In defence of low hazard in stable continental regions: the likelihood of the 1991 seismic hazard map of Australia being correct

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Abstract

The hazard factors in every version of AS 1170.4 since 1993 have been based on a seismic hazard map published in 1991. In this paper I statistically test the validity of that 1991 map.

Two methods are used to calculate the hazard for 24+ sites across Australia. Firstly, for each site I calculate how many standard deviations (σ_1) separate the 1991 hazard value from the calculated PSHA value. Secondly, the magnitude frequency distribution (MFD; i.e. *a* and *b* values) is adjusted so that the calculated hazard matches the 1991 hazard value. The number of standard deviations (σ_2) in the MFD that separate the adjusted MFD differs from the best estimate MFD is subsequently calculated. The first method was applied using four seismic source models (AUS6, DIM-AUS, NSHM13 and these combined), while the second method used NSHM13 only. The average number of standard deviations was calculated from the best 20 of the 24 sites. These statistics are considered a test the validity of the 1991 map. The two methods using five models in total all give similar results. The 1991 map is found, on average, to overestimate the hazard by 3 standard deviations. This suggests that the 1991 map is best described as a 95th+ percentile map.

Practitioners using this map, whether for setting building standards or assessing insurance exposure, need to be conscious that the seismic design values are not scientifically valid relative to modern mean probabilistic seismic hazard assessments.

Keywords: seismic hazard, probabilistic seismic hazard assessment, epistemic uncertainty

Introduction

The aim of a probabilistic seismic hazard assessment (PSHA) is to estimate the mean ground-motion hazard for a given probability of exceedance at a given site (Cornell 1968, McGuire 1976, Field *et al.* 2003), and preferably an estimate of the uncertainty of that hazard (Musson 2012, Bommer 2012). For building codes and insurance risk assessment the mean hazard for a particular probability of exceedance (PoE) is the accepted international standard. For critical infrastructure it has been suggested that an explicit design quantile (e.g. 67 or 90%) rather than the mean be adopted (Bommer and Scherbaum 2008). How this differs from changing the PoE (e.g. 2% in 50 years instead of 10%) has not been well discussed.

The Geoscience Australia (GA) NSHM13 (Leonard et al. 2014) was not a strictly probabilistic hazard assessment, as it used two alternative magnitude frequency distributions (MFD) similar to the "robust" approach of Adams and Halchuk (2003).

The first calculated the MFD for each of the 25 zones in the regional seismic source zonation model. The second used three large background zones. For all source zones the higher of the two activity rates (number per year per km^2) was used. This provided scientifically defensible lower bound hazard values for the purpose of the building code.

The hazard map adopted for AS1170.4 (1993) was not a probabilistic map. Anecdotal evidence suggests that hazard values of the, mostly probabilistic, hazard maps published in the few years prior to 1991 (i.e. Stewart 1984, Gaull and Michael-Leiba 1987, Rynn 1987, Michael-Leiba and Gaull 1989, Gaull et al. 1990) were increased in response to the recent Tennant Creek and Newcastle earthquakes (e.g. McCue 1993). These increases appear to have typically been 150 to 200%. Therefore, even at its time of publication the 1991 map had significantly higher hazard values than suggested by the best science of the time.

This paper estimates the average number of standard deviations the 1991 map differs from a modern model using the latest earthquake catalogue and ground motion prediction equations (GMPEs).

Method

Two methods are used to estimate the goodness of fit of the 1991 hazard maps to contemporary data and models. The first method estimates the number of standard deviations (σ1) that separate the peak ground acceleration (PGA) values of the 1991 hazard map from contemporary hazard maps. The second estimates the number of standard deviations (σ2) separating the magnitude frequency distribution (MFD) required to replicate the hazard from the MFD that best fits the earthquake catalogue.

The National Cities Performance Framework (NCPF, 2017) covers 22 urban centres of Australia, constituting the 21 largest cities plus western Sydney. I used this framework to select 17 cities. An additional seven locations were selected to provide a diverse coverage of geography and high and low seismicity. As Carnarvon, Onslow, Karratha, Dampier and Port Hedland are all in wind loading Region D and buildings must be designed to withstand a Category 5 cyclone (300+ km/hr), they were not included, leaving Broome as the only town in northwest Western Australia included in this analysis (Figure 1). I consider these 24 sites representative of Australia from both an exposure perspective and of areas of relatively high and low seismic hazard.

