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Assessment of Seismic Design Motions in Areas of Low Seismicity: Comparing Australia and New Zealand

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ABSTRACT

MCE ground motions are often defined probabilistically as those having a return period of 10,000 years. 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 either the median or the 84th percentile spectra of a scenario earthquake defined by a maximum earthquake magnitude and a closest distance. In high seismicity regions such as New Zealand, the 10,000 year ARP ground motions 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 seismicity regions such as Australia, the 10,000 year ARP ground motions 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.

Introduction

This paper explores the difference in seismic hazard level between Australia and 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. 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).

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 Figure 2 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. The Kaikoura ground motions were calculated using the earthquake source model of Stirling et al. (2010) and Litchfield et al. (2014) and the ground motion models of Bradley (2013) and the NGA West 1 models (Abrahamson et al., 2008). The Melbourne ground motions were calculated using the earthquake source models of Brown and Gibson (2004), Burbidge (2012), and Hall et al. (2007) and the ground motion prediction models of Allen (2012), Somerville et al. (2009), and the NGA West 1 models (summarised by Abrahamson et al., 2008).

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For both Kairoura and Melbourne, the scenario earthquake is a magnitude 7.5 earthquake at a closest distance of 3 km, on the Hope fault for Kaikoura and on an undefined fault in Melbourne. 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.

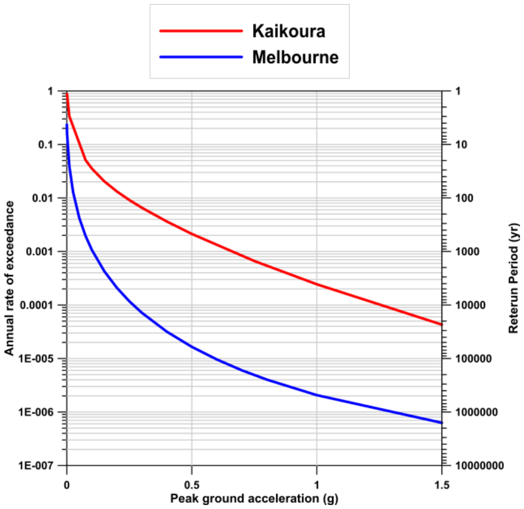

Figure 1. Hazard curves for peak acceleration for Kaikoura and Melbourne.

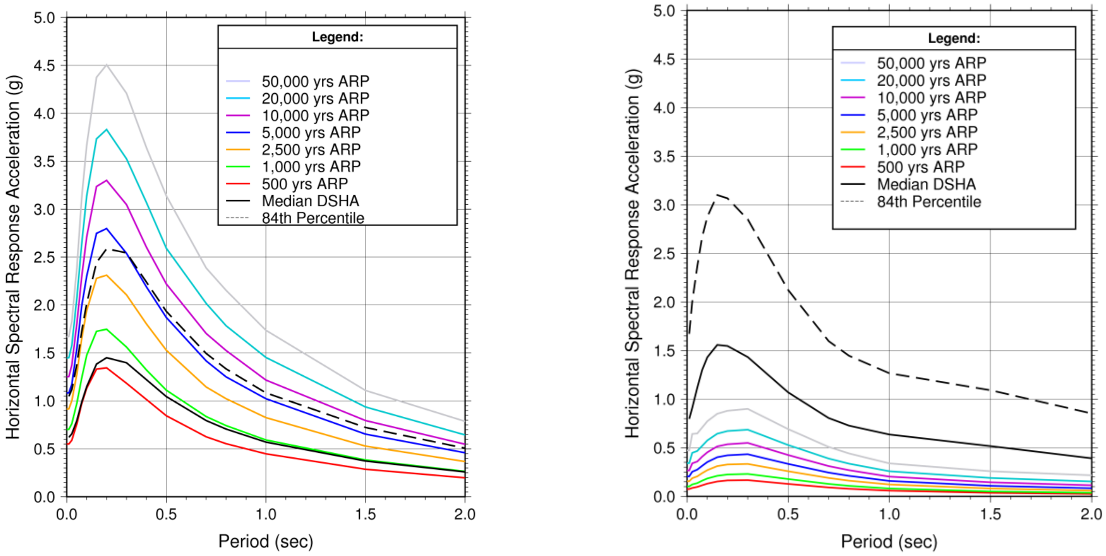

Figure 2. Probabilistic and scenario-based response spectra for Kaikoura, NZ (left) and Melbourne, AU (right).

Deaggregation of the Probabilistic Hazard

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 3, 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.

