Assessment of Seismic Design Motions at Low Probabilities: Comparing Australia and New Zealand

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MCE ground motions are often defined as those having a return period of 10,000 years, as estimated from a site-specific probabilistic seismic hazard analysis. However, in some cases the MCE is defined by "deterministic" ground motions that are defined as the "maximum possible" ground motions that could occur at the site. In practice, these "deterministic" ground motions consist of spectra for either the median ground motion level or the 84th percentile ground motion level of a scenario earthquake defined by a maximum earthquake magnitude and a closest distance. In high seismic hazard regions such as parts of new New Zealand, the probabilistic ground motions at a 10,000 year return period may exceed the scenario-based ground motion, even at the 84th percentile level, and so the use of the "deterministic" approach may be unconservative. In contrast, in relatively low seismic hazard regions such as Australia, the probabilistic ground motions at a 10,000 year return period may be significantly lower than the scenario-based ground motion, even at the median level, and so the use of the "deterministic" approach may be overconservative. Computationally, the scenario-based approach is simpler to apply than the probabilistic approach, since it only requires specification of a single earthquake scenario. However, in practice, the specification of the earthquake source model for the scenario-based approach is much more difficult because it is extremely sensitive to the selection of the maximum magnitude and the location of the controlling earthquake source, which are especially difficult to identify in regions of low seismicity. We also review current ground motion prediction equations and seismic hazard maps for New Zealand and Australia, and note the importance of measuring or estimating the near-surface shear wave velocity in the foundations of the structure for use in calculating near-surface ground motion amplification effects.

Keywords: *Probabilistic seismic hazard analysis, deterministic seismic hazard analysis*

Introduction

This paper explores the difference in seismic hazard level between two sites, one in Australia and the other in New Zealand, compares probabilistic and scenario-based (deterministic) approaches to seismic hazard analysis, and contrasts the relationship between probabilistic and scenario-based hazard analyses in Australia and in New Zealand. This consideration is relevant for critical structures such as dams that are designed for long return periods, but not relevant for ordinary buildings. Additional issues in seismic hazard analysis in Australia and New Zealand have been discussed by Somerville and Gibson (2008), Somerville et al. (2008), and Somerville and Thio (2011a, b). The term "return period" represents the inverse of the more rigorous term "annual exceedance probability."

Comparison of Australian and New Zealand seismic hazards

Figure 1 compares seismic hazard analyses for sites in Melbourne, Australia and Kaikoura, New Zealand. Probabilistic response spectra are shown in rainbow colours for return periods ranging from 500 to 50,000 years. It is immediately evident that the probabilistic seismic hazard is much higher in Kaikoura than in Melbourne. For example, the two hazard curves in the upper panel of Figure 1 show that a PGA of 0.5g has a return period of about 500 years in Kaikoura and about 50,000 years in Melbourne, a factor of 100 longer.

Scenario-based spectra, for the median (solid black line) level and the 84th percentile (dashed black line) ground motion level, are also shown in Figure 1. These scenario spectra are intended to represent "deterministic" ground motions that are sometimes defined as the "maximum possible" ground motions that could occur, and are sometimes used to represent the MCE. The scenario-based spectra for Kaikoura and Melbourne are not very different from each other, because they both represent the ground motions close to very large earthquakes. For Kaikoura, the spectra are for an Mw strike-slip 7.7 earthquake occurring at a closest distance of 3 km on the Hope fault. For Melbourne, the spectra are for an Mw 7.5 thrust faulting earthquake occurring at a closest distance of 3 km on an unidentified fault. Information about the different ground motion prediction equations is given further below.

For Kaikoura, the median scenario has a return period of about 1,000 years, and the 84th percentile scenario has a return period of about 5,000 years. Since the 10,000 year return period ground motion is sometimes used to define the MCE, use of the scenario-based approach would be an unconservative representation of the MCE at highly active sites like Kaikoura in New Zealand.

For Melbourne, the median scenario has a return period of about 250,000 years, and the 84th percentile scenario has a return period of about 2.5 million years. Since the 10,000 year return period ground motion is sometimes used to define the MCE, use of the scenario-based approach would be an overconservative representation of the MCE in regions of low seismicity like those in Australia.

