

Epistemic Uncertainty in Seismic Hazard Analysis for Australia

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Abstract

There is a large degree of uncertainty as to the true state of nature (i.e. epistemic uncertainty) regarding many aspects of seismic hazard analysis. Such differences are often highlighted by differences between alternative models put forth by different model proponents. This epistemic uncertainty is treated by giving weight to all viable alternative models through the use of logic trees in probabilistic seismic hazard analysis, rather than just using a preferred model. This paper reviews epistemic uncertainties that arise in the intraplate setting of Australia from alternative distributed earthquake source models; alternative models for the recurrence of earthquakes on those sources; alternative approaches to including active faults; alternative models for the recurrence of earthquakes on active faults; alternative ground motion prediction models for Australia; and alternative methods for incorporating site response.

Introduction

In this paper, we examine epistemic uncertainties that exist in the specification of many aspects of seismic hazard analysis. These uncertainties arise from alternative distributed earthquake source models; alternative models for the recurrence of earthquakes on those sources; alternative approaches to including active faults; alternative models for the recurrence of earthquakes on active faults; alternative ground motion prediction models for Australia; and alternative methods for incorporating site response.

Alternative Distributed Earthquake Source Models

The Brown and Gibson (2004) distributed earthquake source model (left side of Figure 1) uses geological and geophysical criteria in combination with historical seismicity to identify zones of uniform seismic potential, and then use historical seismicity to characterize the seismic potential of each zone by means of the a-values and b-values of the Gutenberg-Richter earthquake recurrence model, together with an estimate of the maximum magnitude of earthquakes in each zone. A similar approach was used by Gaul et al. (1990) in the current building code ground motion map (AS1170.4). This approach has the advantage of allowing for the incorporation of geological and geophysical information as well as seismicity data in the identification of seismic source zones. However, judgment is required in defining source zone boundaries, and it is unclear what would cause abrupt changes in seismicity levels across source zone boundaries. These considerations motivated the use of spatially smoothed historical seismicity to define the earthquake source model, developed by Risk Frontiers (Hall et al., 2007). This approach is used to describe the seismic potential of the eastern United States (Frankel et al., 1996).

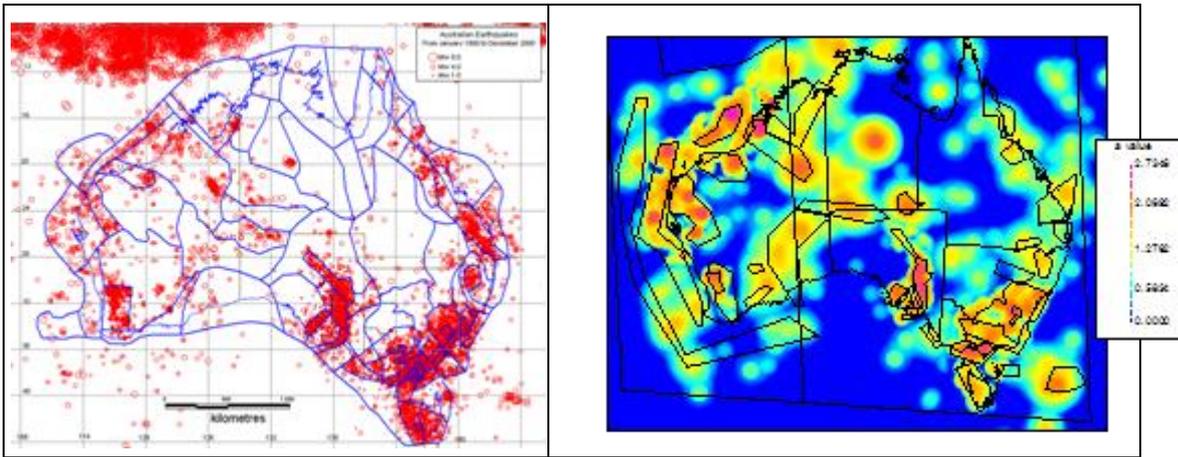


Figure 1. Left: Brown and Gibson (2004) earthquake source model based on geological and geophysical data together with historical seismicity; Right: Hall et al. (2007) earthquake source model based on spatially smoothed seismicity.

