Australian Earthquake Engineering Society 2011 Conference, 18-20 November, Barossa Valley, South Australia

# The 2012 Australian Seismic Hazard Map - Introduction and Approach

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## Abstract

Geoscience Australia is currently drafting a new Australian Earthquake Hazard Map (or more correctly a series of maps) using modern methods and models. Among other applications, the map is a key component of Australia's earthquake loading code AS1170.4. In this paper we provide a brief history of national earthquake hazard models in Australia, with a focus on the map used in AS1170.4, and provide an overview of the proposed changes for the new maps. The revision takes advantage of significant improvements in both the data sets and models used for earthquake hazard assessment in Australia since the original map was produced. These include:

- Earthquake observations up to and including 2010
- Improved methods of declustering earthquake catalogues and calculating earthquake recurrence
- Ground-motion prediction equations (i.e. attenuation equations) based on response spectral acceleration rather than peak ground velocity, peak ground acceleration or intensity-based relations.
- Revised earthquake source zones
- Improved maximum magnitude earthquake estimates based on palaeoseismology
- The use of open source software for undertaking probabilistic seismic hazard assessment which promotes testability and repeatability

The following papers in this series will address in more detail the changes to the earthquake catalogue, earthquake recurrence and ground motion prediction equations proposed for use in the draft map. The draft hazard maps themselves are presented in the final paper.

**Keywords:** probabilistic seismic hazard assessment, national earthquake hazard map, AS1170.4, earthquake loading code

# Introduction

The Earthquake Hazard Map of Australia is a critical input to Australian Standard AS1170.4 "Structural design actions Part 4: Earthquake actions in Australia" which outlines actions for seismic design (Standards Australia, 2007a). The Standard, as prepared by Standards Australia Committee BD/6/11, "…*sets out procedures for determining earthquake actions and detailing requirements for structures and components to be used in the design of structures. It also includes requirements for domestic structures*". The earthquake actions requiring consideration are based on the level of ground shaking for a given location, as represented on the current earthquake hazard map. The ground shaking is expressed as a hazard factor which is equal to the effective peak ground acceleration (PGA) with an exceedance probability of 1 in 475 (rounded to 500) years.

In July 2009, Geoscience Australia (GA) initiated an update of the Earthquake Hazard Map of Australia using modern methods and data. The series of papers presented herein summarise some of the work completed since 2009 and present draft earthquake hazard maps which can form the basis of a new map for the next revision of the Australian earthquake loading code AS1170.4. The intention is to seek feedback on the draft map and publish the final revised set of earthquake hazard maps as a GA Record by June 2012. The maps and supporting publications will become available via the GA website (www.ga.gov.au). In addition, a paper is planned for publication peer-reviewed literature (Bulletin of the Seismological Society of America or similar) to ensure a wider scrutiny and acceptance of the map, its methodology and underlying assumptions.

# History of the map

The first Australian design code for earthquake (AS2121-1979) was published in 1979 (Standards Australia 1979), and was legally adopted only in Western Australia and South Australia (Chandler *et al.* 1992). This Standard was derived from the work of Denham (1979), McCue (1973, 1975, 1979) and McEwin *et al.* (1976). The underpinning data included both historical and (primarily) instrumental seismicity (Brown & Gibson 2004), drawing mainly upon the catalogue of Denham *et al.* (1975), with a catalogue completeness of M>4 from 1969 to 1976. Attenuation relations from McEwin *et al.* (1976) were based on peak ground acceleration, peak ground velocity and intensity, while those of McCue (1973, 1975, 1979) used peak ground velocity and peak ground acceleration.

The current form of the Australian earthquake loading code (AS1170.4) was first published in 1993 (Standards Australia 1993), and revised in 2007 (Standards Australia 2007a). This code has generally adopted the guidelines set out by the Applied Technology Council (ATC 1984), an organisation which had significant input into the earthquake regulations in the USA Uniform Building Code (ICC 1988) (Chandler *et al.* 1992). The earthquake hazard map used in the current earthquake loading code (AS1170.4-2007) is based on the probabilistic peak ground velocity (PGV) hazard map of Gaull *et al.* (1990) as extensively revised by McCue *et al.* (1993).