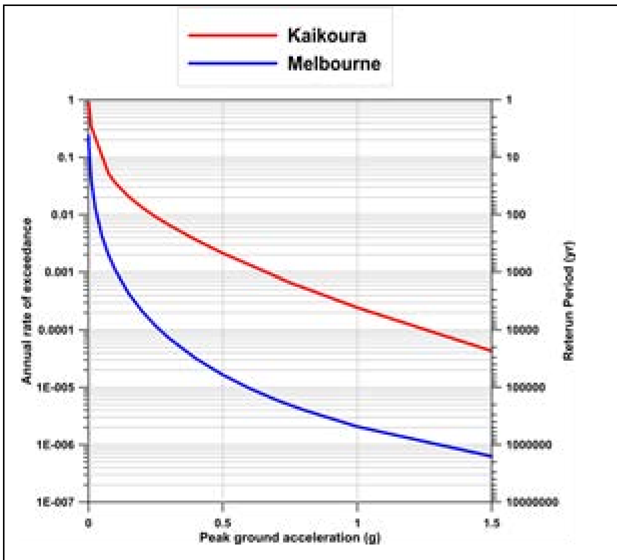
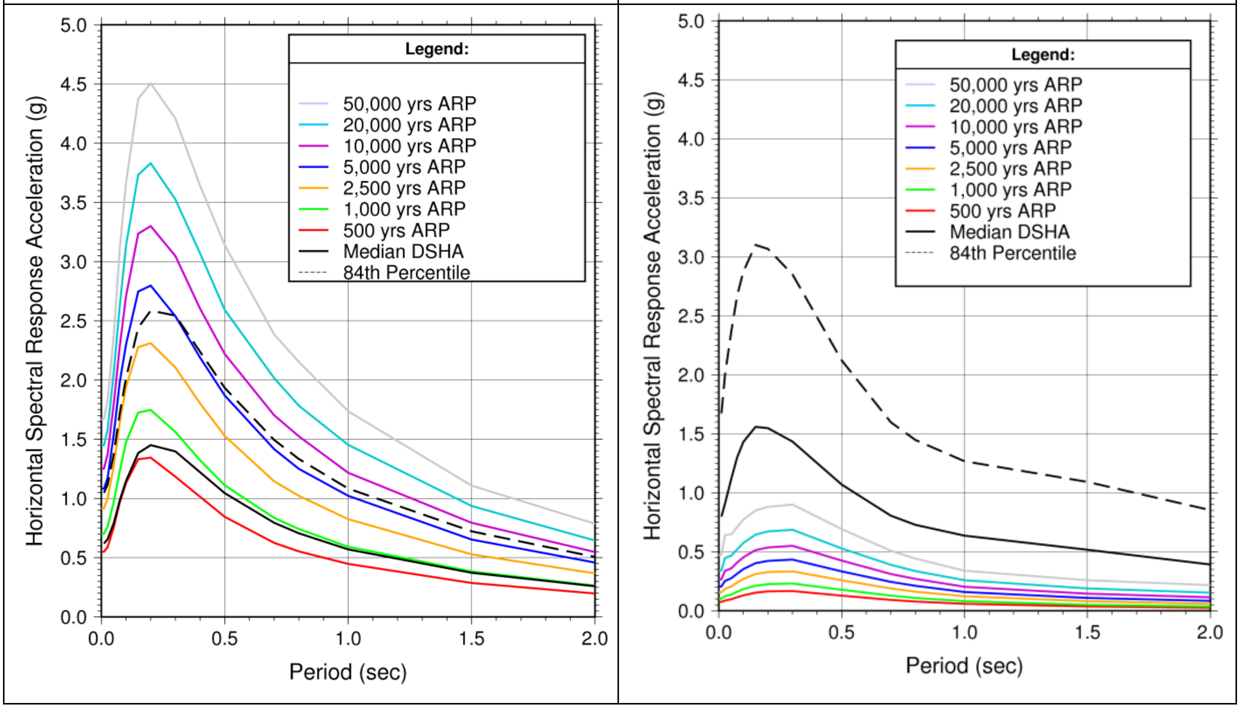


Figure 1. Hazard curves for peak acceleration (left) and probabilistic and scenario-based response spectra for Kaikoura (bottom left) and Melbourne (bottom right).



