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Earthquake Hazard Analysis of Active Neotectonic Faults: Simple and Complex Fault Styles

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ABSTRACT: A comparison of the treatment of active neotectonic faults in Seismic Hazard Assessments conducted for engineered structures within Australia is presented.

In Australia, the contribution of modelled faults to total hazard at longer return periods is far more important than modelled area sources. Identifying the location, dip and slip rate of neotectonic faults is particularly important. Given long recurrence intervals of moderate to large earthquakes within continental Australia, it is difficult to determine the likely phase of the earthquake cycle we are currently observing.

Commonly used models for the magnitude distribution of earthquakes on modelled faults include the exponential (Gutenberg-Richter), characteristic earthquake and truncated models. Determining which model is appropriate for Australian faults will have a major influence on the resultant hazard.

The horizontal compressive stress means that most Australian earthquakes have reverse fault mechanisms. The hanging wall effect on ground motions makes it important to determine the dip of any modelled faults.

Hanging wall effects are demonstrated in a simple treatment of the Lapstone Fault, in New South Wales in terms of peak ground acceleration. However, the more complex nature of the Strzelecki Ranges in eastern Victoria makes it problematic to determine the causative faults and this will impact on the estimated hazard.

1 INTRODUCTION

Seismic Hazard Assessments (SHA) provide an estimate of the level of ground shaking expected at a given site. SHAs typically employ the Cornell (1968) methodology which takes into account the ground motion from a minimum considered earthquake magnitude up to the maximum credible earthquake that can occur in each source zone or along each fault. This is calculated using a rate of occurrence of these earthquakes, their distance from the site and the attenuation ground motion between the earthquake and the site.

Source zones are typically assumed to be either areal (distributed seismicity) or linear (along a fault). Faults are generally included if they are considered to be currently active in the current stress regime with evidence of movement either measured on the fault or striking evidence of seismic activity surrounding the fault. The critical issue is whether it is justifiable to model future seismicity as occurring on these fault sources.

A comparison of two types of faulting (firstly that of a simple single fault and secondly a complex set of multiple faults) is explored in this paper with consideration to the overall seismic hazard.

2 AUSTRALIAN SEISMICITY

Continental Australia is located within the Australian Plate and experiences compressive stress with generally high stress drop earthquakes (Blewett et al, 2012; Clark et al, 2011; see Figure 1), similar to California in western USA. Earthquakes around plate boundaries account for 95% of total seismic energy released around the world, whilst the remaining energy occurs in intraplate regimes which do not follow particular patterns, other than occurring at shallow depths, typically 2 to 20 kilometres.

Historical seismicity of Australia is relatively low compared to neighbouring subduction and collision boundaries but that does not mean there are no large earthquakes – simply a lower rate of large earthquakes. The historical record shows that Australia experiences about 80 earthquakes above magnitude 3.0 every year, moderate earthquakes of magnitude 5.5 every two years and magnitude 6.0 about every 5 years (Geoscience Australia, 2015).

Several regions of the Australian continent have a higher level of activity: coastal Victoria-New South Wales, Flinders-Mt Lofty Ranges in South Australia and east of Perth Basin in Western Australia.

