An approach to response spectrum attenuation modelling for southeastern Australia

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Abstract

An approach is demonstrated for developing response spectrum attenuation relations that are relevant for southeastern Australia through modifying those from elsewhere. The approach recognises that SE Australia combines features of intraplate regions such as Eastern North America (ENA) and plate-boundary regions such as California. It is in a region of intraplate tectonics, but characterised by sedimentary deposits that produce near-surface attenuation rates (kappa) more typical of plate boundary regions. Also, it is uncertain whether stress drops in earthquakes of about magnitude 5 or greater, being those relevant for earthquake-resistant design, are moderate or high.

The approach starts with a range of attenuation relations that between them account for both moderate and high stress drops, but with high near-surface attenuation, modelled using a high kappa value. This can be provided by selecting a combination of attenuation relations from California (moderate stress-drops, high kappa) and ENA relations (high stress drops, low kappa) modified for high kappa values.

A simple exercise shows that it is possible to generate similar spectra starting from either ENA or Californian attenuation models through the application of kappa-dependent modification factors, although the two sets of relations are very different, with strong high-frequency content in the ENA spectra.

Introduction

South-east Australia (SEA), like many parts of the world, suffers from a sparsity of strong-motion earthquake records for the development of appropriate motions for earthquake-resistant design. The sparsity of data hinders the development of empirical attenuation expressions for modelling the strength of earthquake shaking as a function of the earthquake magnitude and distance from the earthquake source and other parameters such as site conditions and source mechanism of the earthquake.

Adoption of models from other parts of the world is difficult because SEA combines features of intraplate regions such as Eastern North America (ENA) and plate-boundary regions such as California (Lam et al 1998, Somerville et al., 1998). It is in a region of intraplate tectonics, which govern the source effects, but is characterised by sedimentary deposits, which produce moderate near-surface attenuation rates more typical of plate boundaries rather than the low attenuation rates usually found in continental regions.

These issues have been tackled in a detailed way by Lam and Wilson (2003) in their Component Attenuation Model, which they have applied in Australia and elsewhere. The current paper represents a more simplistic approach, demonstrating one of the key factors for SEA. It is based largely on an oral presentation that was made at a workshop on attenuation models for Australia at Geoscience Australia in February 2006.

Important parameters affecting earthquake motions

The spectrum of the earthquake motions expected at distance R from the source of an earthquake of magnitude M as a function of frequency f can be expressed as the product of a number of factors, including the source spectrum, geometric attenuation, anelastic attenuation over the whole path and in the near-surface region, and near-surface amplification resulting from wave-propagation velocity contrasts with the rock at depth, (e.g. Lam et al. 1998, Atkinson and Boore, 1997). Many of these factors depend on the tectonic and geological environment.

Source spectrum and stress drop

The source factor S(M, f) is proportional to the displacement spectrum at the source. Brune (1970) provided a simple commonly-used model for the source function:

$S(M,f) = M_0/(1+(f/f_c)^2)$

The seismic moment M_0, which gives the zero-frequency strength of the source spectrum, is simply related to the moment magnitude M of the earthquake.

The corner frequency f_c determines the frequency band of the high-frequency part of the acceleration spectrum at the source, and the source duration. It depends on the stress drop $\Delta\sigma$, the seismic moment and the shear-wave velocity β at the source

$f_c \propto \beta\ (\Delta\sigma/M_0)^{1/3}$

For a given seismic moment or magnitude, stress drop is a key parameter governing the frequency content and amplitude of the spectrum, and the duration of the motion.

Anelastic attenuation

The spectrum generally decays as the distance increases from the source through geometric and anelastic attenuation. Often the geometric attenuation term D(M,R,f) is taken as simply 1/R, but anelastic attenuation is region-dependent.

The whole-path anelastic attenuation can be modelled by a factor $\exp(-\pi fR/Q(f)\beta)$. The quality factor Q(f) depends on both tectonic and geological factors. High Q leads to rapid attenuation, while motions can persist to large distances in low-Q regions.