Deaggregation of the 10,000 year return period seismic hazard by magnitude and distance at Kaikoura (left) and Melbourne (right), for 0.4 second spectral acceleration, shown in Figure 2, shows that the Kaikoura hazard is dominated by nearby large earthquakes (on the Hope fault and other nearby faults), while the hazard in Melbourne contains contributions from large earthquakes occurring over a wide area, with little contribution coming from nearby earthquakes.

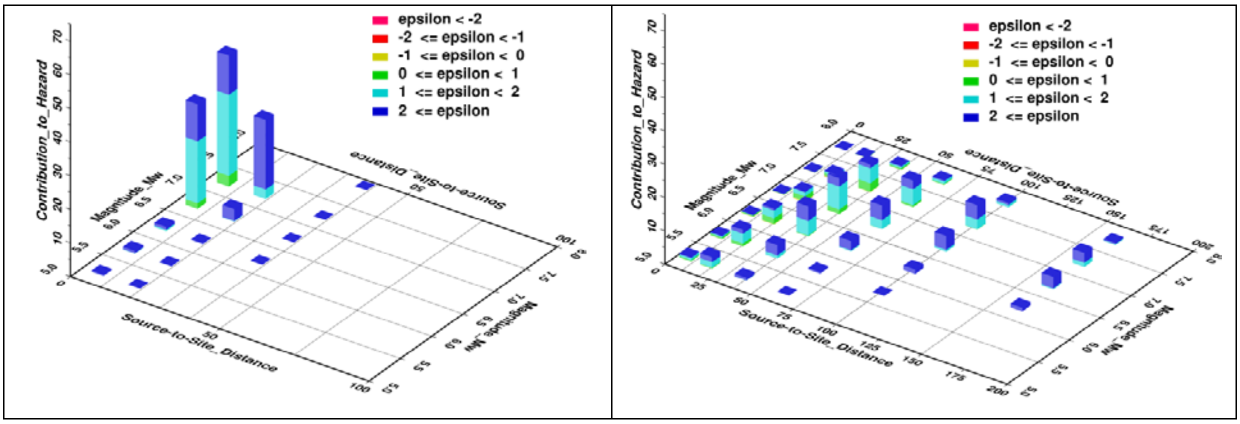


Figure 2. Deaggregation of the 10,000 year return period seismic hazard for 0.4 sec spectral acceleration by magnitude, distance and epsilon at Kaikoura (left) and Melbourne (right).

The deaggregation of the hazard in Figure 2 also shows the epsilon values that contribute to the hazard. Epsilon is the number of standard deviations by which a ground motion level differs from the median level for a specified magnitude and distance. For example, Figure 3 shows the recorded peak accelerations of the 2004 Niigata Chuetsu earthquake (circles and dots), compared with a ground motion prediction model (GMPE). The solid line shows the median prediction of the GMPE, and the dashed lines show the 16^{th} and 84^{th} percentile values, representing one standard deviation in log space, and epsilon values of +/- 1. These dashed lines represent the random variability in ground motion level about the expected (median) level.