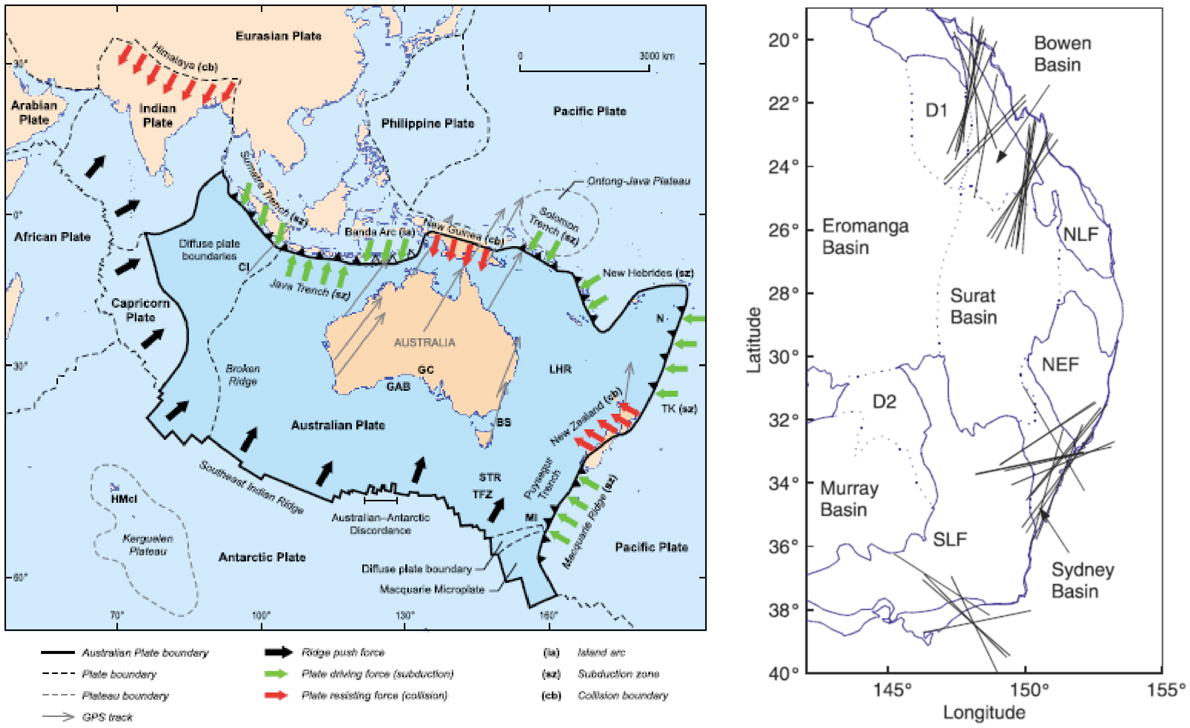

Figure 1 – (left) Location and extent of Australian Plate showing boundary stresses (from Blewett et al, 2012); and (right image) Tectonic stress in eastern Australia from in situ measurements with solid lines show the maximum horizontal compressive stress orientations (from Zhao & Muller, 2001).

3 ACTIVE FAULTS

An active tectonic fault in an active tectonic regime is often defined as being one that has undergone movement in the geologically recent past and is considered likely to be offset again in the near geologic future (Machette, 2000). However, in Australia, where movement on faults appears to be episodic in nature, this definition may not be strictly applicable.

Instead, the term neotectonic fault is used which is defined as faults that host measurable displacement in the current crustal stress regime (within the last 5-10 Ma according to Sandiford et al, 2004) and are therefore suitably oriented to host (or *capable* of hosting) future displacements along them (see Figure 2; Machette, 2000).

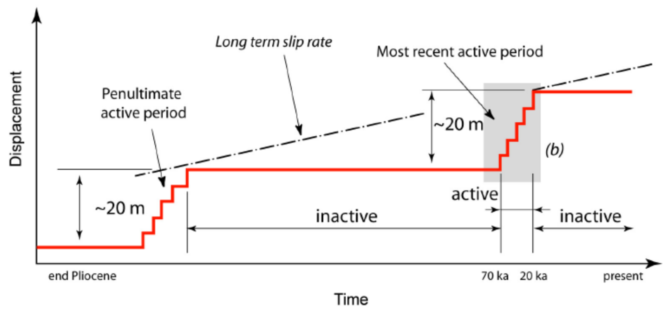

Figure 2 – Schematic diagram showing periods of inactivity with active periods during the stress release cycle for Australian faults (from Clark, 2009).

The idea that fault activity is episodic in nature (Figure 2) seems to be well accepted. The long term slip rate of a fault bears little resemblance to the essentially zero activity over a considerable time span, nor the short-term high activity during the active period. The problem for hazard analysis is that there is no way of knowing where in the cycle we are.

4 MODELLED FAULTS IN SEISMIC HAZARD ASSESSMENTS

4.1 Models for magnitude distributions on faults

There is considerable debate regarding the distribution of earthquake magnitudes on faults. Possible models are: characteristic, exponential, truncated or a hybrid of these.

Figure 3 shows the magnitude-frequency distribution for these models. The red curve is the typical exponential style truncated for a particular maximum magnitude. The black curve is the characteristic earthquake that assumes all earthquakes on this fault will produce similar sized magnitude earthquakes. The blue curve is a hybrid model incorporating an exponential style using the instrumental catalogue and restricting the maximum credible magnitude based on historical catalogue events.

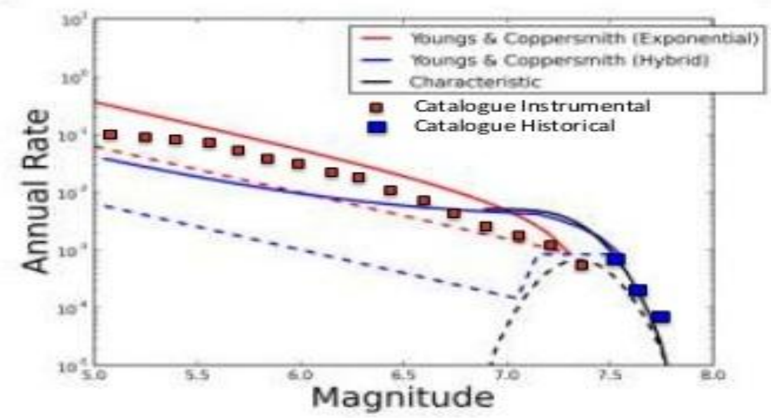

Figure 3 - Magnitude recurrence relations for fault sources; exponential (red) characteristic (black) and hybrid (blue) (from Weatherill et al, 2014).

In the characteristic model, faults are expected to rupture in large earthquakes over 50% to 100% of the fault length, with very few small earthquakes occurring on the fault. The characteristic model is used mostly to combine recorded seismicity in a region with geologically derived slip-rates on individual faults.