## The Gaull *et al.* (1990) Probabilistic Seismic Hazard Maps

As identified in the Commentary document for AS1170.4-2007 (Standards Australia 2007b) and elsewhere, the development of any probabilistic seismic hazard map based on source zones requires the following steps:

a) Areas where past earthquakes occurred or would be expected to occur are identified and brought together on a source zone map. This can be done by contouring a plot of earthquake epicentre density and can also incorporate some *a priori* geological knowledge.

b) For each source zone, the recurrence rates of earthquakes of all magnitudes above some critical lower magnitude and up to a maximum magnitude are estimated. The earthquake recurrence values are usually found by fitting the observed earthquake distribution to that predicted by the Gutenburg-Richter (G-R) equation (Reiter 1990). The G-R equation is described by two parameters; the "*a*" value, which is the rate of earthquakes above magnitude 0 in the zone, and the "*b*" value which is the slope of this relationship. The *b*-value is a function of the ratio of large-to-small earthquakes in a given area. Curve fitting is usually done using either the maximum likelihood method or least squares regression.

c) Attenuation relationships, now commonly referred to as Ground Motion Prediction Equations (GMPE's), are used to predict the amplitude of the ground motion [represented by intensity, peak ground acceleration, spectral acceleration, etc.] as a function of magnitude and distance (amongst other parameters) from the earthquake.

d) A probabilistic analysis (e.g. Cornell 1968; Basham *et al.* 1985; Robinson *et al.* 2006), using the above information as input, is carried out to generate values which are used to produce contours of locations with equal median probabilities of being shaken at specific amplitudes of ground motion. The calculated amplitudes apply to average ground conditions (as specified in the attenuation relation applied).

The Gaull *et al.* (1990) map was calculated using the standard Cornell-McGuire probabilistic method. A set of uniform seismicity source zones (Figure 1), based heavily on McCue (1973, 1975) and Rynn (1987), was defined based primarily on the observed pattern of seismicity, with selective reference to geological and tectonic information. The Gutenberg-Richter *a* and *b* values were found in each zone using the maximum likelihood method while the maximum earthquake magnitude ($M_{max}$) in each zone was found by adding 0.5 to the largest earthquake observed in the zone or from previously published papers for that area. Note that the former method can produce very low $M_{max}$ values. For example, the $M_{\mathrm{max}}$ value for the Melbourne zone (not shown in Figure 1 but presumably in the vicinity of Zone 20) was only $M_L$ 3.6, and for Zone 25 in northern NSW $M_{\mathrm{max}}$ is only 4.5. In contrast the $M_{max}$ value for Zone 4 (offshore WA) was based on Gaull & Michael-Leiba (1987) and is very high at $M_L$ 8.0.