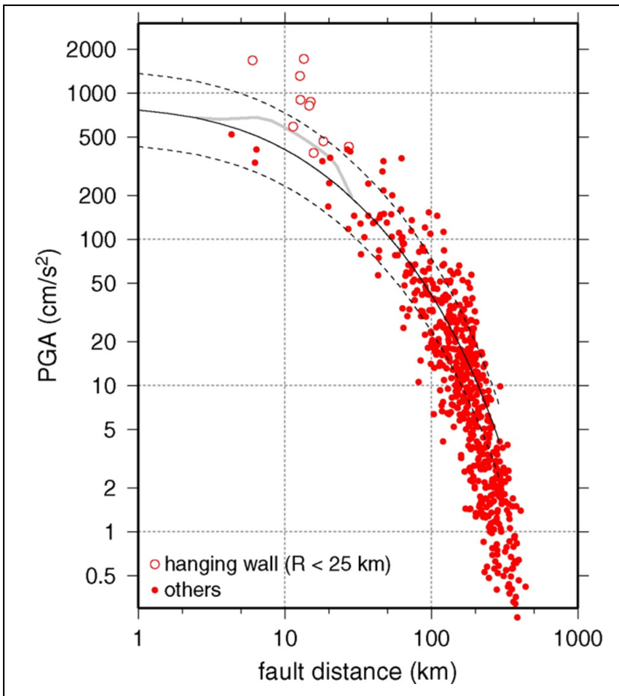


Figure 3. Recorded peak accelerations of the Mw 6.6 2004 Niigata Chuetsu, Japan earthquake (circles and dots), compared with a ground motion prediction model (GMPE). The solid line shows the median prediction of the GMPE, and the dashed lines show the 16th and 84th percentile values, representing one standard deviation on log space, and epsilon values of +/- 1. The circles show hanging wall recordings, for comparison with the solid grey line showing the Abrahamson and Somerville (1998) hanging wall model. Source: Hiroe Miyake.

This random variability in ground motion level is taken into account in seismic hazard analyses. In scenario-based SHA, it is common to use either the median or 84th percentile levels, corresponding to epsilon values of 0 and 1 respectively. In probabilistic SHA, the hazard is integrated over the lognormal distribution of ground motion values for each earthquake scenario that is treated in the hazard analysis. When the hazard is deaggregated, as shown in Figure 2, it is possible to identify ranges of epsilon that contribute to the hazard. At the probability level of 1/10,000 years shown in Figure 2, all of the contributions come from epsilon values greater than 1. The more distant the earthquake, or the smaller the earthquake magnitude, the larger the epsilon value needs to be to allow the ground motion level to reach the value represented by the 10,000 year spectrum.

Scenario based seismic hazard analysis

In scenario-based SHA, the hazard level is controlled solely by the combination of earthquake magnitude and distance that gives the highest ground motion level for a fixed value of epsilon, regardless of how unlikely its occurrence may be. Consequently, in scenario-based SHA, the seismic hazard level is very sensitive to the maximum magnitude and location of the controlling earthquake source. The epsilon is usually assigned a fixed value (such as 0 for the median level or 1 for the 84th percentile level), and the frequency of occurrence of the scenario earthquake is not a consideration.

Probabilistic seismic hazard analysis

Unlike the case for scenario-based SHA, the frequency of occurrence of earthquakes is a primary consideration in probabilistic SHA. In probabilistic SHA, the ground motion hazard contains contributions from earthquakes of all magnitudes occurring on all of the earthquake sources that can affect the site. This is in contrast with scenario-based SHA, which only considers a single scenario earthquake.

The methodology for probabilistic seismic hazard analysis (PSHA) was developed by Cornell (1968). If seismicity is considered to follow a random Poisson process, then the probability that a ground motion, such as Spectral Acceleration (SA) exceeds a certain value (s) in a time period t is given by:

$$P(SA > s) = 1 - e^{-\phi(s)t}$$

where $\phi(s)$ is the annual mean number of events (also known as “annual frequency of exceedance”) in which the ground motion parameter of interest exceeds the value s. For engineering purposes, we are interested in computing s for a certain probability of occurrence, P, in a time period t, such as 1/10,000; we usually refer to the latter as a return period of 10,000 years.

The annual frequency of exceedance is calculated by integrating the contributions from all faults or seismic sources as follows:

$$\phi(s) = \sum_{i=1}^{Faults} (\iint_{m,r} f(m)(P(SA > s \mid m, r)P(r \mid m)dmdr)_i$$

where:

f(m) = probability density function for events of magnitude *m*

P(SA>s|m,r) = probability that *SA* exceeds a given magnitude *m* and distance *r*

P(r|m) = probability that the source to site distance is *r*, given a source of magnitude *m*.