According to Pilia et al (2013) and Love (2013) of comparisons of fault activity within the Flinders and Mt Lofty Ranges, there is no clear correlation of seismicity with known active faults in this region. Other recent studies in the East Gippsland region have drawn similar conclusions to the lack of correlation between observed seismicity and known active faults (Brown & Gibson, 2004; Gibson & Dimas, 2012). Leonard (2008) also draws these same conclusions on the Darling Fault east of Perth and the Lapstone Monocline west of Sydney. All these observations (or lack of correlations) are therefore representative of the characteristic model rather than the Gutenberg-Richter model for earthquake recurrence on faults.

4.2 FAULTS IN THE SRC SEISMICITY MODEL

There are various approaches for the input parameters in PSHA studies with some being better suited to specific conditions. For example in a low seismic region, a smoothed seismicity model may overcome issues of lack of data over a vast area, whilst in an active region with prominent and well known faulting an approach of using only fault sources, such as in a Probabilistic Fault Displacement Hazard Analysis (PFDHA), may be appropriate.

The seismicity model developed by the Seismology Research Centre (SRC) is based on the work commenced by Brown & Gibson (2000, 2004). This model divides Australia into area source zones based on seismicity as well as geology (particularly neotectonics relating to Quaternary and Tertiary deformation) and geophysics (particularly gravity and magnetic data).

A rate of activity is assigned to each zone. Within each zone, earthquakes are assumed to be distributed uniformly in time and space (with depths from 2 to 20 kilometres), with an exponential Gutenberg-Richter magnitude recurrence relation with a defined maximum magnitude.

The current version of the model (AUS6) treats faults and area sources separately, by assigning any activity obviously associated with a fault to that fault with all other activity being assigned to the area source. Each fault has a minimum and maximum magnitude assigned according to fault length. We assume that the b-value of a fault is the same as that for the zone which contains it.

The AUS6 treatment of faults assumes a typical reverse angle of 35^{o}, based on the active horizontal compression within the Australian continent.

Information is sourced from Geoscience Australia's "Neotectonic Features Database" as first described in (Clark, 2015) for active neotectonic faults with details on location, dip direction, slip rates (where available or measured), surface expressions, total length and dip angles. Where there is limited information regarding the measured or observed slip rate of a fault we make reasonable estimates based on other known faults and information on associated seismicity in a given area.

The maximum magnitude assigned to area source zone depends upon our knowledge of faults in that area. Where there are no identified faults within a zone or suspect there is active faulting that has not been identified we assign a Mmax of 7.3. In areas where some active faults have been identified, but based on seismicity we believe there could be more unidentified active faults we assign a Mmax of 6.8. In areas where we assume we know all of the neotectonic active faults we assign a Mmax of 6.4.

4.3 **Fault behaviour within Australia**

Plots of activity rates (magnitude versus frequency) for area source zones of the AUS6 model often exhibit a linear slope (constant b-value) for small to moderate magnitude earthquakes but with a dislocation in the slope at larger magnitudes. If there are larger magnitude earthquakes in the zone, these generally plot with the same slope (b-value) but are displaced from the extrapolation of the linear segment from lower magnitudes.

This observation fits the characteristic earthquake model for faulting as described earlier.

An example of this is shown in Figure 4 which is a plot for the Newcastle source zone. It shows events of magnitude 2.0 to 4.0 modelled using an exponential style, with an absence of events between magnitudes 4.0 to 5.0, followed by an almost identical exponential style for events with magnitudes between 5.0 to 5.7. In the case of the Newcastle area source zone, there are no faults mapped, so the larger events remain within the area zone and are not treated separately.

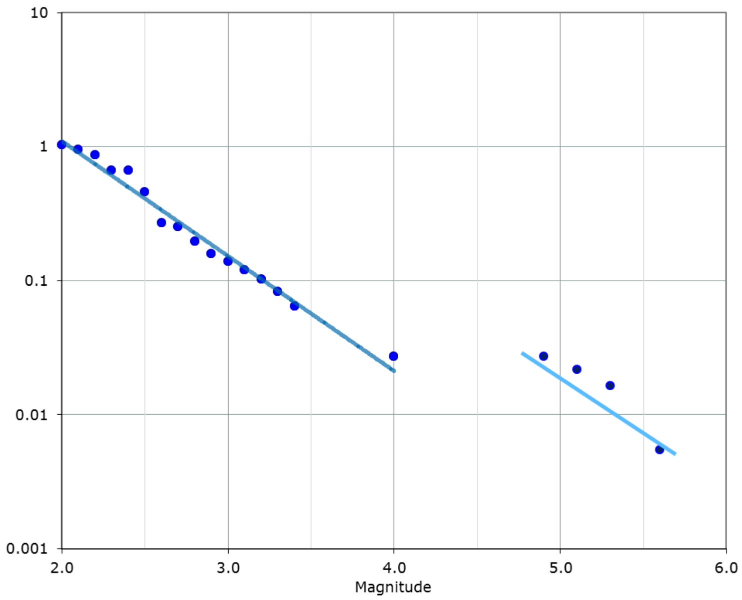

Figure 4 - Example of earthquake magnitude recurrence plot for Newcastle source zone