In calculating the hazard uncertainties Leonard (2018) used 11 and 12 GMPEs for Cratonic and Non-Cratonic crust respectively. The two GMPEs that most closely represent the mean hazard curves were Chiou and Young (2008) and Pezeshk et al. (2011) respectively. These are the two GMPEs used in this study, along with Atkinson and Boore (2006) for active earthquake sources to the north of Australia.

For the first method a measure of the uncertainty of the calculated hazard (e.g. PGA at the 1/500-year annual exceedance probability) that arises from the combination of the uncertainty within a seismic source model and lack of knowledge of the best GMPE is required. This is epistemic uncertainty. Leonard (2018) demonstrated that epistemic uncertainty was dominated by uncertainty in the MFD and the selection of GMPEs, with other parameters describing the seismic source model being less important. Leonard (2018) found that in stable continental regions, for a reasonably well constrained MFD and appropriately selected GMPEs, the 1σ hazard uncertainty is a factor of 1.4. To account for possible uncertainties in the catalogue (e.g. ML to Mw conversations), in this study I have used a slightly higher factor of 1.6 as the value of $1\sigma_1$ in this study.

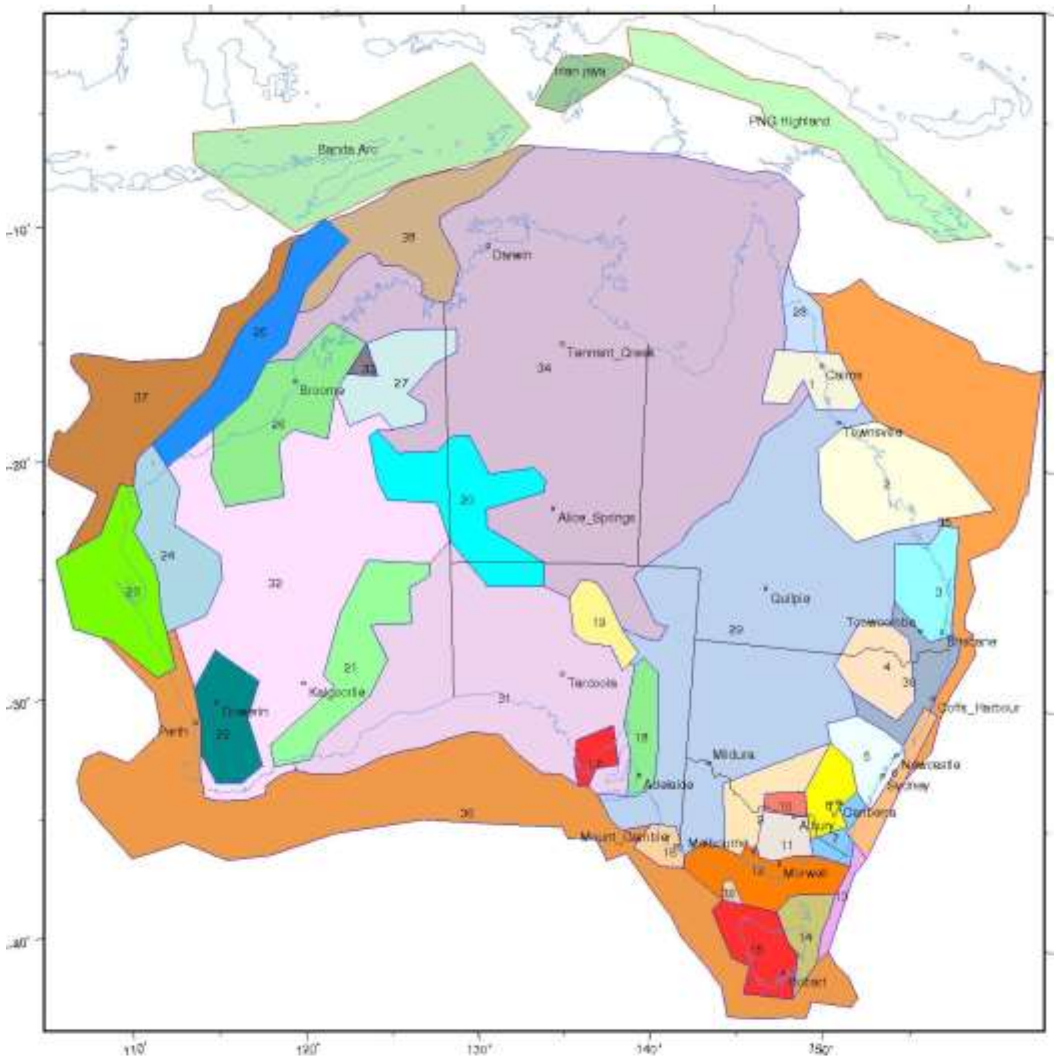

Figure 1 The 2012 NSHM source zone model, with the 24 sites examined in this study.

