Contribution of Identified Faults to the Seismic Hazard of Stable Continental Regions

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1. ABSTRACT

There is a large degree of uncertainty regarding many aspects of seismic hazard analysis in Stable Continental Regions (SCR's), which we define as regions of low to moderate seismic activity remote from plate boundaries. This is because earthquake occurrence is often poorly understood in SCR's and there are usually few strong ground motion recordings available to constrain ground motion estimates. Earthquake forecasts in SCR's are usually based on distributed source models, because there are few if any identified active faults on which to base earthquake forecast models. In some SCR's including Australia, identified active faults contribute significantly to the hazard at low probability levels.

Clark et al. (2011) 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. Using their results, it may be possible to identify in which phase these faults currently are and then apply this information to the evaluation of their seismic potential.

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, estimating the slip rate of identified active faults and neotectonic features involves considerable uncertainties. One of the main issues is the uncertainty in whether the neotectonic features are currently active (i.e. relevant to the hazard expected over a time frame of 100,000 years) and it seems reasonable to reduce the estimated slip rate by the probability that it is currently active in that time frame. Moreover, the slip rates are averaged over a much longer time interval than the time frame of engineering interest, making it difficult to know the current slip rate. An additional complexity comes from the observation that surface faulting earthquakes, especially in Australia, exhibit temporal and spatial clustering due to the episodic nature of earthquake activity on faults as identified by Clark et al. (2011). Procedures for addressing these time-dependent hazard issues in SCR's need to be developed.

The distribution of earthquakes of different magnitudes 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, some with magnitudes large enough to potentially cause damage, 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.

2. INTRODUCTION

Identified active faults which could significantly contribute to the ground motion for a site should be identified, and be accounted for in the seismic hazard assessment. The purpose of this work is to provide guidance on the conditions under which these contributions could be significant in a probabilistic seismic hazard analysis (PSHA).

At most sites that are distant (several tens of km) from faults, the probabilistic seismic hazard is dominated by randomly occurring earthquakes that are modeled by distributed earthquake sources, 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 rupture areas are quite small 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 no longer so. Consequently, the correlation between small historical earthquakes and mapped faults is generally not very strong.

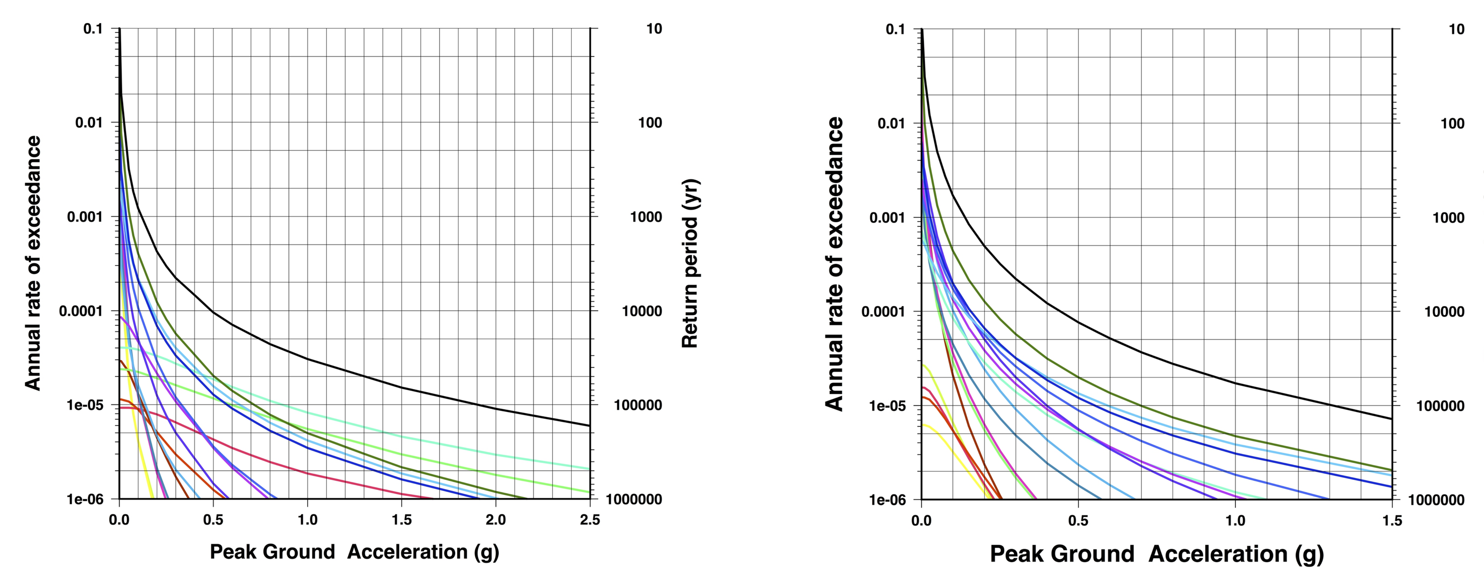
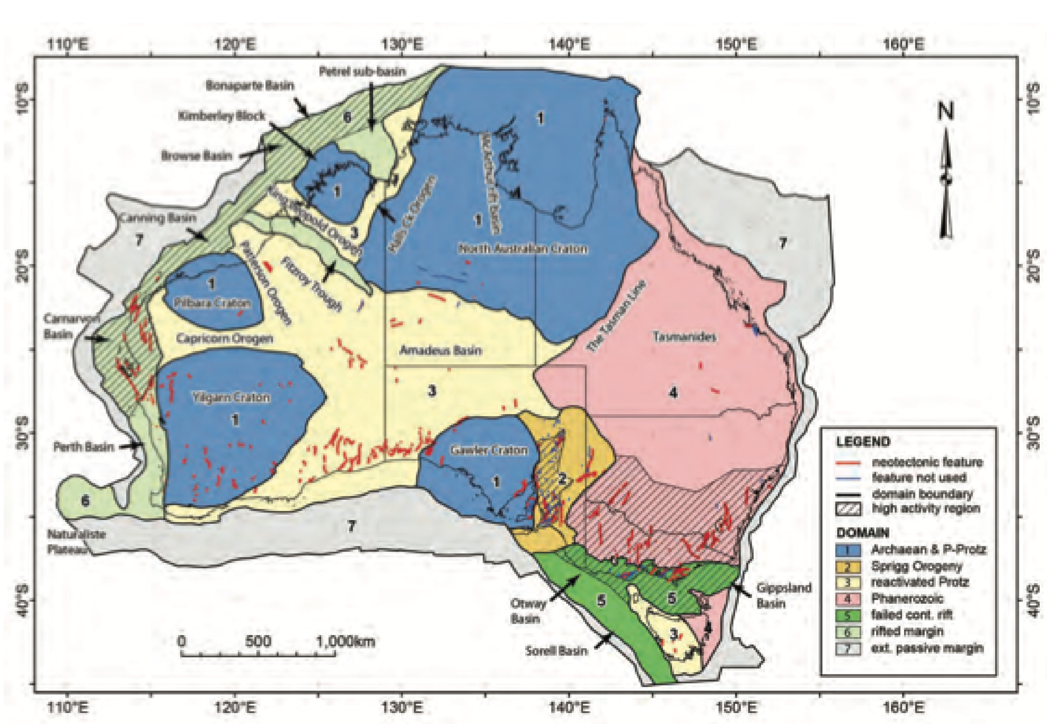