Significant attenuation of earthquake motions, especially of their high-frequency content, occurs in the last few kilometres of the source-to-site path, in the near-surface region. This effect can be modelled through the parameter kappa (κ), with the near-surface attenuation factor P(f) given by $\exp(-\pi\kappa f)$.P(f) is strongly dependent on the geological environment, with low κ for strong crystalline rock and much higher κ for weak sedimentary rock or deep soil deposits.

Comparison of tectonic and geological environments

Eastern North America (ENA)

ENA is a stable geological region with strong crustal rock. Strong rock allows earthquakes with high stress drops, low attenuation over both the whole path and near-surface. High stress drops produce spectra with stronger high-frequency components for a given magnitude. Low attenuation maintains strong high-frequency content to large distances.

California

California is a plate boundary region and geologically active. Stress drops are generally lower than in ENA, and attenuation is rapid (low Q and high kappa). As a consequence, spectra lack the strong high-frequency content of ENA.

Southeast Australia (SEA)

South-eastern Australia is within a tectonic plate (i.e. in an intra-plate setting) like ENA rather than at a plate boundary such as in California or New Zealand. However, it is geologically active with sedimentary deposits, so that it does not have the same crustal conditions as stable shield regions such as ENA and western Australia. Consequently, conditions in south-eastern Australia are intermediate between those of ENA and California. It has been found that Q(f) (characterising whole-path attenuation) and kappa values in SEA are more similar to those of California than those of ENA. There is very limited information about stress-drops in south-east Australian earthquakes large enough to be of engineering importance (about magnitude 5 or greater), and it is inconclusive whether the stress-drops are more similar to those in ENA or Californian earthquakes.

Modification of attenuation expressions for SEA

The approach adopted in the case study was to modify a selection of published attenuation models to be more suitable for conditions in SE Australia

Selected attenuation models

Attenuation models were selected from both ENA, characterised by high stress drops, and from California, where stress drops are lower, because of the uncertainty about stress drops in SE Australia at magnitudes important for seismic hazard.

Two models were selected to be representative of ENA models. The two models have different ways of representing source spectra and of modelling attenuation with distance. The ENA models selected for the case study were those of Atkinson & Boore (1995), denoted as AB95, and Toro et al. (1997), both modified as described in the next section to account for the observed upper-crustal attenuation in south-east Australia.

The Sadigh et al. (1997) model was selected to represent recent Californian models. It produces reasonable estimates of earthquake motions in SEA (G.Gibson, pers. comm.).

Modifications to ENA models

Both the Atkinson & Boore and Toro et al. ENA models give sharp short-period spectral peaks from a combination of high stress-drops and low attenuation of high-frequency motions (e.g. Figure 1). The low attenuation of the ENA models is inappropriate for SEA (e.g. Lam et al. 1998). However, it is considered appropriate to retain the possibility of high stress-drops. This has been achieved by selecting the ENA models, which inherently are influenced by high stress drops, but adjusting their kappa values from those appropriate for ENA to values appropriate for California, and, it is believed, SE Australia.

Adjustments for kappa κ

For south-east Australia, kappa has been taken as 0.04s, as given by Lam et al. (1998). Atkinson & Boore (1997, p26) state that the kappa value for ENA equivalent to their modelling is 0.002s. Toro et al. (1997, p43) give a value of 0.006s as an appropriate value typical of ENA for their model. The differences between the kappa values of these models arise from interactions between kappa and other parameters in the modelling.