In probabilistic SHA, the seismic hazard is integrated over the random distribution of ground motion level (epsilon), rather by selecting a discrete value (usually 0 or 1). The seismic hazard level increases indefinitely with increasing return period unless a limit is placed on epsilon. To date, it has not been possible to identify any significant departure from a lognormal distribution in recorded ground motion levels at epsilon values as high as 2.5 to 3, at which the data are too sparse to provide further resolution.

At short return periods, the increase in hazard with increasing return period is due to the occurrence of progressively larger earthquakes in progressively closer proximity to the site, as well as to the random sampling of progressively higher epsilon values. At longer return periods, where the occurrence of the largest earthquake on the closest fault has been taken into account, the hazard still grows with increasing return period, as shown in Figure 1,due to the random sampling of progressively larger values of epsilon (Figure 3). For example, at the Kaikoura site, magnitude 7.7 earthquakes on the Hope fault have a recurrence interval of 1690 years. For return periods longer than 1690 years, the increase in hazard level with increasing return period shown in the top panel of Figure 1 is mainly due to epsilon.

Although the 84th percentile spectrum at Melbourne is very large and is associated with a very long return period (about 2.5 million years), higher ground motions could occur, with even lower probability, because of the random variability in ground motion levels about the median value (epsilon). For this reason, the concept of a "deterministic" bound on the ground motion level is poorly defined, and some criterion, such as the number of standard deviations above the median value, would be required to specify the "deterministic" ground motion level, but that would tacitly concede that still larger values are possible. That is why it is preferable to refer to a "scenario-based" approach rather than to a "deterministic" approach, because it is based on the selection of a single ground motion scenario that cannot be shown to be the "largest possible" ground motion.

When used in conjunction with the recurrence interval of the maximum magnitude earthquake, the specification of the number of standard deviations (epsilon) associated with the scenario-based response spectrum can be interpreted probabilistically. This brings us back to the underlying probabilistic nature of seismic hazard, which renders it impossible to define an upper bound on the ground motion level. It is therefore preferable to use a probabilistic approach to estimate the ultimate ground motion level. That level would be associated with a return period or annual probability of exceedance that is defined in a regulatory environment as constituting an acceptable risk.

Information required for scenario-based and probabilistic SHA

Computationally, the scenario-based approach is simpler to apply than the probabilistic approach, since it only requires specification of a single earthquake scenario, and the hazard level is controlled solely by the combination of earthquake magnitude and distance that gives the highest ground motion level for a fixed value of epsilon. However, in practice, the specification of the earthquake source model for the scenario-based approach is much more difficult because it is extremely sensitive to the selection of the maximum magnitude and the location of the controlling earthquake source, which are especially difficult to identify in regions of low seismicity.

This is especially true for regions such as Australia in which few active faults have been identified, and so it is necessary to assume that large earthquakes could occur at any location unless extensive geological investigations are undertaken to demonstrate the absence of faults having the potential to generate large earthquakes below or near the site. In current Australian earthquake source models, it is assumed that these earthquakes could have magnitudes as large as Mw 7.5. In New Zealand, many active faults have been identified, and it is easier to localise large earthquakes on these faults (such as the Hope fault in Kaikoura). However, even in New Zealand, it is assumed that earthquakes with magnitudes as large as 7.2 could occur on unidentified faults, as illustrated by the occurrence of the Mw 7.1 Darfield earthquake on the previously unidentified Greendale fault west of Christchurch on September 4, 2010.

Given that the maximum earthquake can occur arbitrarily close to the site, and unless extensive geological investigations are undertaken to demonstrate the absence of faults having such potential below or near the site, then the scenario-based approach consists of deciding on precisely how large the maximum earthquake can be, and how shallow and how close to the site to allow this maximum earthquake to occur. These are difficult parameters to identify in regions of low seismicity such as Australia, where the largest historical earthquakes have magnitudes of Mw 7.2.

