INTRODUCTION:

It has long been recognised by engineers and seismologists alike, that the traditional measure of earthquake ground-motion, *peak ground acceleration* (PGA), is not a particularly good indicator for estimating structural damage (e.g. Hanks and McGuire, 1981). For this reason, frequency-dependent models are favoured to assess the degree of vulnerability a structure may be exposed to in earthquake hazard and risk studies. These models are referred to as *ground-motion attenuation models*.

Earthquake hazard and risk assessments in Australia typically adopt ground-motion models from other stable continental regions such as eastern North America (ENA) (e.g. Dhu and Jones, 2002; Jones *et al.*, 2005). However, there has been very little analysis undertaken to show whether ENA models (e.g. Atkinson and Boore, 1997; Toro *et al*., 1997) are applicable to Australian conditions. Moreover, there has been some conjecture that ground-motion in some parts of Australia resembles that of active tectonic regions and may be better described by models such as Sadigh *et al.* (1997), developed for western North America (WNA). Uncertainties in the choice of attenuation model could potentially lead to undesirable outcomes, such as unrealistically high (or low) loading standards in the design and construction of critical infrastructure (e.g. large dams, power stations, hospitals, etc.). Furthermore, the choice of attenuation model has been demonstrated to have a significant impact on risk estimates in Australia (e.g. Patchett *et al.*, 2005).

Attenuation relations appropriate for the Australian crust have, in the past, been difficult to quantify owing to a lack of ground-motion data from moderate-to-large local earthquakes. Geoscience Australia (GA), in association with Environmental Systems and Services (ES&S) and the Australian National Committee on Large Dams (ANCOLD) have collaborated to assemble an Australian ground-motion database suitable for attenuation studies. The key focus of this project is to improve future earthquake hazard and risk assessments in Australia. The present paper summarises the development of the first spectral ground-motion attenuation models for the Australian crust that are based entirely on Australian data. The models have been derived from two key datasets; one from data recorded in the Palaeozoic crust of southeastern Australia (SEA) and the other from the Archean shield region of southwestern Western Australia (WA).

GA will make these datasets freely available to the earthquake engineering community. To date, the Australian ground-motion database comprises some 400 records from WA, primarily acquired from the 2001-02 Burakin earthquake swarm. Of the many hundreds of located events, a subset of 69 earthquakes of moment magnitude $2.2 \leq \mathbf{M} \leq 4.6$ were analysed. In addition, it will comprise approximately 1000 strong- and weak-motion records from 80 earthquakes acquired from ES&S and Joint Urban Monitoring Program (JUMP) archives. These events occurred from 1993 to 2004 and magnitudes range from $2.0 \leq \mathbf{M} \leq 4.7$. Data in SEA has a good spatial distribution (to approximately 700 km).The database will be systematically updated as new data is acquired. It is envisaged that historic data that pre-dates the data used in the present study (e.g. McCue, 2004) will also be added to the database in time.

EMPIRICAL GROUND-MOTION MODELS:

The development of empirical ground-motion attenuation models for Australia largely follows the methods adopted by Atkinson (2004a) for ENA. Detailed analysis of the SEA dataset indicates that the decay of Fourier spectral amplitudes can be described by a trilinear geometrical attenuation model. The subsequent decay of spectral amplitudes can be approximated by the coefficient of $R^{-1.3}$ (where R is hypocentral distance) within 90 km of the seismic source. From 90 to 160 km, the SEA dataset indicates a zone whereby the seismic coda appear to be affected by crustal reflections and refractions. In this distance range, geometrical attenuation is approximately $R^{+0.1}$. Beyond 160 km, low-frequency seismic energy (i.e. f = 1 Hz) attenuates rapidly with R, having a geometrical attenuation coefficient of $R^{-1.6}$.

The short hypocentral distance range (R < 170 km), coupled with the limited number and spatially clustered nature of the WA dataset caused some ambiguity in interpreting the shape of the geometrical attenuation curve, particularly for R > 100 km. Consequently, this makes it difficult to quantify a complex attenuation model similar to that for SEA. For R < 80 km, low-frequency geometrical attenuation for the WA dataset is approximated by $R^{-1.0}$ (Allen *et al.*, in press). Beyond the post-critical distance of 80 km, we assume theoretical cylindrical attenuation of $R^{-0.5}$ (e.g. Herrmann and Kijko, 1983). The post-critical distance is an approximation based on the estimates of twice the crustal thickness for the region (Dentith *et al*., 2000).

