Conditions under which identified faults contribute significantly to seismic hazard in Australia

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Abstract

The 2017 draft ANCOLD Guidelines for Design of Dams and Appurtenant Structures for Earthquake specify that active faults (with movement in the last 11,000 to 35,000 years) and neotectonic faults (with movement in the current crustal stress regime, in the past 5 to 10 million years) which could significantly contribute to the ground motion for the dam should be identified, and be accounted for in the seismic hazard assessment. The purpose of this paper is to provide guidance on the conditions under which these contributions could be significant in a probabilistic seismic hazard analysis (PSHA) and a deterministic seismic hazard analysis (DSHA). We consider five primary conditions under which identified faults can contribute significantly to the hazard: proximity, probability of activity, rate of activity, magnitude distribution, and return period under consideration.

Keywords: Active fault, neotectonic fault, probabilistic seismic hazard analysis, deterministic seismic hazard analysis.

INTRODUCTION

The 2017 draft ANCOLD *Guidelines for Design of Dams and Appurtenant Structures for Earthquake* (ANCOLD, 2017) specify that active faults (with movement in the last 11,000 to 35,000 years) and neotectonic faults (with movement in the current crustal stress regime, in the past 5 to 10 million years) which could significantly contribute to the ground motion for the dam should be identified, and be accounted for in the seismic hazard assessment. The purpose of this paper is to provide guidance on the conditions under which these contributions could be significant in a probabilistic seismic hazard analysis (PSHA) and a deterministic seismic hazard analysis (DSHA). At most sites that are distant (several tens of km) from faults, the probabilistic seismic hazard is dominated by randomly occurring earthquakes that are modelled by distributed earthquake sources (Brown and Gibson, 2004; Hall et al., 2007; Burbidge, 2012), as in the example on the right side of Figure 1. Like all earthquakes, these distributed earthquakes also occur on faults, but usually their fault dimensions are quite small (less than 5 km) and they do not break the ground surface, so it is usually not possible to associate them with identified surface faults. Conversely, there are typically numerous mapped faults close to or in the region surrounding dam sites in Australia, but most or all of these faults are “bedrock faults” (ones that do not displace geologically younger materials such as alluvium) which were once active but are not known to be currently active, although they potentially could be. Consequently, the correlation between small historical earthquakes and mapped faults is generally not very strong. Nevertheless, the topographic conditions that make viable dam sites are sometimes attributable to the movement of faults which in some cases may be ongoing, and so the contribution of potentially active faults to the seismic hazard at dam sites requires careful consideration.