The location of seismic source zones and the sizes of the maximum earthquake magnitudes that are assigned to them are also important for PSHA, but their influence on the calculated ground motions is not as strong as in scenario-based SHA. This is less true in locations such as Kaikoura where the seismic hazard is dominated by one or more identified local faults (left side of Figure 2), but is especially true in regions of low seismicity such as Australia. This is because the ground motion hazard contains contributions from earthquakes of all magnitudes occurring on all of the earthquake sources that can affect the site, as can be seen in the contributions from earthquakes having a range of magnitudes at many different distances on the right side of Figure 2. The reasons for the relative insensitivity of probabilistic SHA to the characterization of the maximum magnitudes and locations of earthquake sources in regions of low seismicity, compared with the case of scenario-based SHA, are as follows.

Maximum Magnitude

In regions of very low seismicity, the largest earthquakes may have such long recurrence intervals that they do not contribute strongly to the seismic hazard. In this case, the hazard is dominated by earthquakes whose magnitudes are less than the maximum magnitude that is assigned to the seismic source, as demonstrated for Melbourne on the right hand side of Figure 2, and so the selection of the maximum magnitude is less critical than in the case of scenario-based SHA. However, in PSHA, the frequency of occurrence of smaller earthquakes becomes important.

Source Location

Probabilistic SHA takes account of earthquakes occurring on all of the known earthquake sources that can affect the site, including both nearby and distant sources. In regions where the identified faults are located at some distance from the site, the seismicity in the region around the site is commonly represented by a zone of uniformly distributed seismicity, and the probabilistic SHA contains contributions from the whole zone surrounding the site, not just the part of the zone that is closest to the site, as seen for Melbourne on the right side of Figure 2. Consequently, the precise location of the zone, which in the scenario-based approach may be specified by the shallowest depth of the zone beneath the site, has less impact in the probabilistic SHA approach.

Epsilon

In probabilistic SHA, the seismic hazard is integrated over the random distribution of ground motion level (epsilon). Consequently, the ground motions from a distant source can potentially exceed a given ground motion level at a site more often than the ground motions from a nearby source, if the distant source has more frequent earthquakes than the nearby source. This is evidently the case for Melbourne, as seen on the right hand side of Figure 2. This may be true even if the distant and nearby sources have the same maximum magnitude. This is because the larger frequency of earthquakes on the distant source may give rise to the random occurrence of high epsilon values more often than the infrequent earthquakes on the nearby source. In scenario-based SHA, the epsilon is usually assigned a fixed value (such as 0 for the median level or 1 for the 84th percentile level) that is the same for all earthquake sources, and so earthquake frequency is not a consideration, and the outcome is controlled solely by the combination of magnitude and distance that gives the highest ground motion level for a fixed value of epsilon.

New ground motion prediction equations for Australia and New Zealand

New Zealand

Bradley (2012) analysed the Next Generation (NGA) GMPE's (Abrahamson et al. 2008) and found that the Chiou and Youngs (2008) NGA GMPE provided the best fit to the New Zealand strong motion data set (prior to the inclusion of the Canterbury Plain events). Based on the New Zealand strong motion data set, he used the functional form of the Chiou and Youngs (2008) model to develop a ground motion model for application in New Zealand, modifying some of the coefficients and adopting the remaining ones from that model. The Abrahamson and Silva (2008) and Boore and Atkinson (2008) models also fit the Canterbury Plain ground motion data quite well. The Bradley (2012a) model generally predicts larger ground motions than the NGA models. Bradley (2012b) demonstrated that his model provides a better fit to the Canterbury Plain data than McVerry et al. (2006). The Bradley model has the advantages of being based on a large global data set, of having been calibrated to optimally fit New Zealand data (pre Canterbury), and of being compatible with the Canterbury data.

Australia

Ground motion prediction equations, including those described above, are most commonly derived from strong ground motion recordings. However, the few ground motion recordings of earthquakes in Australia are all from small magnitude events, and do not provide a direct means for developing ground motion prediction models for Australia. Accordingly, recent investigators (Liang et al., 2008; Somerville et al., 2009; and Allen, 2011) have used seismologically based methods to develop ground motion prediction models for Australia.

Liang et al. (2008) estimated strong ground motions in southwest Western Australia using a combined Green's function and stochastic approach. This model is applicable to the Yilgarn Craton, and may also be applicable to other cratonic regions of Australia, but may not be applicable to non-cratonic regions, including Perth.