Predicted Fourier ground-motion models for SEA, WA (Allen *et al.*, in press) and ENA (Atkinson, 2004a,b) are compared for hypocentral distances at 1, 10, 50 and 100 km for a hypothetical earthquake of **M** 4.5 (Figure 1). In general, we observe that SEA and ENA models are relatively consistent since the geometrical attenuation is essentially the same over this distance range [geometrical attenuation for ENA is $R^{-1.3}$ for R < 70 km (Atkinson, 2004a)]. Owing to the higher geometrical attenuation observed in SEA for R > 70 km, the models differ considerably at larger distances (Figure 2). Low-frequency spectral amplitudes calculated for the WA model are significantly higher with increasing source-receiver distance than both SEA and ENA. It is important to note that attenuation models from empirical studies cannot be reliably extrapolated to ground-motions for earthquakes larger than those in the catalogue.

STOCHASTIC GROUND-MOTION MODELS:

The stochastic method is particularly useful for simulating earthquake ground-motions in regions of the world where recordings from large damaging earthquakes are simply not available (Hanks and McGuire, 1981; Boore, 2003). The method relies on an initial Brune (1970, 1971) source model, coupled with further source and attenuation information derived from empirical studies.

We use software developed by Pacific Engineering & Analysis, El Cerrito, USA (Silva, 1987), to simulate ground-motions for a series of magnitude-distance bins. To accommodate uncertainty owing to the unpredictable nature of future events, model parameters are randomised about the base (median) value 30 times for each magnitude-distance bin. For each randomisation, 5% damped Response Spectral Acceleration (RSA) are calculated. Subsequent regression analysis yields a stochastic ground-motion model that also incorporates estimates of uncertainty in the predicted ground-motion.

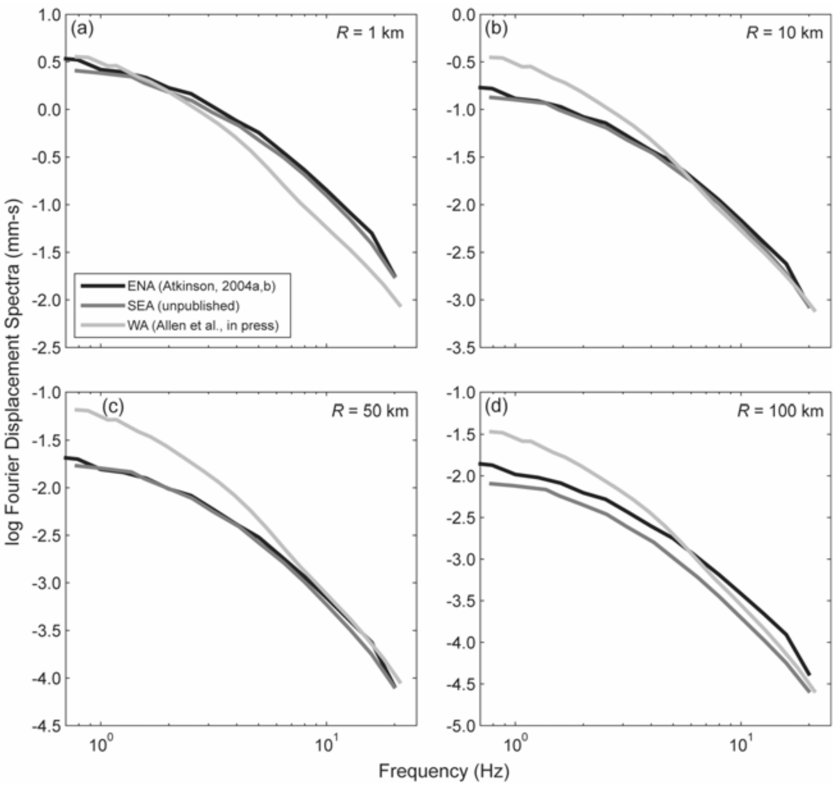

Figure 1: Comparison of predicted Fourier displacement spectra at hypocentral distances of (a) 1, (b) 10, (c) 50 and (d) 100 km for an earthquake of M 4.5. Note that for all three models, source spectra (i.e. *R* = 1 km) converge at low-frequency indicating that estimates of M are consistent (a). In figures (b-d) we observe the effect of lower rates of attenuation in WA.

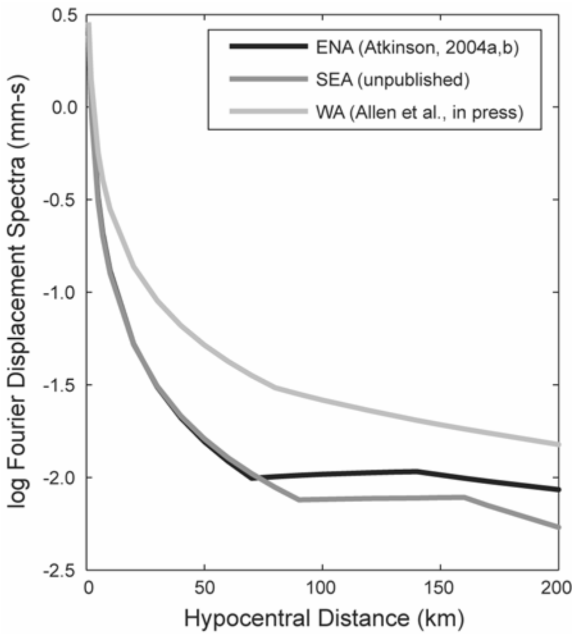

Figure 2: Comparison of Fourier displacement spectra at a frequency of 1.0 Hz for hypocentral distances to 200 km for an earthquake of M 4.5. It can be observed that attenuation in SEA and ENA are very similar for *R* < 70 km. Beyond this distance we observe higher rates of ground-motion attenuation in SEA.

