Comparison of earthquake source spectra and attenuation in southeastern Australia and eastern North America

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Abstract

The paucity of ground-motion data in Stable Continental Regions (SCRs) remains a key limitation when developing relations that seek to predict effects of strong ground-shaking from large damaging earthquakes. It is desirable to combine data from more than one SCR in order to increase database size, but this raises questions as to whether the source and attenuation properties of the SCRs are equivalent. We merge recently-compiled spectral-amplitude databases from small-to-moderate events (moment magnitudes $2.0 \leq M \leq 5.0$) in both southeastern Australia and eastern North America in order to compare the key characteristics of ground motion in these two regions. Both are SCRs, but are widely separated, spatially and in tectonic history.

We statistically compare ground motions by plotting mean and standard deviations of spectral amplitudes for data grouped in magnitude and distance bins. These comparisons show that the source and attenuation properties of the two regions are very similar, particularly at shorter hypocentral distances R (i.e. R < 70 km). At larger distances, regional attenuation differences are observed that may be attributed to differences in crustal structure. We conclude that it is valid to combine the Australian and ENA ground-motion datasets in the development of ground-motion relations.

These may serve as generic functions for SCRs around the world.

Introduction

A major shortcoming of all predictive ground-motion models developed for Stable Continental Regions (SCRs) is that they are based on relatively scarce observational data in comparison to ground-motion models derived for more tectonically active regions (e.g. Sadigh et al., 1997; Boore and Atkinson, 2006; Campbell and Bozorgnia, 2006). Stochastic simulation methods are often employed to develop predictive ground-motion equations that describe the ground-motion expected from large earthquakes in SCR regions, to mitigate the lack of strong-motion data. However, the reliability of the stochastic relations depends entirely on the reliability of the assumed source and attenuation models, which must be developed from limited SCR databases. It is therefore important to know whether the assumption of generic source and attenuation models is appropriate for all SCR regions. If so, we may combine data from more than one SCR in order to improve the database on which our models are based.

Bakun and McGarr (2002) used limited intensity and digital data to compare the attenuation properties of ground motion among several SCRs. They concluded that attenuation in the Australian continent is greater than that of eastern North America (ENA), but less than that in interplate regions such as southern California. These comparisons were based upon observations from the MS 6.3, 6.4 and 6.7 earthquakes of the 1988 Tennant Creek, Northern Territory, sequence that occurred in the Proterozoic crust of central Australia (Jones et al., 1991; Bowman and Kennett, 1991). However, it is recognised that attenuation across Australia cannot be captured with a single attenuation model (e.g. Gaull et al., 1990). Rather, it is observed the attenuation of seismic wave energy varies transversely across the continent, with relatively low attenuation in the Archaean and Proterozoic terranes of western and central Australia and higher attenuation in the younger Palaeozoic terranes of eastern Australia (Allen et al., in review). Furthermore, recent analysis of data recorded during the 2001-02 Burakin earthquake swarm (Allen et al., 2006) suggests that attenuation of low-frequency ground-shaking in the Archaean cratons of Western Australia may be lower than that observed in ENA (e.g. Atkinson, 2004) at short hypocentral distances. Consequently, significant uncertainty still surrounds the attenuation behaviour of SCRs and, in particular, whether attenuation models developed for one SCR are applicable to another region for the purposes of earthquake hazard assessment (Bakun and McGarr, 2002). In this study, we compare recorded ground-motion spectral amplitude data from ENA and southeastern Australia (SEA) to examine whether it is applicable to derive a common ground-motion model from the combined dataset.

Ground-motion data & methodology

The data used in the analysis are the vertical-component spectral amplitude databases recently compiled by Atkinson (2004) and Allen et al. (in review) for ENA and SEA, respectively. Figure 1 indicates the magnitude-distance distribution of the datasets. The inclusion of data is limited by the magnitude-distance criterion employed by Atkinson (2004) to eliminate low-amplitude quantisation noise problems. The magnitude of all events is represented by moment magnitude M, as calculated from the spectral amplitudes by Atkinson (2004) and Allen et al. (in review). It is worth noting that much of the data employed from SEA were recorded on short-period weak-motion instruments with natural frequencies at 1.0 or 2.0 Hz. Consequently, the SEA data for frequencies below 2 Hz are less reliable than at higher frequencies.