Somerville et al. (2009) demonstrated their ability to simulate the recorded ground motions of small earthquakes that occurred in Eastern and Western Australia, and developed earthquake source scaling models for Australian earthquakes based on earthquake source modelling of the Mw 6.8 1968 Meckering and the Mw 6.25, 6.4 and 6.6 1988 Tennant Creek earthquakes. They then used a broadband strong ground motion simulation procedure based on the elastodynamic representation theorem and Green's functions calculated from crustal structure models for various regions of Australia to calculate ground motions for earthquakes in the magnitude range of 5.0 to 7.5. These ground motions were then used to develop ground motion prediction equations, which were checked for consistency with available data from Australian earthquakes up to magnitude 4.7 at each step. These ground motion models predict response spectra in addition to peak acceleration for two crustal domain categories: Cratonic Australia and Non-Cratonic Australia. 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 (Clark et al, 2011). The remainder of Australia, including Eastern Australia and part of the coastal margin of Western Australia, is on Non-Cratonic Australia, which includes all of the state capital cities except Darwin.

Allen (2012) developed a ground motion model for southeastern Australia based on the stochastic model, having calibrated the parameters of the stochastic model using recordings of small earthquakes in southeastern Australia (SEA). These updated source and attenuation parameters were used as inputs to the stochastic finite-fault software package, EXSIM (Motazedian and Atkinson, 2005; Atkinson and Boore, 2006). Five percent damped response spectral accelerations were simulated for earthquakes of moment magnitude MW 4.0 to 7.5. These stochastic data were then regressed to obtain model coefficients and the resulting ground motion prediction model was evaluated against recorded response spectral data for moderate-magnitude earthquakes recorded in southeastern Australia.

In view of the significant differences in the ground motions that are predicted by the different ground motion models for Australia, it is necessary to include alternative ground motion prediction models in seismic hazard analyses in order to account for epistemic uncertainty in which of these models is most applicable in Australia.

New ground motion hazard maps for Australia and New Zealand

New ground motion maps have been developed primarily for building code applications in Australia and New Zealand. These maps are not well suited for the estimation of site-specific ground motions at long return periods as required for dams.

New Zealand

The current probabilistic seismic hazard maps for New Zealand were developed by Stirling et al. (2012).

Australia

The most recent seismic hazard maps for Australia are those developed by Burbidge et al. (2012), but they not yet been incorporated in the Earthquake Loading Standard. Additional earthquake source models were developed by Brown and Gibson (2004) and Hall et al. (2007). In view of the differences in the ground motions that are predicted by the different earthquake source models for Australia, it is necessary to use alternative earthquake source models in seismic hazard analyses in order to account for epistemic uncertainty in the degree of applicability of each of these models in Australia.

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 prediction models such as Sadigh et al. (1997).

Recently, new ground motion models, such as the NGA models (Abrahamson et al., 2008) have been developed that quantify site characteristics in a much more rigorous way. Specifically, these new models specify the site characteristics using Vs30, which is the average shear wave velocity in the uppermost 30 meters below the ground surface. In the course of the NGA project, it was discovered that the “rock” GMPE of Sadigh et al. (1997) represents a Vs30 of 520 m/sec, which is only about half the value that is typical of rock sites at Australian dams. Amplification of ground motion is inversely proportional to Vs30, and is roughly equal to the square root of the ratio of subsurface to surface shear wave velocity. Although Vs30 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. It is very advantageous for Vs30 profiles to be surveyed at tailings dams, because they are often founded on soft soils, and it is important to know their shear wave velocity profile, as well as that of bedrock, for analysis of the nonlinear response of those soils to ground motions that are input at bedrock.

Conclusions

In high seismic hazard regions such as New Zealand, the probabilistic ground motions at a 10,000 year return period may exceed the scenario-based ground motion, even at the 84th percentile level, and so the use of the “deterministic” approach may be unconservative. In contrast, in low seismic hazard regions such as Australia, the probabilistic ground motions at a 10,000 year return period may be significantly lower than the scenario-based ground motion, even at the median level, and so the use of the “deterministic” approach may be overconservative.

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