Given the difficulties associated in constraining reliable source and attenuation parameters for the WA dataset, development of stochastic ground-motion models concentrate on SEA. Since the initial model parameters are based on ground-motion recordings on rock, our default attenuation model will be for rock sites. Brune spectra are calculated using randomised values of the seismic quality factor Q_0 [where $Q(f)$ =

$Q_0 f^{\eta}$, f is frequency and η is a numerical constant], stress drop $\Delta\sigma$ and kappa κ. Initial values for these parameters are Q_0 = 620, $\Delta\sigma$ = 12 MPa and κ = 0.03 sec. Given the high correlation of Q_0 and η, we keep η constant at 0.26. We also assume source scaling at constant stress drop (i.e. seismic moment M_0 is proportional to corner frequency f_c^{-3}; e.g. Aki, 1967). In addition, we employ a magnitude-dependent geometric attenuation that considers the effects of fault finiteness. It is observed in tectonically active regions that near-source geometrical attenuation varies from greater than $R^{-1.0}$ for small events to approximately $R^{-1.0}$ for larger events (approx. **M** 6.5; W.J. Silva, pers. comm., 2005). Unfortunately, we have no quality data from which to validate this effect in SEA.

Figure 3 shows the stochastic SEA rock ground-motion model compared to three North American models. Two of these were developed for the stable crust of ENA (Atkinson and Boore, 1997; Toro *et al.*, 1997) and the other for seismically active Californian crust of WNA (Sadigh *et al.*, 1997). RSA indicate that the SEA rock ground-motion models have similar spectral shape to the Sadigh *et al.* (1997) model with low levels of high-frequency motion (and PGA) compared to the two ENA models at varied magnitude-distance couples. The discrepancies between the SEA and ENA stochastic models are unclear at this stage given the similarity between the empirical models at hypocentral distances less than 70 km.

IMPLICATIONS FOR EARTHQUAKE HAZARD:

Results from the present study indicate that ground-motion attenuation in SEA is higher than previously assumed in earthquake hazard and risk studies that assume ENA ground-motions. For smaller events (**M** < 6.0), the SEA stochastic model predicts slightly higher attenuation with hypocentral distance than even WNA models (Figure 3d). Given earthquake hazard is in Australia typically dominated by moderate-sized events at close range (e.g. Jones *et al.*, 2005), these results may have a significant impact on future hazard estimates.

Although we have not been able to develop a reliable stochastic ground-motion model for WA at present owing to the anomalous nature of the WA dataset, results from empirical studies suggest that the attenuation of strong ground-shaking will be lower than in SEA. Comparison of Fourier spectral models by Allen *et al.* (in press) indicate that at lower-frequency ground-motions (f < 2 Hz) attenuate less in WA than in ENA. In contrast, they observe lower levels in high-frequency motions relative to lower-frequency motions. It may be that the use of current attenuation models actually underestimates hazard at low-frequencies in WA. Therefore, low-frequency ground-motions may be slightly higher than that predicted by ENA models, but with diminished high-frequency motions. This is somewhat consistent to studies by Hao and Gaull (2004), who apply low-pass filters to ENA ground-motion models to fit observed ground-motion from WA.

