiation at both high and low frequencies between ENA and California earthquakes with the same moment magnitude. She cites a comparison of MMI data in WNA and ENA done by Hanks and Johnston (1992) as suggesting that near-source damage levels, and by inference near-source ground-motion amplitudes, are similar in the two regions for a given moment magnitude. However, Hanks and Johnston concluded that the MMI data, especially at the intensity VII level, are extremely limited and are not by themselves sufficient to rule out a potential factor of 2 higher average stress drop in ENA. Bollinger *et al.* (1993) performed a similar study and concluded that the scatter in the MMI data was indeed large but that, in their opinion, it could support a possible factor of 2 higher average stress drop in ENA. After additional analysis, Atkinson subsequently concluded that earthquakes probably do have a higher stress drop in ENA than in WNA and that this stress drop appears to be independent of magnitude for events of $\mathbf{M} > 4$ (Atkinson, 2004; Atkinson and Boore, 2006).

Atkinson and Boore (1998) used the stochastic method to modify the empirical California source model of Atkinson and Silva (1997) for differences in crustal properties and generic rock characteristics between California and ENA. They found that this modified model matched the limited ENA strong-motion data almost as well as the stochastically derived ground-motion model of Atkinson and Boore (1995) and better than many of the other stochastic ground-motion models that had been developed for use in ENA up to that time. Beresnev and Atkinson (1999, 2002) performed finite-fault stochastic simulations of well-recorded moderate-to-large earthquakes in both California and ENA and suggested that the observed differences in ground motion between these two regions were largely caused by regional differences in crustal structure and anelastic attenuation. These studies would seem to suggest that any differences in source spectral shape and stress drop that might exist between ENA and WNA would seem to have a smaller impact on observed and simulated ground motions than differences due to crustal properties.

All of the aforementioned studies point to the fact that one cannot disprove the hypothesis that source spectral shapes, aside from differences due to stress drop (if any) and crustal structure, are the same or are very similar in ENA and WNA. As stated previously, one of the attributes of the HEM is that it is not sensitive to whether the source spectral shapes are single corner, double corner, or have some other arbitrary shape; it is only sensitive to whether these shapes are regionally consistent. Certainly, there seems to be ample evidence to support Campbell's (2003, 2004) hypothesis that ENA and WNA source spectra have similar spectral shapes.

As previously noted, Tavakoli and Pezeshk used a stress drop that decreases with magnitude in conjunction with the double-corner source spectrum of Atkinson and Silva (2000) in their WNA model. The moment magnitude and the corner frequencies (f_a and f_b) and weight (ε) of the two equivalent Brune single-corner source spectra are the only parameters that are required to completely define the double-corner source spectrum. This is because Atkinson and Silva's formulation of the double-corner model implicitly includes any magnitude dependence of stress drop that might be embedded within the empirical observations. Thus, Tavakoli and Pezeshk's use of a stress drop that decreases with magnitude (or any stress drop, for that matter) produces a new model that is inconsistent with Atkinson and Silva's empirically constrained spectral model (G. Atkinson, personal comm., 2007). The same is true for the ENA double-corner source spectrum. Atkinson and Silva (1997) used the same WNA strong-motion database as Atkinson and Silva (2000) to derive parameters for a seismological model that was based on a single-corner rather than a double-corner source spectrum. They found that they needed to use a stress drop ($\Delta\sigma$) and a site kappa (κ_0) that were a function of magnitude in order to fit the California strong-motion data with a single-corner source spectrum. For example, they found that $\Delta\sigma = 120$ bars and $\kappa_0 = 0.035$ sec best described the equivalent single-corner source spectrum for an average **M** 5.0 event and that $\Delta\sigma = 50$ bars and $\kappa_0 = 0.05$ sec best described the equivalent single-corner source spectrum for an average **M** 7.5 event. These results are consistent with Atkinson and Silva's (2000) conclusion that high-frequency ground motions calculated for a **M** 6.5 event using the double-corner source spectrum are consistent with those calculated using a single-corner 80-bar source model or a finite-source model (Beresnev and Atkinson, 1998). Atkinson and Silva (1997) went on to suggest that the magnitude-dependent stress drop might reflect saturation effects attributable to the point-source distance measure rather than to real stresses on the fault and that the magnitude-dependent kappa could be interpreted as evidence of nonlinearity for typical California soil sites. Such properties are transferred from the host to the target region in the HEM through the magnitude scaling and site response characteristics of the host region's empirical ground-motion model. At small magnitudes, Atkinson and Silva (1997, 2000) concluded that the source spectra in California based on the single-corner, double-corner, finite-source, and empirical source models are generally consistent with one another.

In conclusion, it appears that Tavakoli and Pezeshk incorrectly used a magnitude-dependent stress drop with the double-corner source spectrum of Atkinson and Silva (2000) and a constant stress drop with the double-corner source spectrum of Atkinson and Boore (1995) in the parameterization of their WNA and ENA seismological models, whereas both models already inherently include stress drop. The problem was exacerbated by using stress drops that were a different function of magnitude. Although their use of a double-corner source spectrum in both ENA and WNA does not necessarily constitute an error, there is ample evidence to indicate that such a spectrum is only necessary when the point-source stochastic method is used to estimate absolute amplitudes of ground motion from large-magnitude earthquakes. The HEM avoids this issue by using relative rather than absolute ground-motion amplitudes and using empirical ground-motion models in the host region to incorporate finite-source effects. Furthermore, there is sufficient evidence to suggest that source spectral shapes are similar (within observational uncertainty) in ENA and WNA after accounting for differences in stress drop. If this is indeed the case, then even if a double-corner source spectrum is used in both regions, the ratio of these source spectra would be the same as the ratio of the equivalent single-corner source spectra and, therefore, would not lead to different estimates of the regional adjustment factors.

Acknowledgments

Research was supported by the U.S. Geological Survey (USGS), Department of the Interior, under Award Number 05HQGR0032. The views

and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official polices, either expressed or implied, of the U.S. Government.

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Manuscript received 5 November 2007