We compare spectral ground-motion amplitudes for the two regions in a range of magnitude-distance bins: M 2.6 (±0.1), 2.8 (±0.1), etc., sorted by distance bins 0.1 log units wide in hypocentral distance. We calculate the mean and standard deviation of the log spectral amplitudes for each bin, for a range of frequencies from 0.5 to 20 Hz.

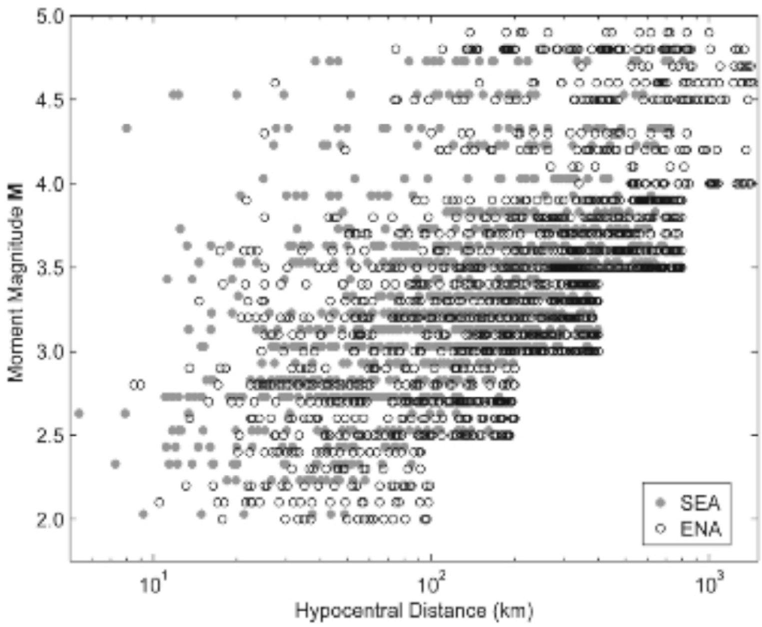

Figure 1. Magnitude-hypocentral distance distribution of the ENA and SEA datasets. Note: a small vertical offset (+0.03) has been applied to the SEA magnitude values for plotting clarity.

Results

Figure 2 compares ENA and SEA spectral amplitudes for a discrete magnitude range (M 2.8) that is well represented in both databases, at frequencies of 1, 2, 5, and 10 Hz. Overall, near-source (approximately R < 30 km) low-frequency (f ≤ 2 Hz) amplitudes match well across the two regions, although this is difficult to see in individual magnitude plots such as Figure 2, due to the limited number of near-source data for any one magnitude. This serves as an important quality check that the moment magnitudes assigned to ENA and SEA earthquakes are consistent between the regions.

In general, there appears to be no statistical difference in source amplitudes or attenuation between the two SCRs for distances out to approximately 100 km. Beyond this distance range, average spectral amplitudes from SEA appear to be consistently lower than the corresponding ENA amplitudes. Furthermore, higher-frequency SEA ground-motions (f ≥ 10 Hz) appear to diverge faster from ENA with increasing distance than do the low-frequency SEA data, indicating a greater contribution of anelastic attenuation in the upper mantle (i.e. lower quality factor Q). This result is consistent with large-scale tomographic studies that demonstrate low Q in the upper mantle beneath Australia (Mitchell et al., 1998).