This approach gives a spatially continuous source model without boundaries except in b-value (right side of Figure 1). The spatial smoothing approach has the advantages of simplicity and of avoiding uncertainty in the geological definitions of zones, but has the disadvantage of not making use of potentially informative geological data.

Alternative Earthquake Recurrence Models

The distribution of earthquake magnitudes in these earthquake source zones is usually assumed to follow the Gutenberg-Richter model (left side of Figure 2). However, the distribution of earthquake magnitudes on discrete active faults may be better represented by the characteristic recurrence model, in which most of the fault slip is taken up in large earthquakes (right side of Figure 2).

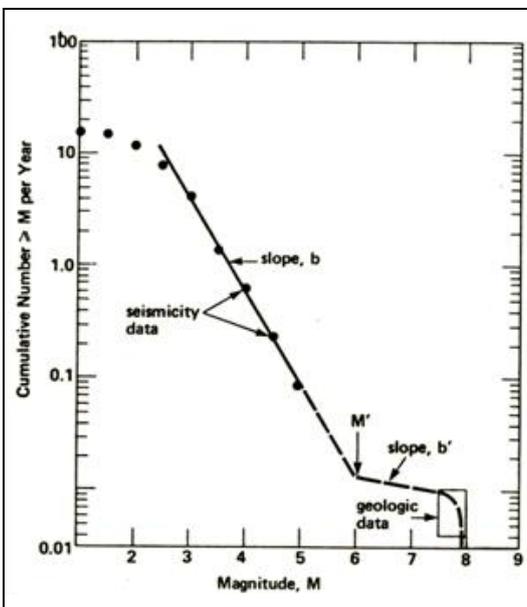


Figure 2. Earthquake recurrence model, consisting of the combination of a Gutenberg-Richter model for small magnitudes, derived from historical seismicity, and a characteristic model for large events derived from geological data.

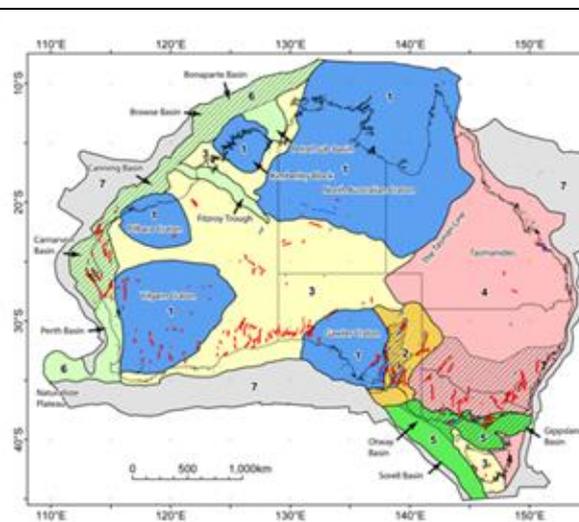


Figure 3. Tectonic domains of Australia; cratons are shown in blue. Source: Clark et al. (2011).

If the characteristic recurrence model applies, then the recurrence rate of large earthquakes within a narrow zone around a fault may be underestimated by the Gutenberg-Richter model based on historical seismicity if it only contains small earthquakes. For active faults, it is preferable to estimate the recurrence rate of large earthquakes from geological data, such as fault slip rates, rather than historical seismicity.

Alternative Approaches to Incorporating Active Faults

In view of the short time span of the historical earthquake catalogue in Australia, it is unclear how best to incorporate active faults into the earthquake forecast. Brown and Gibson (2000) subtract what they interpret as fault-related seismicity from the area source zone in which the fault occurs, and insert a fault source having that seismicity, using a Gutenberg-Richter recurrence model. This approach assumes that the fault seismicity is represented in the background seismicity of the area source. An alternative approach (Somerville, 2008) is to add a fault source for which seismicity is based on slip rate, without modifying the background seismicity of the area source, using a characteristic earthquake recurrence model. This approach assumes that the fault seismicity is not represented in the background seismicity of the area source, in accordance with the characteristic earthquake recurrence model.

Near active faults having slip rates of 0.1mm/yr or more in intraplate Australia, the highest hazard at return periods of 10,000 years, those faults contribute more to the seismic hazard than distributed earthquake source zones. Thus identification of active faults and estimation of the associated slip rates are important for reliable estimation of ground motion hazards near active faults at long return periods. At a return period of 475 years, the hazard contributions from the active fault sources and the distributed seismicity sources are approximately equal at near fault locations in the Australian intraplate tectonic setting.