Adjustment for kappa was performed using a model provided by N. Abrahamson that has been used for studies of the Yucca Mountain Nuclear Waste Repository project in the U.S. The frequency-dependent modification to the response spectra models for a change from kappa=κ_2 for ENA to kappa= κ_1 for SEA is:

$$\ln(\text{Scale Factor}(f)) = c_{10}(f) * (\kappa_1 - \kappa_2) + c_{11}(f) * ((\kappa_1-0.025)^2 - (\kappa_2-0.025)^2)$$

The coefficients $c_{10}(f)$ and $c_{11}(f)$ are:

Frequency f (Hz)	$c_{10}(f)$	$c_{11}(f)$
0.5	-1.540	-38.64
1.0	-3.156	-24.59
2.0	-6.056	-5.412
5.0	-13.76	26.11
10	-23.37	98.78
≥20	-31.83	378.67
PGA	-18.64	301.22

Examples of original and kappa-modified spectra

Figure 1 compares median 5% damped acceleration response spectra for rock conditions for the Sadigh et al. (1997), Atkinson & Boore (1995) and Toro et al. (1997) models. The two ENA models are unmodified in the left-hand plots and have the kappa modification factors applied in the right-hand plots. The comparisons are shown for horizontal distances from the earthquake source of 10 km (top plot), 30 km (middle plot) and 60 km (bottom plot), for a reverse-faulting magnitude 7.0 earthquake at a focal depth h of 7 km. The Sadigh et al. model includes its reverse fault factor of 1.2. The other models do not contain a reverse fault factor, but it is inherent in them as they have been developed from data from regions where thrusting is likely to be the dominant mechanism.

The two ENA models are plotted with square symbols (■ for Atkinson & Boore and □ for Toro et al.). The very short-period peaks of the unmodified spectra in the left-hand predicted by these two models are apparent at periods of 0.05s and less. This behaviour requires low attenuation at high frequencies, and is thought to be inappropriate for south-eastern Australia. This characteristic has disappeared in the right-hand plots where these models have been modified for higher upper-crustal attenuation (kappa increased to 0.04s, typical of south-eastern Australia and California). With modification for kappa, the two ENA models become similar to the Californian Sadigh et al. model. There has been little modification to the spectra at periods of 0.5s and greater. The right-hand plots are thought to be representative of median spectra for south-eastern Australia for rock conditions. Individual spectra may vary considerably around these median values, with each of the median spectra plotted being associated with a log-normal probability distribution that represents this variability. There is typically a factor of two range between the median spectra for the Sadigh et al. and modified Toro et al. spectra, and up to about a factor of three at long periods when the modified Atkinson & Boore model is included.

Figure 2 shows median attenuation curves for the original and modified forms of the ENA attenuation models, corresponding to the response spectra of Figure 1. Again, the unmodified models are shown on the left and the kappa-modified models on the right. The top plot in each figure is for a period of T=0s, corresponding to peak ground acceleration; the middle plot is for T=0.2s, corresponding to the peak of the spectrum for most cases except for the Atkinson & Boore model; and the bottom plot is for T=1s. The kappa-modified models show considerably reduced accelerations at all distances at short periods (0s and 0.2s). The increased kappa has little effect at 1s period.

Conclusions

From a consideration of tectonic and geological conditions, in southeastern Australia, it was desired to develop spectra with the possibility of high stress drops, as for ENA, but with attenuation characteristic similar to California. It is shown that modifying ENA response spectrum models for near-surface attenuation kappa values appropriate for California largely removes the sharp short-period spectral peaks of the ENA spectra, producing spectra similar to those of Californian models.