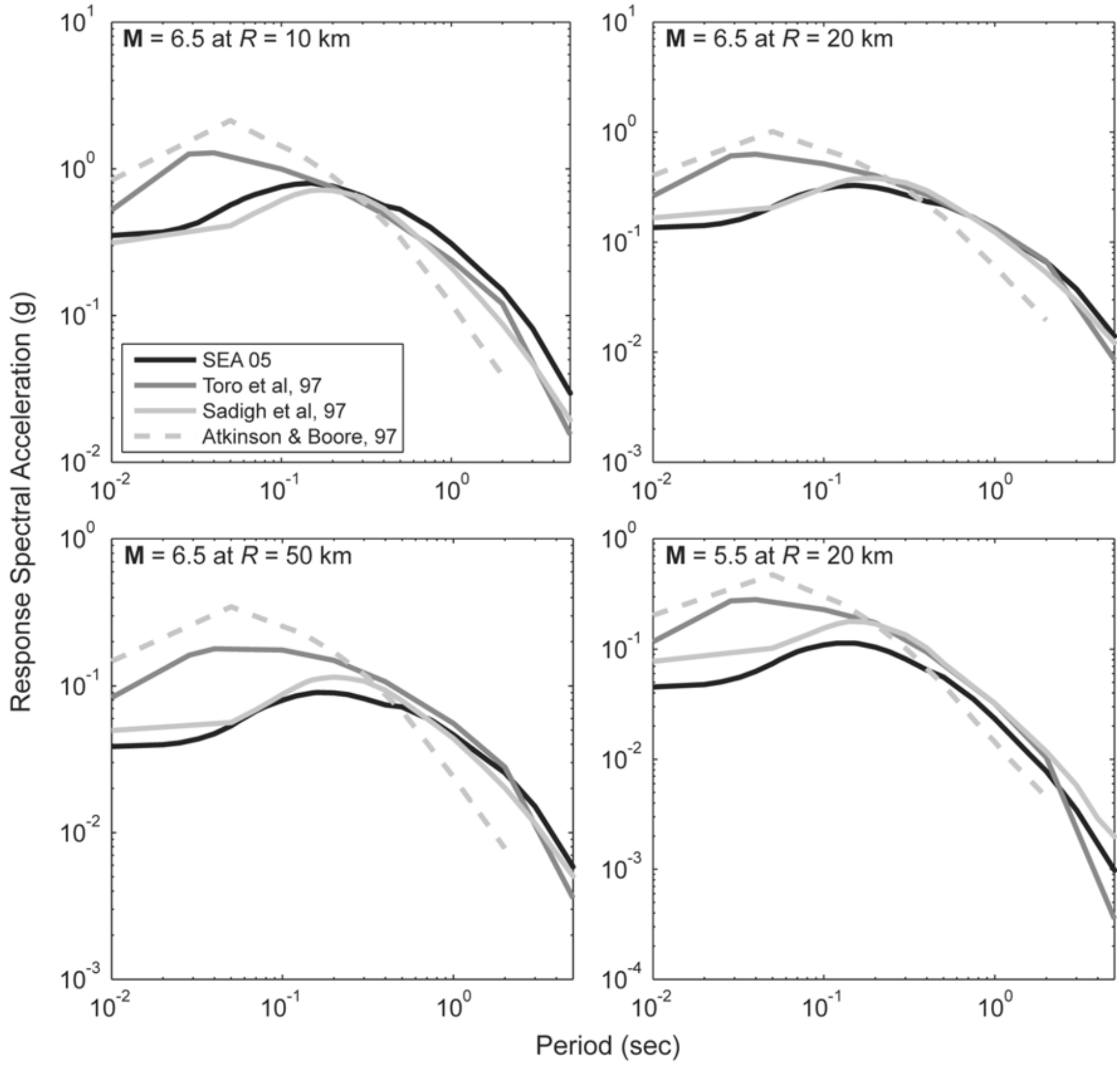

Figure 3: Comparison of 5% damped RSA for the three North American ground-motion models and the stochastic SEA model. The SEA model appears to be similar to the WNA model of Sadigh *et al.* (1997) for most magnitude-distance couples. In addition, the SEA model predicts lower ground-motions at periods less than about 0.3 sec relative to ENA models. Each of the predictive spectral plots assume an earthquake focal depth of 8 km.

CONCLUSIONS:

This study presents the first ground-motion attenuation models that are appropriate for Australian crustal conditions that are based almost entirely on data recorded in Australia.

Empirical attenuation models have been developed from two key datasets; one from WA and the other from SEA. In general we observe that ground-motion attenuates less in WA than in SEA, particularly at lower-frequency. WA earthquakes, however, appear to have lower high-frequency motion relative to SEA earthquakes.

Given the difficulties associated in constraining reliable source and attenuation parameters for the WA dataset, development of stochastic ground-motion models are limited to SEA rock sites. We observe that SEA RSA indicate similar spectral shape to the Sadigh *et al.* (1997) model developed for WNA with low levels of high-frequency motion (and PGA) compared to the two ENA models. As distance is increased from the source, we observe that all predictive attenuation models from North America tend to overestimate ground-motion relative to the SEA model, particularly for smaller events (Figure 3d). These findings have significant implications for earthquake hazard and risk in this region. They suggest that by using North American ground-motion models, we are currently overestimating earthquake hazard in SEA. Consequently, we may be over-engineering infrastructure for strong ground-motion, particularly for frequencies greater than 2 Hz. More work is required to quantify these results, and also to develop useful models across all of Australia for both rock and soil sites. We aim to refine this work to provide ground-motion models to apply to Australian specific hazard and risk analyses. Moreover, this study highlights the ongoing need to record high-quality strong-motion data in Australia in order to validate and improve both empirical and stochastic models.

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