Alternative Recurrence Behaviour of Active Faults

Clark et al. (2006) found that earthquake activity on faults in Australia is episodic, with clusters of earthquakes on a given fault occurring close together in time (several tens of thousands of years), separated by longer periods (several hundreds of thousands of years) of no large earthquake activity. This is inconsistent with the random temporal (Poisson) distribution of earthquakes that is usually assumed in seismic hazard analysis. Using the results of Clark et al. (2006), it may be possible to identify which faults are currently in an active phase and which are currently in an inactive phase. This could then be applied to the evaluation of the seismic potential of active faults in seismic hazard evaluations.

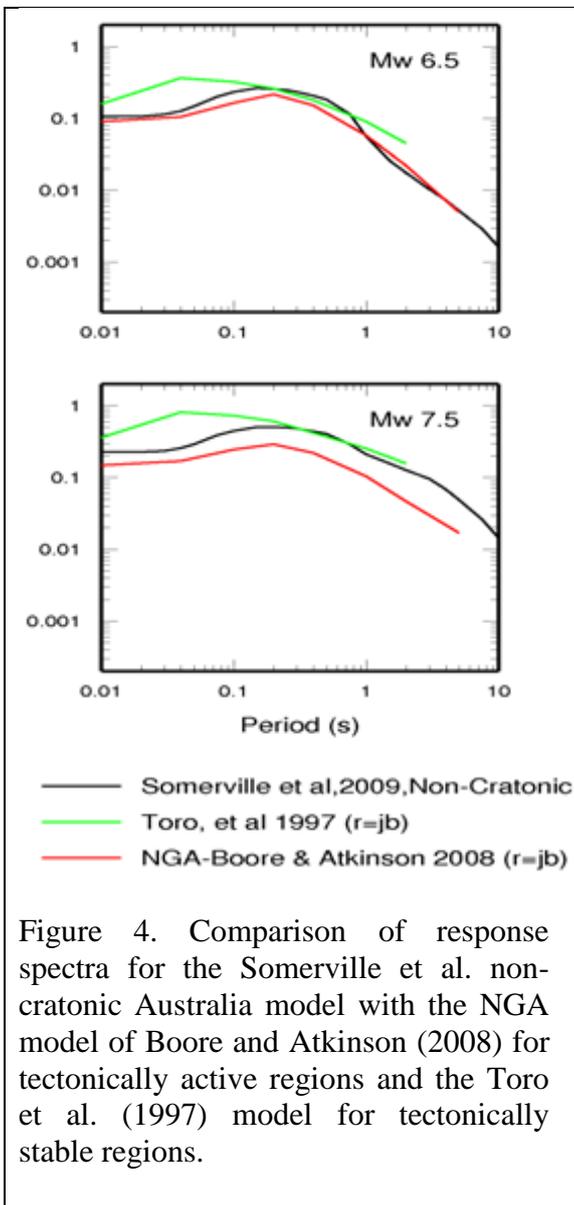
Clark et al. (2011) reviewed knowledge pertaining to the seismogenic deformation of the Australian continent over the last 5-10 Ma (the Neotectonic Era). Based upon perceived differences in character of the seismogenic faults across the continent, and guided by variations in the geologic and geophysical makeup of the crust, they propose six onshore neotectonic domains, summarized in Figure 3. A seventh offshore domain was defined based upon analogy with the eastern United States.

Alternative Ground Motion Models for Australia

Brown and Gibson (2000) analysed the attenuation of recorded ground motion in eastern Australia from three earthquakes in the magnitude range of 4.8 to 5.1 in eastern NSW and Victoria (Figure 9 of their paper), and showed that it is more compatible with the Sadigh et al. (1997) model for tectonically active regions than the Toro et al. (1997) model for tectonically stable regions. Studies by Allen et al. (2005) and McPherson and Allen (2006) using stochastic modeling of ground motions in

Southeastern Australia also produce response spectra whose shapes are more compatible with the Sadigh et al. (1997) model than the Toro et al. (1997) model.