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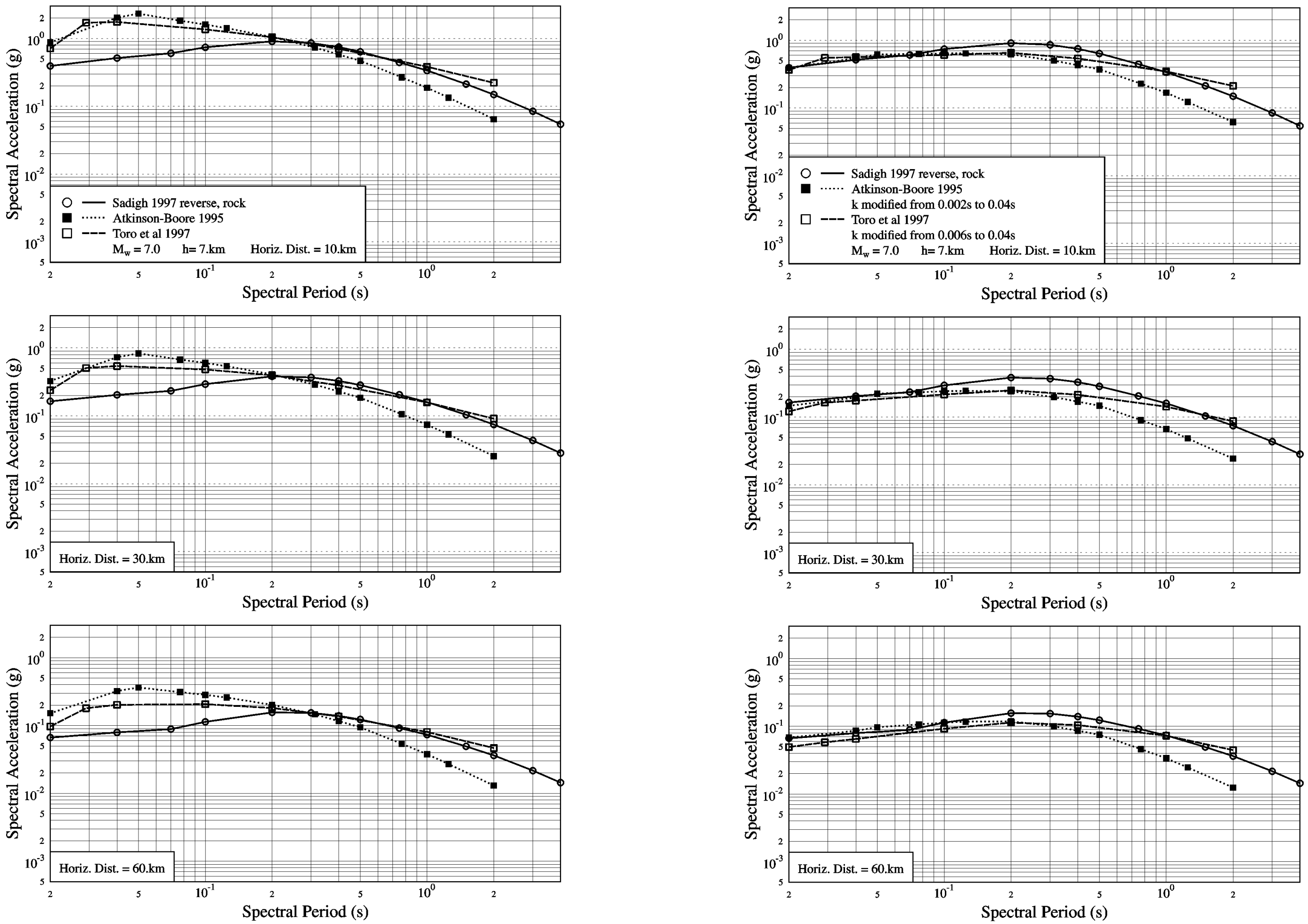

Figure 1 Spectra for magnitude 7 reverse-mechanism earthquakes on rock at horizontal distances of 10, 30 and 70 km. The highly peaked unmodified Atkinson & Boore and Toro et al. spectra (left) become similar to the Sadigh model on application of kappa modification (right).