Figure 4 compares the relative high frequency characteristics of the data in more detail. We plot average ENA and SEA acceleration spectra versus frequency for a few selected magnitude-distance bins. These are selected based on which near-source distance bins ($20 \le R \le 35$ km) have the most abundant data for the comparison in both regions. Data are scaled to a hypocentral distance of 20 km by assuming a geometrical attenuation coefficient of $R^{-1.3}$ (e.g. Atkinson, 2004; Allen et al., in review). These spectral comparisons suggest significant differences in high-frequency attenuation (f>10 Hz), indicating that the near-surface effects that control ground-shaking at higher frequencies, as modelled with the coefficient kappa (κ), may be stronger in the upper crust of SEA than in ENA. It is worth noting that in this distance range, we would not expect the spectral amplitudes to be affected significantly by Q.

Consequently, high-frequency effects can be attributed largely to influences from the near-surface geology.

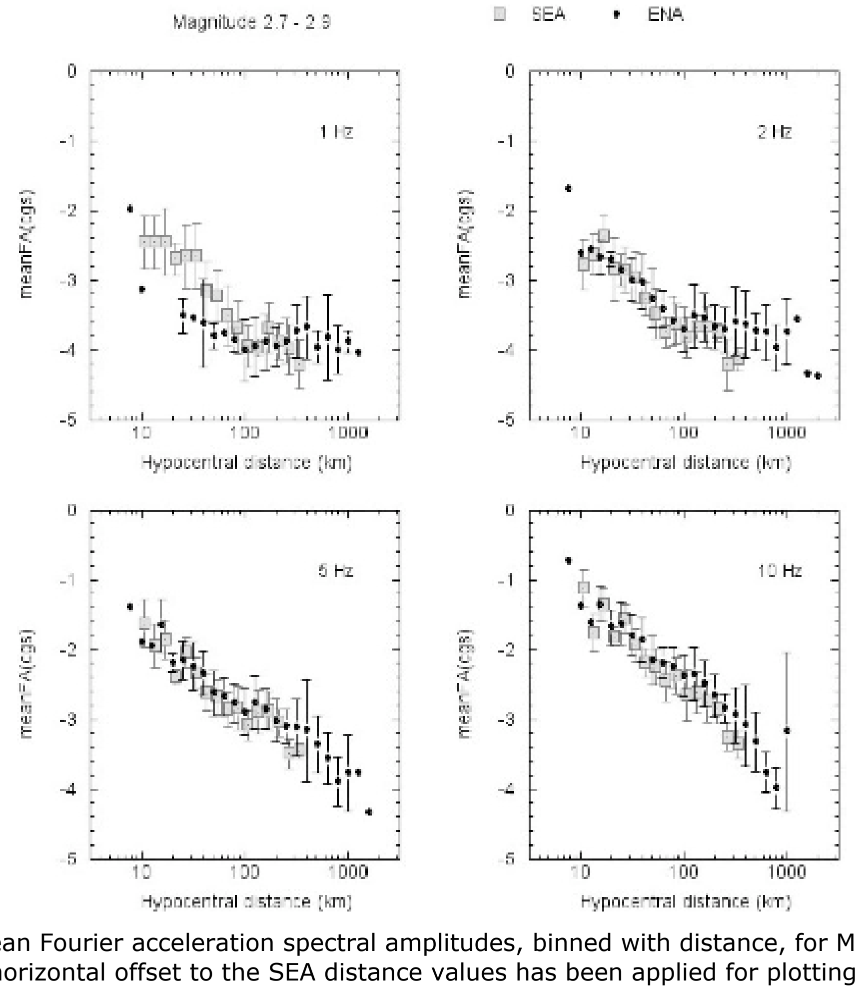

Figure 2. Mean Fourier acceleration spectral amplitudes, binned with distance, for M 2.8 ± 0.1. A small horizontal offset to the SEA distance values has been applied for plotting clarity.