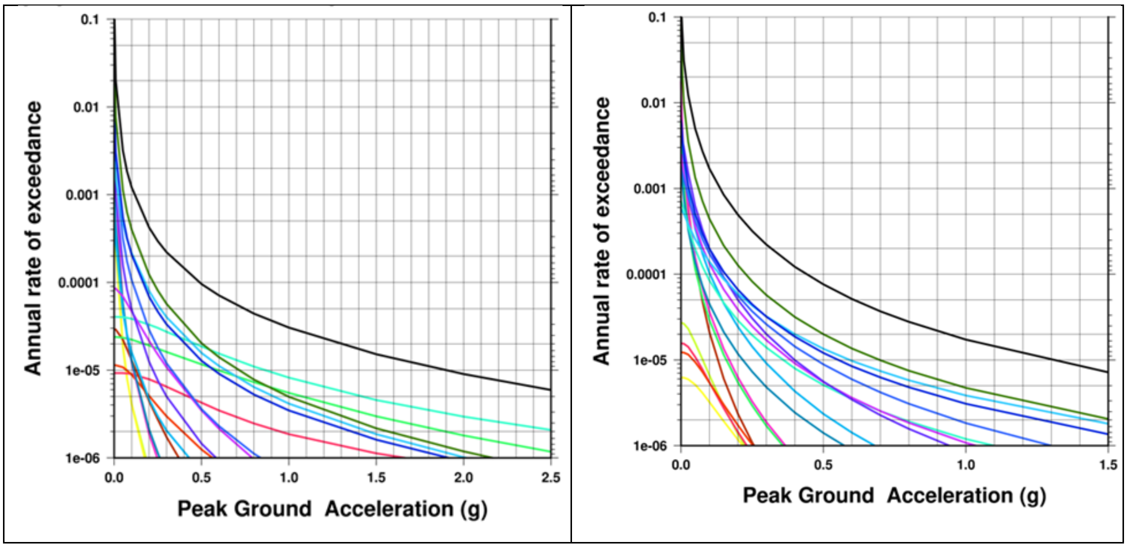

Figure 1. Source deaggregation of PGA hazard at a near-fault site (left) and at a site distant from faults (right) showing contributions of distributed earthquake sources (concave hazard curves); fault sources (convex hazard curves), and total hazard (black concave hazard curve that lies above the others).

In the past century, about ten Australian earthquakes have broken the ground surface (Clark et al., 2011; 2012) and thus can be associated with identified faults. All of these earthquakes occurred in cratonic regions of the western part of Australia, where hypocentres tend to be very shallow because the shallow crust is very strong. None of these earthquakes occurred on a fault that had already been identified as a potentially active fault.

CONSIDERATIONS

Definition and Identification of Active Faults

An Australia-wide assessment of active faulting based on neotectonics data was made by Clark et al (2011, 2012). They analysed a catalogue of 333 neotectonic features, 47 of which are associated with named fault scarps. The data were derived from analysis of Digital Elevation Models (DEMs), aerial photos, satellite imagery, geological maps and consultation with state survey geologists and a range of other earth scientists. A neotectonic fault is defined as one that has hosted measurable displacement in the current crustal stress regime (Machete, 2000), i.e. within the last 5-10 Ma in Australia (Sandiford et al. 2004) but is not necessarily an active fault. Verifying these features as active faults (or not) is an ongoing process. The catalogue varies in completeness because sampling is biased by the available databases, the extent of unconsolidated sedimentary cover, and the relative rates of landscape and tectonic processes.

Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis involves a comprehensive set of considerations relating to the likelihood and frequency of occurrence of the full magnitude range of earthquakes. These considerations include the probability that the fault is indeed active; its rate of earthquake activity; the magnitude distribution of earthquakes that the fault is assumed to generate; the return period of interest; and the proximity of the fault to the site.

Probability of Activity

Clark et al. (2012) assessed their confidence that each feature in their data base is a neotectonic feature (active in the past 5 to 10 million years), using the rankings of A: Definite; B: Probable and C: Possible. The distribution of numbers of features in each category is 17%, 32% and 51% respectively. It seems reasonable to reduce the estimated slip rate by the probability that the fault is currently active in the time frame of the next 100,000 years, which is ten times the return period of 10,000 years used for the Safety Evaluation Earthquake (SEE) for Extreme Consequence Dams in the draft 2017 ANCOLD Guidelines), using decreasing probability values for successively lower rankings.

Rate of Activity

The rate of exceedance of a specified ground motion level from a given fault is directly proportional to the slip rate of the fault for a specified magnitude distribution, so this parameter directly affects the hazard level. As outlined below, Australian faults are typically estimated to accumulate slip deficits in the range of 0.1 to 1 metres over 10,000 years, sufficient to generate earthquakes in the approximate magnitude range of 5 to 7 if all of the accumulated slip is released in a single earthquake. If they are sufficiently close to the site, faults with slip rates at the upper end of this range can therefore have a significant impact on the probabilistic hazard for a return period of 10,000 years, as shown on the left of Figure 1.