The few ground motion recordings of earthquakes in Australia are all from small magnitude earthquakes, and do not provide a direct means for developing ground motion models for Australia. Accordingly, Somerville et al. (2009) used seismological theory and calculations to develop ground motion models, checking the calculations for consistency with available data from Australian earthquakes at each step. These ground motion models predict response spectra in addition to peak acceleration. Except in cratonic regions of Australia, Somerville et al. (2009) found that ground motions in Australia are like those from tectonically active regions of the world, consistent with past practice (Brown and Gibson (2000)). The cratonic regions of Australia include much of Western Australia (but not the coastal strip west of the Darling Fault, including Perth); south-central South Australia; the northern part of the Northern Territory; and northwestern Queensland (Figure 3, Clark et al, 2011). Figure 4 compares response spectrum predictions of the non-cratonic Australia model of Somerville et al. (2009) with the predictions of the NGA model of Boore and Atkinson (2008) for tectonically active regions and the Toro et al. (1997) model for tectonically stable regions.



A new set of ground motion prediction models for tectonically active regions, termed the NGA models, has been developed recently (Abrahamson et al., 2008). The metadata describing the strong motion recordings used in the development of the NGA models are well documented, and a vastly larger data set was used than in the previous generation of models (Abrahamson and Shedlock, 1997). As a result, the NGA ground motion models that have a much more substantial basis than the 1997 generation of models. In particular, as discussed further below, the specification of site response using V_{s30} has provided much greater flexibility in the application of these models to hard rock sites. The developers of each of the five NGA models were involved in the development of one of the earlier generation of models summarised in Abrahamson and Shedlock (1997). In each case, the authors of the NGA models specified that their NGA model supersedes their previous model. For example, the Chiou and Youngs (2008) model supersedes the Sadigh et al. (1997) model.

Figure 4. Comparison of response spectra for the Somerville et al. non-cratonic Australia model with the NGA model of Boore and Atkinson (2008) for tectonically active regions and the Toro et al. (1997) model for tectonically stable regions.

Impact of Site Conditions on Ground Motion Level

Ground motion prediction models used in earthquake engineering are based on three main parameters: the magnitude of the earthquake, the distance of the earthquake from the site, and the site characteristics. It has long been known that site characteristics have a strong influence on ground motion level. Until recently, site characteristics have been represented by broad geological categories such as “rock” or “soil.” In eastern Australia, it has been common to assume that the site characteristics of dam abutments can be represented by the “rock” site category in ground motion models such as Sadigh et al. (1997).

Recently, new ground motion models, such as the NGA models (Abrahamson et al., 2008) have been developed, and these models quantify site characteristics in a much more rigorous way. Specifically, these new models specify the site characteristics using V_{s30} , which is the average shear wave velocity in the uppermost 30 meters below the ground surface. Amplification of ground motion is inversely proportional to V_{s30} , the average shear wave velocity in the top 30 metres. The amplification is roughly equal to the square root of the ratio of subsurface to surface shear wave velocity. Although V_{s30} is not yet routinely measured in the foundation investigations for dams, it can usually be inferred from the P-wave velocities obtained from seismic refraction surveys whose purpose is to assess the rippability of rock materials.

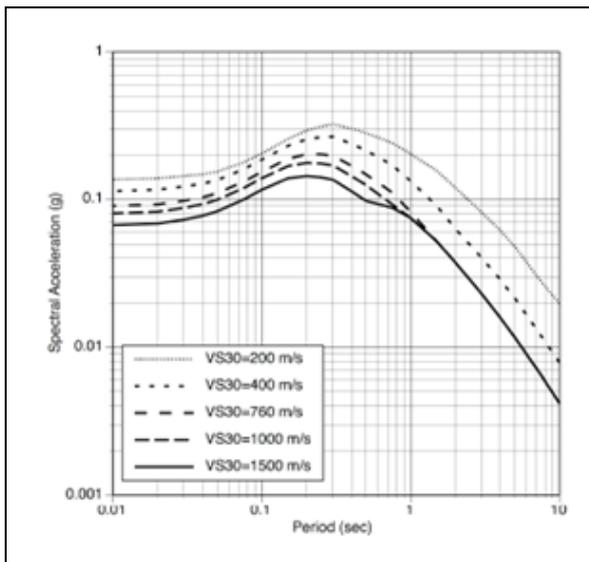


Figure 5. Dependence of response spectral acceleration on V_{s30} for a magnitude 7 earthquake at a distance of 30 km. Source: Abrahamson and Silva, 2008.