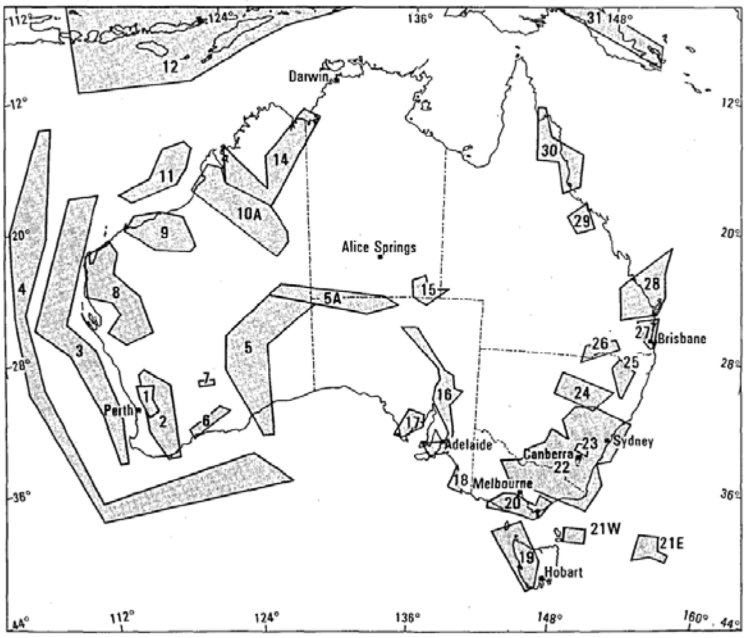


**Figure 1.** *Earthquake source zones defined by Gaull et al. (1990).*

The strong ground motion estimates used by Gaull *et al.* (1990) were defined by developing an empirical relationship between isoseismal intensity and distance (Gaull *et al.* 1990, p. 177), and then converting the intensities into PGA or PGV using published formulae based on California or Papua New Guinea earthquakes respectively (Gaull *et al.* 1990). The resulting PGA and PGV hazard maps produced by Gaull *et al.* (1990) are shown in Figures 2a and b.

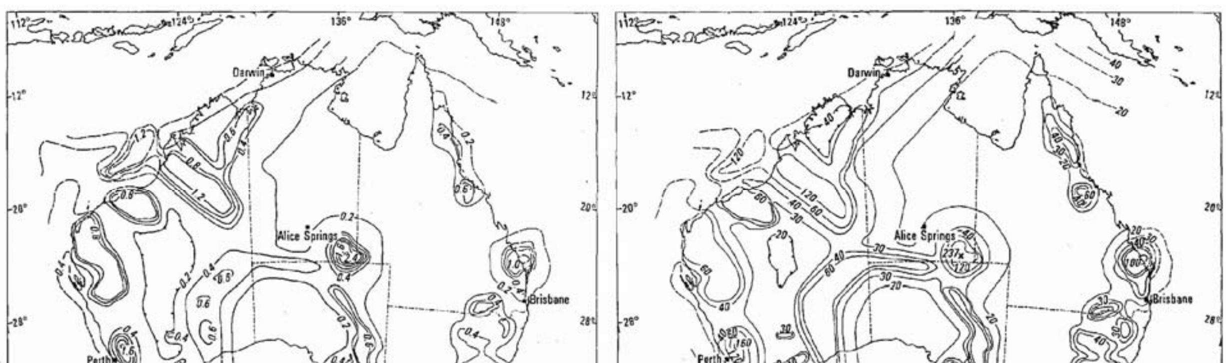


**Figure 2. (a)** *The peak ground velocity (PGV) (in mm/s) earthquake hazard map of Gaull et al. (1990), which underpins the current hazard map. This map shows hazard with a 10% of being exceeded in 50 years (i.e. 1 in 475 year exceedance probability).* **(b)** *The peak ground acceleration (PGA) (in m/s$^2$) earthquake hazard map of Gaull et al. (1990) for comparison.*

## The McCue *et al.* (1993) AS1170.4 Map

Of the two hazard maps produced by Gaull *et al.* (1990), the PGV output was chosen to underpin AS1170.4 as it was considered by the committee responsible for AS1170.4 to be a better predictor of damage or intensity than PGA (McCue 1993; Standards Australia 2007b). Values of PGV (in mm/s) were divided by a factor of 750 to determine the acceleration coefficient in the final hazard map as a fraction of the acceleration due to gravity (*g*) (McCue 1993; Standards Australia 2007b). The acceleration coefficient equates to the hazard factor (Z) in AS1170.4-2007 (Standards Australia 2007b). Note that this method generally produced higher PGA values than the calculated PGA hazard values in Gaull *et al.* (1990). For example, in the South West Seismic Zone east of Perth the maximum PGV hazard in the Gaull *et al.* (1990) map was 160 mm/s. Converted to PGA using the above method the hazard factor is 0.21 *g*. However, the maximum PGA calculated by Gaull *et al.* (1990) for this area was only 1.6 $m/s^2$ = 0.16 *g* (see Fig. 2b). This was presumably done to reflect the observation of McCue (1993) (cf. Standards Australia 2007b) that some accelerograms of engineering interest in Australia had PGA much higher than that predicted by the Gaull *et al.* (1990) equations.