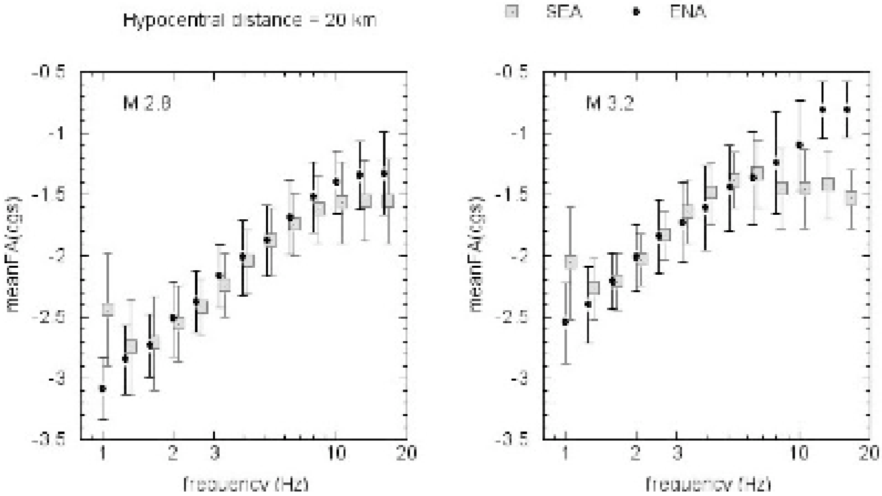

Figure 3. Mean Fourier acceleration spectra for data recorded within a hypocentral distance range of 20 to 35 km. Data are scaled to R = 20 km applying a geometrical spreading coefficient of R-1.3. A small horizontal offset has been applied to the SEA frequency values for plotting clarity.

Discussion

Previous studies suggested that attenuation in ENA is significantly less than that for other SCRs (e.g. Bakun and McGarr, 2002). This conclusion is correct over a large distance range (i.e. out to 1,000 km) when we compare SEA to ENA data. However, if we only consider data for R < 100 km, which is the critical distance range in terms of earthquake hazard and risk, we observe that there is no statistically significant difference in the source and attenuation properties of the respective SCR crusts. These observations are consistent with the studies of Allen et al. (in review) that compare predictive spectral models and demonstrate that ground-motion in ENA and SEA is fundamentally equivalent for sites at distances of R < 70 km for moment magnitudes 2.0 ≤ M ≤ 4.7.

Both regions are characterised by a trilinear attenuation model featuring an initial amplitude decay of $R^{-1.3}$ to a transition zone in which direct waves are joined by postcritical reflections from the Moho. The transition zones appear to take effect near R = 70 km in ENA and R = 90 km in SEA, suggesting differences in regional crustal structure. In these transitional zones, spectral amplitudes decay slowly at high frequencies, and demonstrate a slight increase with distance for low frequencies (Atkinson, 2004; Allen et al., in review). Beyond the transition zone, spectral amplitudes fall off again. Attenuation beyond the second transition distance in SEA appears to be greater than that of ENA. The high attenuation at larger distances is attributed to the well-established velocity gradient in SEA (Collins et al., 2003) that allows dispersion of Lg-wave energy into the upper mantle (e.g. Bowman and Kennett, 1991).

Conclusion

Through this simple statistical analysis, we can conclude that there is no significant difference in source characteristics of ENA and SEA earthquakes. Attenuation differences between the regions are significant, but only for distances greater than 100 km. SEA crust appears to be characterised by slightly larger kappa values (high-frequency attenuation) than ENA crust. Based on these observations, it is reasonable to use ENA and SEA earthquake ground motion data as "analogs" for each other, at least for hypocentral distances less than 100 km and frequencies less than 10 Hz. This is a key result, as it suggests that it is valid to derive a common ground-motion model based on combined data for these two regions. By merging the datasets, we have significantly increased the number of available ground-motion data from which to perform ground-motion studies. This is important in deriving more robust estimates of earthquake source and attenuation parameters for input into stochastic simulations of large damaging earthquakes, and in reducing the epistemic uncertainty associated with such models. It also implies that they may serve as generic predictive ground-motion models for other SCRs around the world.

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