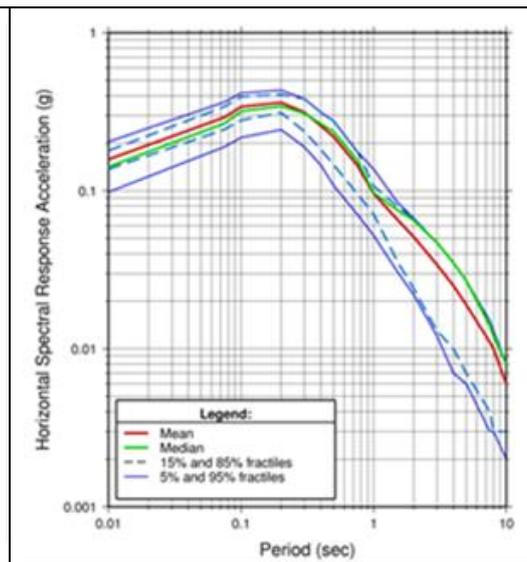


Figure 6. Mean and fractiles of the probabilistic seismic response spectrum for a return period of 10,000 years.

The large sensitivity of ground motion level to V_{s30} is shown in Figure 5. The ground motion level is represented by the response spectrum, in which the peak acceleration is represented on the left side (equivalent to spectral acceleration at a natural period of 0.01 seconds). In Australia, it has been common to assume that the site characteristics of dam abutments can be represented by the “rock” site category in ground motion models such as Sadigh et al. (1997). However, this ground motion model is representative of soft rock sites in California having an average shear wave

velocity (V_{s30}) of only 520 m/sec, while many dams in Australia may be founded on hard rock having V_{s30} of 1,000 m/sec or more. Re-evaluation of the seismic hazard may identify a significant level of conservatism in those dams located on hard rock foundations.

Representation of Epistemic Uncertainty using Fractiles of the Hazard

The preceding sections of this paper have described the epistemic uncertainties that exist in the choice of many of the input parameters required for probabilistic seismic hazard analysis. These include models for forecasting earthquakes, predicting the ground motions and characterising the site response. These epistemic uncertainties are treated using alternative branches in a logic tree, with weights given to the various alternative models based on evaluation of the likelihood that each represents the true state of nature. This results in a seismic hazard curve for each branch of the logic tree. The distribution of the various hazard estimates can then be examined using the fractiles of the hazard, as shown in Figure 6. The fractiles include the median (50th percentile) and the 85th and 95th percentiles of the hazard. Design ground motions are usually based on the mean hazard, but the fractiles provide an indication of the uncertainty in the true value of the mean hazard.

Summary and Conclusions

There is a large degree of uncertainty as to the true state of nature (i.e. epistemic uncertainty) regarding many aspects of seismic hazard analysis for the intraplate setting of Australia. Such differences may be highlighted by alternative models put forth by different proponents. These uncertainties pertain to alternative distributed earthquake source models; alternative models for the recurrence of earthquakes on those sources; alternative approaches to including active faults; alternative models for the recurrence of earthquakes on active faults; alternative ground motion prediction models for Australia; and alternative methods for incorporating site response.

This epistemic uncertainty is treated by giving weight to all viable alternative models, rather than just using a preferred model. This is done through the use of logic trees in probabilistic seismic hazard analysis. Each branch of the logic tree gives rise to a different estimate of the median hazard level. Epistemic uncertainty gives rise to uncertainty in the true value of the median ground motion estimate; this uncertainty can be represented by fractiles of the hazard.

In Australia, it has been common to assume that the site characteristics of dam abutments can be represented by the “rock” site category in ground motion models such as Sadigh et al. (1997). However, this ground motion model is representative of soft rock sites in California having an average shear wave velocity (V_{s30}) of only 520 m/sec, while many dams in Australia may be founded on hard rock having V_{s30} of 1,000 m/sec or more. Re-evaluation of the seismic hazard may identify a significant level of conservatism in those dams located on hard rock foundations.

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