In Australia, the rate of earthquake activity on most active faults and tectonic features is estimated from the amount of vertical displacement of landscape features they are inferred to have caused due to dip-slip (reverse) faulting. The inferred displacements are typically in the range of several tens of metres to several hundred metres, and the ages over which they are assumed to have occurred are typically 5 to 10 million years, yielding fault slip rates in the approximate range of 0.01 to 0.1 mm/yr, and recurrence intervals in the tens of thousands to hundreds of thousands of years or more. Consequently, the slip rates are typically averaged over a much longer time interval than the 100,000 year interval which we consider to be an approximate upper limit of engineering significance. Hence, as pointed out by Clark (2009), it is unclear whether long term slip rates (and the recurrence estimates based upon them) are appropriate for probabilistic seismic hazard assessment.

Further, there is evidence for pronounced episodic surface rupture behaviour on many Australian faults (e.g. Crone et al. 1997; Clark et al. 2011; 2012). Typically, clusters of several surface faulting events occur with intervals between events of several tens of thousands of years, separated by intervals of hundreds of thousands or millions of years without surface faulting. Conventional seismic hazard analysis assumes that earthquakes on faults occur randomly in time, at an average rate that is controlled by the long term average slip rate of the fault. However, it is unclear whether long term slip rates (and the recurrence estimates based upon them) are appropriate representations of the temporal and spatial clustering of surface faulting earthquakes for probabilistic seismic hazard assessment. Nevertheless, until procedures for addressing this kind of time-dependent hazard are further developed, these long-term time-independent slip rate estimates will typically be used in PSHA in Australia.

Magnitude Distribution

The distribution of earthquakes of different magnitudes (related to different average amounts of fault rupture area and fault slip) can have a large impact on the calculated hazard. If it is assumed that the slip deficit is released by a broad range of magnitudes, such as the Gutenberg-Richter (GR) distribution (top left of Figure 2), then there will be many earthquakes, most having smaller magnitudes but still causing relatively high probabilistic seismic hazard. However, if it is assumed that most of the slip deficit is released in large earthquakes (Characteristic earthquake recurrence model, shown on the bottom left and right side of Figure 2), then these large earthquakes are relatively infrequent and cause the probabilistic seismic hazard to be relatively low. Like the GR model, the Characteristic model also has smaller earthquakes but they are much less frequent than in the GR model. In the Maximum Magnitude model, there are no smaller earthquakes, only large earthquakes.

Previously, it was commonly assumed that the small earthquakes occurring around a fault could be attributed to that fault, and that the fault’s earthquake activity rate could be estimated from those earthquakes, for example using the GR magnitude distribution in which the logarithm of the number of events is inversely proportional to their magnitudes. The current trend is to assume that the small earthquakes occurring around a fault may not be occurring on it, and a GR model based on them may not provide a reliable estimate of the rate at which the fault might produce large earthquakes, as shown in the case of the Characteristic model on the right side of Figure 2. This has led to the use the Characteristic and Maximum Magnitude distributions, in which most or all of the slip deficit is released in large earthquakes, significantly reducing the probabilistic hazard at long return periods such as 10,000 years compared with the hazard from a GR distribution, although the Characteristic model is disputed (Kagan et al., 2012)