The 750 divisor appears to be a rounded off version of the number recommended by the Applied Technology Council for converting "effective" peak velocity to "effective" peak ground motion, although a more precise determination of this conversion factor would give a value of 762 (ATC 1984, p. 301). The reason that these ground motions were called "effective" by the ATC is that they were the peak velocity or acceleration in a limited period range (ATC 1984). The effect of this on the resulting hazard map is unclear as "effective" PGA or PGV is "*not necessarily the same or even proportional to*" (ATC 1984) the actual values of PGA or PGV. This may explain some of the difference in estimated PGA from the two methods.

In any event, the converted PGV map was still deemed unsuitable for AS1170.4 so it underwent further revisions by the seismicity working group for the code. McCue (1993) reports that: "*rather than redo a hazard analysis...members of the seismicity working group, BD/6/4/1, subjectively smoothed, and where necessary extended the contours of Gaull and others [Gaull et al. 1990] in the light of earthquake activity in the period 1984-1990 and recently revised historical earthquakes not considered by them, and the broad correlation with geological, topographic and tectonic features. In recognition of the fact that no part of Australia is free from the possible occurrence of earthquakes…the contours were broadened to include the whole continent and appropriate reductions were made to the 'bullseyes' around past areas of high seismicity such as that in the Simpson Desert*". This is similar to the process applied in developing the hazard map for 1979 earthquake loading code, AS2121-1979 (McCue 1993).

These modifications included:

- the addition of a bullseye over the 1988 Tennant Creek earthquake sequence
- addition of contours around Newcastle following the 1989 earthquake
- significant changes to the distribution of hazard in and around Tasmania
- an area of elevated hazard at the end of zone 10A (WA)
- removal of the hazard 'hotspots' from zones 7 and 8 (WA)
- a substantial reduction in the hazard from the Simpson Desert zone 15 (NT/SA); using the above formula the peak should be 0.32 g instead of 0.12 g in the AS1170.4 map.

The AS1170.4 maps are shown in Figures 3a and b.