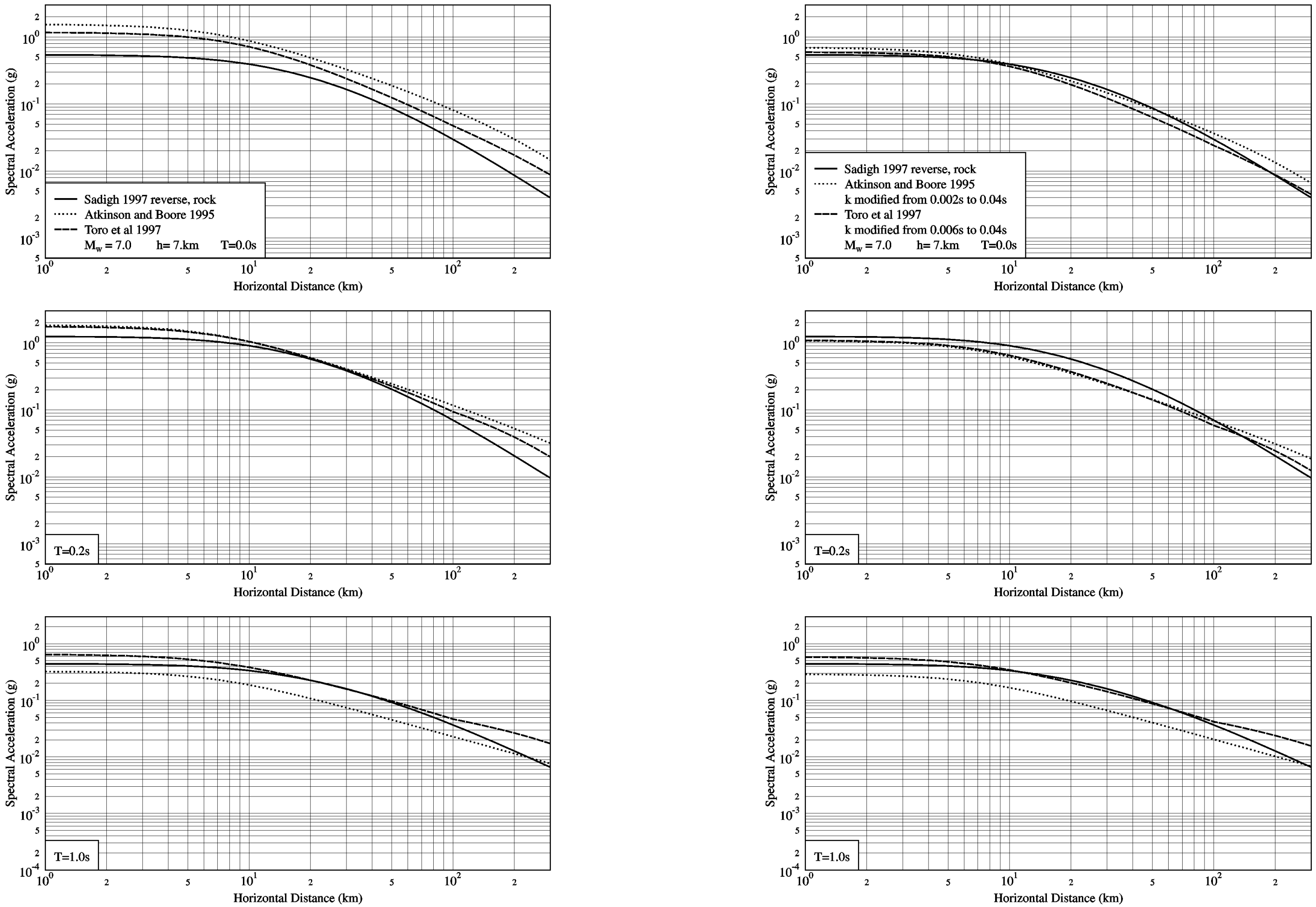

Figure 2 Attenuation curves for periods of 0s (pga), 0.2s and 1.0s, corresponding to the spectra of Figure 1. The short-period (0s and 0.2s) kappa-modified ENA accelerations (right) are much reduced at all distances, but there is little change at 1s period