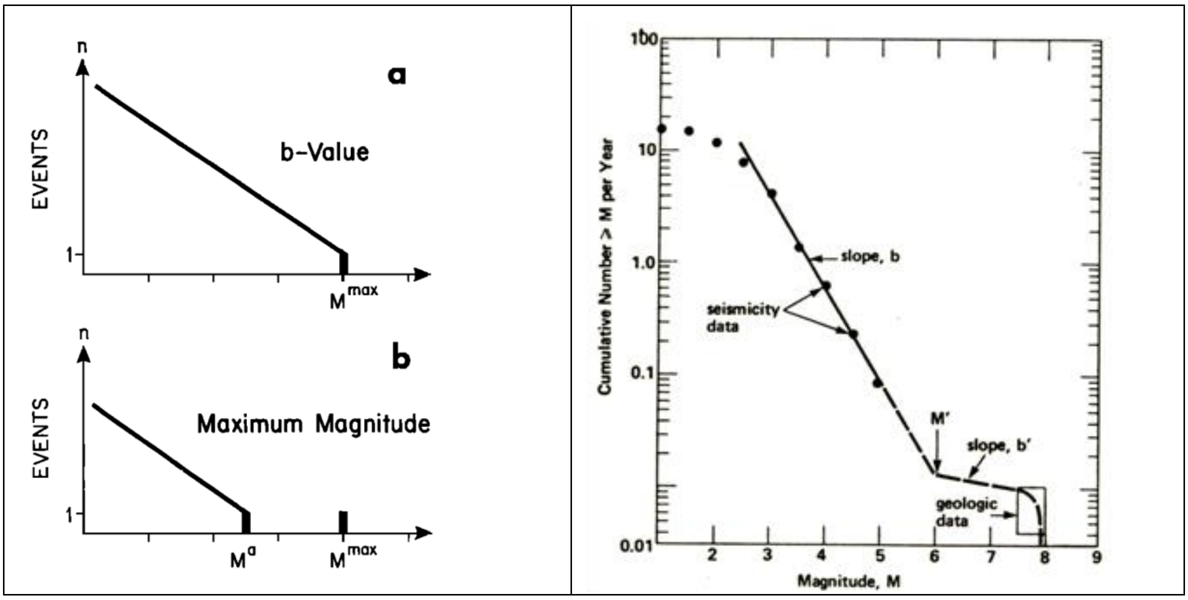

Figure 2. Left: Interval recurrence for the Gutenberg-Richter (top) and Characteristic earthquake recurrence models (bottom). Source: Wesnousky et al., 1983. Right: Cumulative recurrence for the Characteristic earthquake recurrence model. Source: Schwartz and Coppersmith, 1984.

Return Period

The contribution of fault sources relative to that of distributed seismic sources typically increases with increasing return period. This is especially the case if the maximum magnitude recurrence model is used, shown on the left side of Figure 1, because the slip rates of faults in Australia are quite low, resulting in long recurrence intervals of maximum magnitude earthquakes. Such faults begin to make contributions to the PSHA at long return periods.

Proximity

Ground motion levels decrease rapidly with increasing closest distance from a fault. The rate of decrease depends on the earthquake magnitude, site conditions and ground motion period; at 20 km ground motions are about one-third the level within a few km of the fault, and at 50 km they are about one-tenth of the level within a few km of the fault (Somerville et al., 2009; Gregor et al., 2014). Earthquakes in distributed source zones can occur arbitrarily close to the site, so that in a PSHA distant faults typically contribute less seismic hazard than distributed seismic sources, as shown on the right side of Figure 1, depending on the slip rate of the fault and the recurrence model assumed for the fault.

Deterministic Seismic Hazard Analysis

The deterministic approach only considers one – proximity - of the five considerations, described above, that affect the results of a probabilistic seismic hazard analysis. In the deterministic case, it is necessary to assign a probability of activity of the fault of either zero or one. The rate of activity is not considered; even very unlikely events are assumed to occur. The magnitude distribution is also not considered; only the maximum magnitude earthquake is considered. Also, the return period is not considered. Consequently, the result of the deterministic seismic hazard analysis depends only on the maximum magnitude and the geometrical parameters of the fault and its orientation with respect to the site. The most important of these geometrical parameters is the closest distance, but other geometrical parameters that describe the location of the site on the foot wall or hanging wall (Gregor et al., 2014; Somerville, 2016c), and the potential for forward rupture directivity (Somerville, 2016c; Somerville et al., 1997; Spudich et al., 2013) may also be important at close distances (within about 20 km).