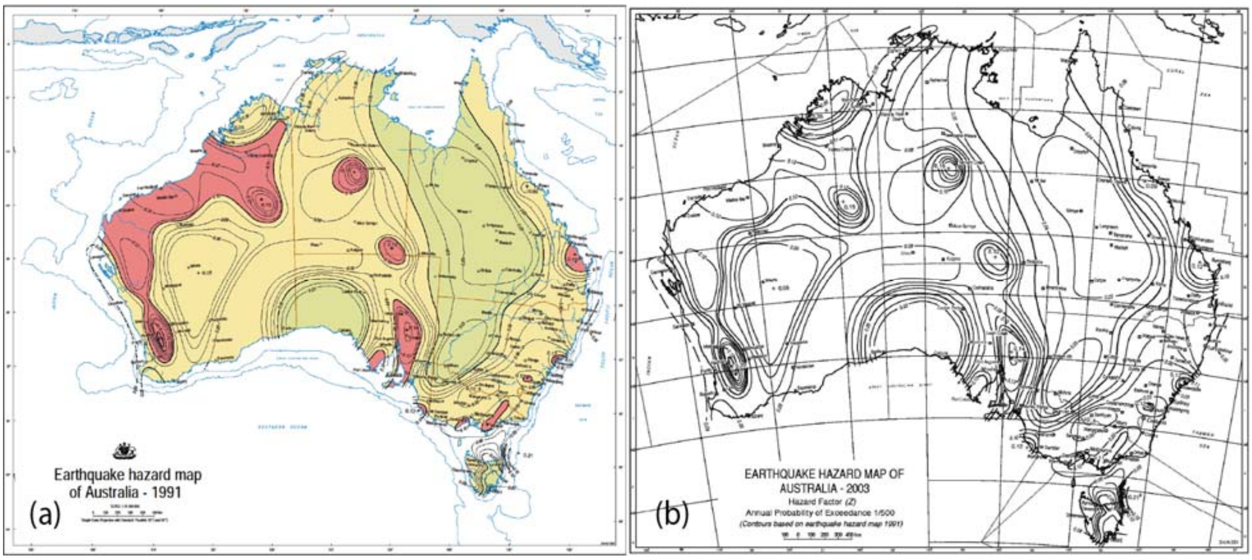


**Figure 3. (a)** *1991 earthquake hazard map of McCue et al. (1993); cf. McCue (1993);* **(b)** *the current earthquake hazard map for Australia as applied in AS 1170.4-2007 (Standards Australia 2007a). Both maps show the peak ground acceleration (PGA) with a 10% chance of being exceeded in 50 years; equivalent to PGA with an annual probability of exceedance of approximately 1/500 (BSSC 2004, 2009).*

The requirement to smooth and interpolate the acceleration coefficients, was apparently imposed upon the seismicity working group BD/6/4/1 by Standards Australia committee BD/6/11 (K. McCue, pers. comm., 2011) in order to improve the utility of the map for engineers. McCue (1993) argues that this smoothing was reasonable, stating that while seismic source zone boundaries are sharp, they are spatially imprecise. If applied in a building code, this would mean that buildings only a short distance apart may have to be designed to withstand lateral loads which differed by a factor of two. The details and justification for particular changes were not substantively or publicly documented.

## Benefits of a new map

The earthquake events included in the Gaull *et al.* (1990) assessment were limited by a cut-off date of between about 1983 and 1986, meaning that the map is now over 25 years old. Since the publication of the Gaull *et al.* (1990) map, and the McCue *et al.* (1993) revision, the catalogue of Australian earthquakes has increased in size from approximately 9,000 to over 35,000 earthquakes (*ca*. August 2010). For the draft map, we utilise a declustered version of the catalogue, which still has about 21,000 records, many more than were available in the mid-1980s. As a result, the catalogue now provides a more robust dataset for characterising contemporary seismicity and improved information on the likely recurrence of Australian earthquakes. Since there are now many more earthquakes in a typical source zone, estimates of the Gutenburg-Richter *a* and *b* values should be more representative of the long-term estimates of these values.

In addition to almost two decades of additional earthquake hypocentre data, researchers now have a better understanding of the attenuation of earthquake ground-shaking throughout the Australian crust (e.g. Allen *et al.*, this volume). Our understanding of the structure and geological evolution of the continent has also improved, allowing new insights into the potential association between earthquake occurrence and geological/tectonic setting. This knowledge, coupled with significant advances in palaeoseismology, for the first time, allow for quantification of the maximum earthquake magnitude ($M_{max}$) likely to occur in different parts of Australia. Accordingly, the update of these hazard inputs has the potential to significantly improve the earthquake hazard map underpinning AS1170.4. The source zones themselves in Gaull *et al.* (1990) are also now more than 25 years old, and in many instances are difficult to substantiate (e.g. Gaull *et al.*'s (1990) Zone 4 (WA) which is defined by the 5000 m isobath). In short, there have been major improvements in both the quantity and quality of data available to undertake earthquake hazard assessments in Australia than was available to Gaull *et al.* (1990).

However, it is important to note that the actual hazard map in AS1170.4 is only loosely based on Gaull *et al.* (1990). As a result of the "subjective smoothing" applied in the revision of the Gaull *et al.* (1990) PGV map, the McCue *et al.* (1993) hazard map is very difficult, even impossible, to reproduce in a probabilistic seismic hazard assessment. The validity of the assumptions used to estimate the hazard at any given point is impossible to test. For example, in the current hazard map the amplitude and spatial extent of the Tennant Creek 'hot spot' (see Fig. 3b) cannot be associated with any publicly available identified source zone, earthquake recurrence model or set of ground motion equations. Therefore it is difficult to devise an objective test to determine whether or not the hazard values require updating.