Figure 1. Source deaggregation of PGA hazard at a near-fault site (left) and at a site distant from faults (right) showing contributions of distributed earthquake sources (concave hazard curves); fault sources (convex hazard curves), and total hazard (black concave hazard curve that lies above the others).

3. DEFINITION AND IDENTIFICATION

A typical example of how identified active fault sources are defined in a SCR is Australia. An Australia-wide assessment of identified active faulting based on neotectonics data was made by Clark et al. (2011, 2012). They analyzed a catalogue of 333 neotectonic features, 47 of which are associated with named fault scarps. The data were derived from analysis of 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 identified active fault. Verifying these features as identified 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. A map with the neotectonic features identified in those studies is shown in Figure 2.

Figure 2. Map of neotectonic domains. Features marked in blue were not used in the analysis. Hatched polygons represent areas within domains of relatively higher activity. Source Clark et al., (2012).

4. PSHA

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.

Probability of Activity

Clark et al. (2012) assessed their confidence that each feature in their database 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 it is currently active in the time frame of the next 100,000 years, using probability values of 1.0, 0.67, and 0.33 respectively for these three rankings.

Rate of Activity

In Australia, the rate of earthquake activity on most identified 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 (ten times the probabilistic MCE return period of 10,000 years). 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 behavior 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.

4. PSHA cont.

Magnitude Distribution

If it is assumed that all or most of the slip deficit is released in large earthquakes, then these earthquakes are relatively infrequent and cause the probabilistic seismic hazard to be relatively low. However, 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. 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. However, the practice currently is to assume that the small earthquakes occurring around a fault may not be occurring on it and may not provide a reliable estimate of the rate at which it might produce large earthquakes because the fault does not have a GR magnitude distribution. This has led to the use of alternative magnitude distributions, such as 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 GR distribution.

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

For a specific ground motion level (e.g. median; 50th percentile) amplitudes 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 of 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.

5. CONCLUSIONS AND RECOMMENDATIONS

This work aims to provide guidance on the conditions under which the contributions of identified faults could be significant in a probabilistic seismic hazard analysis (PSHA). We consider five primary conditions under which identified faults can contribute significantly to the hazard:

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 it is currently active in that time frame, using probability values of 1.0, 0.67, and 0.33 respectively for the Definite, Probable and Possible rankings of Clark et al. (2012).

Rate of Activity

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. 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. 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 at longer return periods such as 10,000 yrs, used in the design of critical infrastructures.

Return Period

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

Proximity

Ground motion amplitudes for a specific ground motion level, 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.