The Safety Evaluation Earthquake (SEE) is defined by ICOLD (2016) as “the maximum level of ground motion for which the dam should be designed or analysed.” Since in Australia there are no “locations with relatively frequent earthquakes that occur on well-identified sources, for example near plate boundaries” which is the ICOLD (2016) criterion for using a deterministic approach to estimating the SEE, this implies that the SEE in Australia should be evaluated probabilistically. Nevertheless, ANCOLD (2017) has retained the use of the larger of the probabilistic and deterministic approaches to establishing the Maximum Credible Earthquake (MCE) to represent the SEE. However, the deterministic approach of using fault sources to estimate the MCE may result in much larger ground motions (with return period much longer than 10,000 years), as demonstrated by Somerville (2016a, b). As indicated by ANCOLD (2017), it is preferable to treat such low probability events using a risk-based approach. This may be particularly relevant to tailings dams whose nominal design life is unbounded.

CONCLUSIONS AND RECOMMENDATIONS

This paper provides guidance on the conditions under which the contributions of identified faults could be significant in a probabilistic seismic hazard analysis (PSHA) and a deterministic seismic hazard analysis (DSHA). We consider five primary conditions under which identified faults can contribute significantly to the hazard: proximity, probability of activity, rate of activity, magnitude distribution, and return period under consideration. The ground motions estimated using a probabilistic seismic hazard analysis are sensitive to all five of these conditions, whereas the ground motions estimated from a deterministic approach depend on only one – proximity.

Probability of Activity

There is considerable uncertainty in whether the neotectonic features that have been identified in Australia are currently active (i.e. relevant to the hazard expected over a time frame of 100,000 years). It seems reasonable to reduce the estimated slip rate by the probability that the fault is currently active in the time frame of the next 100,000 years (ten times the probabilistic MCE return period of 10,000 years), using decreasing probability values for successively lower rankings.

Rate of Activity

The rate of exceedance of a specified ground motion level from a given fault is directly proportional to the slip rate of the fault for a specified magnitude distribution, so this parameter directly affects the hazard level. However, the slip rates are averaged over a much longer time interval than the time frame of engineering interest. Moreover, surface faulting earthquakes in Australia exhibit temporal and spatial clustering, with clusters of several surface faulting events having intervals between events of several tens of thousands of years, separated by intervals of hundreds of thousands or millions of years without surface faulting. Nevertheless, until procedures for addressing this kind of time-dependent hazard are further developed, we expect that long-term slip rate estimates that ignore temporal clustering will typically be used in PSHA in Australia.

Magnitude Distribution

The distribution of earthquakes of different magnitudes (related to different average amounts of fault slip and fault rupture area) can have a large impact on the calculated hazard. If it is assumed that the slip deficit is released by a broad range of magnitudes, such as the Gutenberg-Richter (GR) distribution, then there will be many more earthquakes, mostly with smaller magnitudes, but some with magnitudes large enough to potentially cause damage (typically assumed to be magnitude 5), thereby increasing the probabilistic seismic hazard. However, it is now more common to use the Characteristic or Maximum Magnitude recurrence model, in which it is assumed that most or all of the slip deficit is released in large earthquakes, yielding relatively infrequent earthquakes and relatively lower probabilistic hazard.

Return Period

The contribution of fault sources relative to that of distributed seismic sources typically increases with increasing return period.

Proximity

Ground motion levels decrease rapidly with increasing closest distance from a fault, so identified faults rarely dominate the probabilistic hazard if they are 20 km or more from the site.

Deterministic Approach

In the deterministic approach, the only one of the above five considerations that affects the hazard level is the proximity of the fault to the site. Other geometrical parameters describing the location of the site on the foot wall or hanging wall (Gregor et al., 2014; Somerville, 2016c), and the potential for forward rupture directivity (Somerville, 2016c; Somerville et al., 1997; Spudich et al., 2013) may also be important at close distances (within about 20 km). ANCOLD (2017) has retained the use of the larger of the probabilistic and deterministic approaches to establishing the MCE to represent the SEE. However, using the deterministic approach to estimate the MCE using fault sources may result in estimated ground motions that are much larger than and have much longer return periods than the probabilistic MCE with a return period of 10,000 years. As indicated by ANCOLD (2017), it is preferable to treat such low probability events using a probabilistic risk-based approach rather than a deterministic approach.

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