## Key differences between GA's draft map and AS1170.4-2007

The key differences between the draft maps presented in the final paper of this series and the one currently applied in AS1170.4-2007 (i.e. Gaull *et al.* (1990) revised by McCue *et al.* (1993)) can be summarised as follows:

- the earthquake catalogue for the current map is documented as being based only on events up until the mid-1980s, while McCue (pers. comm. 2011) suggests that the 2007 version incorporates seismicity up to and including 2006. The catalogue used here for the draft maps include events up to August 2010.
- the earthquake catalogue used here has been declustered using a combination of methods based on the latest thinking regarding how earthquakes cluster in intraplate regions. While the method almost certainly has not removed every single dependent event, mine blast or swarm, the declustered catalogue used here represents a cleaner and more robust data set than the catalogues available in the mid-1980s. The Gaull *et al.* (1990) map does not appear to have used any declustering method.
- the earthquake source zones have been completely revised. Relative to those published by Gaull *et al.* (1990), several zones have been removed and those remaining have been modified to more closely align with the new declustered earthquake catalogue. The zones have also been investigated with respect to their geological and tectonic setting. Here we use multiple sets of source models instead of the one zone model used in Gaull *et al.* (1990). The zones used here have been designed to balance the stability and smoothing requirements of a hazard map for the building code while still allowing it to be easily updated in future (see Leonard *et al.* this volume)
- in each zone we estimate the earthquake probability by fitting the declustered earthquake data to the Gutenburg-Richter relations using maximum likelihood and least squares methods (see Leonard *et al.* this volume).

- the choice of maximum magnitude of earthquakes within each zone is based on the neotectonic domains of Clark *et al.* (2011) and the value uses the results of Leonard & Clark (2011), who derived $M_{max}$ by statistical analysis of a catalogue of palaeo-fault scarps. This makes the map one of the first in the world to use any kind of semi-quantitative measure of $M_{max}$ for the source zones instead of simply adding a constant to the observed maximum magnitude from a historic catalogue (see Leonard *et al.* this volume).
- the ground motion prediction equations (GMPEs) used in Gaull *et al.* (1990) were based on both peak ground velocity and (primarily) very limited intensity data. In the new hazard model, we have compared 12 candidate response spectral acceleration-based GMPEs with existing earthquake data for Western Australia and southeastern Australia. In the draft hazard map, we have used semi-quantitative methods to identify and weight the 3 or 4 most appropriate models (see Allen *et al.* this volume).
- the final hazard map is calculated using EQRM – GA's open source, earthquake hazard and risk modelling software (Robinson *et al.* 2005). The open source nature of this tool enhances the testability and repeatability of the methods we apply. Furthermore, the use of EQRM readily permits the calculation of earthquake risk (e.g. likelihood of damage) in addition to the hazard (i.e. likelihood of ground-shaking), subject to the availability of the necessary exposure and vulnerability models.

We consider these enhancements to hazard modelling processes will provide a more robust input to the AS1170.4 earthquake loading code by:

1. bringing the earthquake hazard map up-to-date using the currently available datasets and models;
2. producing a repeatable and readily updateable hazard map through documentation of all model input parameters and processes.

The final draft maps produced through this process are presented in Burbidge *et al.* (this volume). Hazard maps are produced at PGA, 0.2 s and 1.0 s spectral periods, and at return periods ranging from 475 years to 10 000 years. While further work on the maps and their underlying assumptions is planned to occur over the next 6 months, GA considers that, as a result of the revisions outlined above, these maps represent a significant improvement over those produced by Gaull *et al.* (1990) and McCue *et al.* (1993).

## Acknowledgements

This paper is published with the permission of the CEO of Geoscience Australia. We gratefully acknowledge feedback on this document from two GA internal reviewers and Kevin McCue.

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