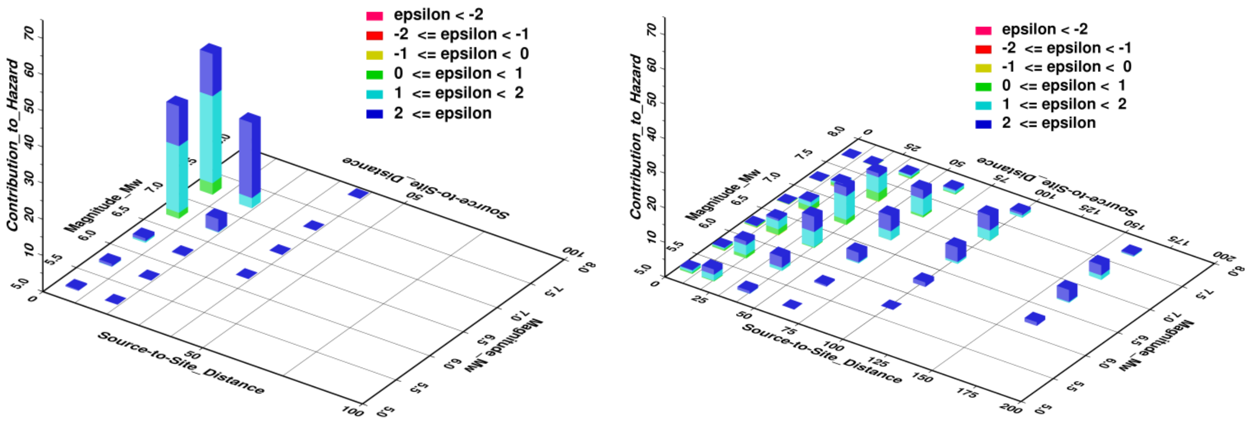

Figure 3. Deaggregation of the 10,000 year return period seismic hazard for 0.4 sec spectral acceleration by magnitude, distance and epsilon at Kaikoura (left) and Melbourne (right).

The deaggregation of the hazard in Figure 3 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 4 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 16th and 84th 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.

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. Consideration of Figure 3 indicates that, unless the lognormal random variability about the median value of the GMPE is truncated at some value, which to date has proved difficult to justify, the hazard is unbounded, and that it is therefore preferable to use the term “scenario-based” rather than “deterministic.” 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 3, 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 3, 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. ASCE7-10/IBC recommends taking the lower of the probabilistic or the 84% deterministic ground motion in order to truncate the probabilistic hazard. A more rational approach would be to adjust the probability level of the MCE.

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.

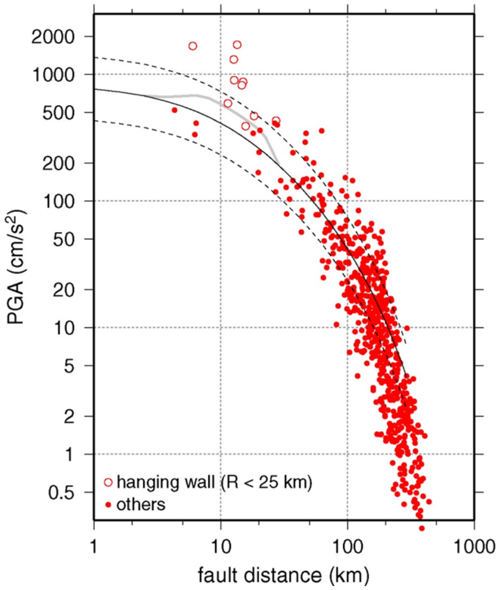

Figure 4. Recorded peak accelerations of the Mw 6.6 2004 Niigata Chuetsu, Japan earthquake (circles and dots), compared with a ground motion prediction model (GMPE). The solid line shows the median prediction of the GMPE, and the dashed lines show the 16th and 84th percentile values, representing one 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.

Probabilistic Seismic Hazard Analysis

Unlike the case for scenario-based SHA, the frequency of occurrence of earthquakes is a primary consideration in probabilistic SHA (PSHA). In PSHA, 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 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:

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

where $\varphi(s)$ 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:

$$\boldsymbol{\phi}(s) = \sum_{i=1}^{Faults} (\iint_{m,r} f(m)(P(SA > s \mid m,r)P(r \mid m)dmdr)_i \quad (2)$$

where *f(m)* is the probability density function for events of magnitude *m*, *P(SA>s|m,r)* is the probability that *SA* exceeds a given magnitude *m* and distance *r* and *P(r|m)* is the probability that the source to site distance is *r*, given a source of magnitude *m*. In PSHA, 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 Figure 2 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 most active faults have not yet 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 newly discovered 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 Mw 6.8.

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 3), 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 3. 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 3, 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 is important.

Source Location

PSHA takes account of earthquakes occurring on all of the 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 PSHA 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 3. 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 PSHA approach.

Epsilon

In PSHA, 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 3. 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.

Conclusions

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 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. 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.

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