Method 1 was applied to three seismic source models: NSHM13 (Leonard et. al. 2013); AUS6 (Dimas et al. 2016, Brown and Gibson 2004); DIM-AUS (Dimas and Venkatesan 2016). Method 1 was also applied to these three models evenly weighted (NAD). The MFD for each zone is identical to that used for the NSHA18 (Allen *et al.*, 2018a), which used a regionally calculated *b*-value with the *a*-value calculated for each zone. The reason for this two-step approach is that a well constrained estimate of *b* requires at least 100, preferably 400, earthquakes, whereas *a* requires only 20 (Bender 1983, Leonard 2017, 2018). With the AUS6 and DIM-AUS having 125 and 69 source zones, respectively, relatively few zones meet the 100 earthquake required to determine a reliable estimate of *b*. Where the source zones do meet this criterion, the local and regional estimates of *b* are consistent, suggesting that the assumption of *b* being regionally constant is valid.

For the second method, the NSHM13 model was used and the *a*-value of the MFD for the zones within 200 km of each site were scaled, by trial and error, until the resulting hazard matched the 1991 hazard map. Several sites were located near the border of two or even three zones in which case the MFD of multiple zones were modified. For 20 of the sites the PGA was matched within 10%. For the other four sites the miss-fit could not be reduced without increasing the miss-fit at other sites. For seismicity levels typical of Australia, there is a strong correlation between the expected number of Mw 5.5 earthquakes (from the MFD) and the 500-year PGA hazard. As the uncertainty in the expected number of Mw 5.5 earthquakes per year (A5.5) captures both the uncertainty of *a* and *b* this is the statistic chosen to test the goodness of fit of the expected A5.5 and the A5.5 required to match the earthquake hazard. Combining the uncertainty of *b* from using 100 earthquakes to estimate it (i.e. 0.1) and uncertainty of *a* from using 20 earthquakes (i.e. 0.08), Leonard (2018) gives an uncertainty of A5.5 of a factor of 2.0. For most zones, many more than 100 and 20 earthquakes were used to estimate *b* and *a,* respectively. Consequently, a factor of 2.0 on the rate of M_W 5.5 earthquakes will be an overestimate of the uncertainty. Due to possible concerns over the catalogue I have used the conservative factor of 2.0. As the Gutenberg-Richter MFD is the log of the activity rate the value of σ_2 used in this study is 0.3 (log10(2.0)). As the A5.5 is linked to the 500-year PGA hazard this uncertainty is linked the 500-year PGA hazard.

Results

The results from the first method, comparing the PGA from the NSHM12, AUS6, DIM-AUS and NAD models to the 1991 map hazard values, are given in Table 1. In each case the worst fitting four sites were removed from the calculation, with the goodness of fit calculated from the 20 sites with the lowest number of σ_1 separating the 1991 and the model PGA. For the four models, the average number of standard deviations (σ_1) separating the calculated PGA and the 1991 map, at the 1/500-year annual exceedance probability, are 3.2, 3.5, 3.4 and 3.0 respectively.

For the second method, the MFDs of the 20 source zones within the NSHM13 source model were adjusted such that the1/500-year PGA at the 24 sites was a reasonable fit to the 1991 PGA values in the AS1170.4-1993. For the 20 source zones, the average number of standard deviations separating the A5.5 required to match the 1991 PGA and the best estimate of A5.5, from the 2018 NSHA18 Mw catalogue (Allen *et al.*, 2018b), was 2.7. For the 14 sites that are well within a single zone (i.e. > 100km from a zone boundary), the average number of standard deviations (σ_2) required to match the 1991 PGA values is 3.0.

Discussion

Figure 2 shows the hazard values for the three individual source models, the NAD model and the 1991 map for 12 Australian cities and selected towns. The 1/500-year NAD model PGA values for Sydney, Melbourne, Hobart, Adelaide and Perth are all about $2\sigma_1$ below the 1991 map. The estimated hazard for Brisbane is approximately $4\sigma_1$ lower than the 1991 map. Canberra is the only capital city where the calculated hazard is consistent with the values from the 1991 map, for all three source models. The low hazard sites in particular, such as Alice Springs and Brisbane, are many σ_1 below the 1991 map, with the hazard at several of the low hazard sites in Figure 3 being more than $4\sigma_1$ below the 1991 map hazard. Some sites, mostly those on Cratonic crust, are within $2\sigma_1$.

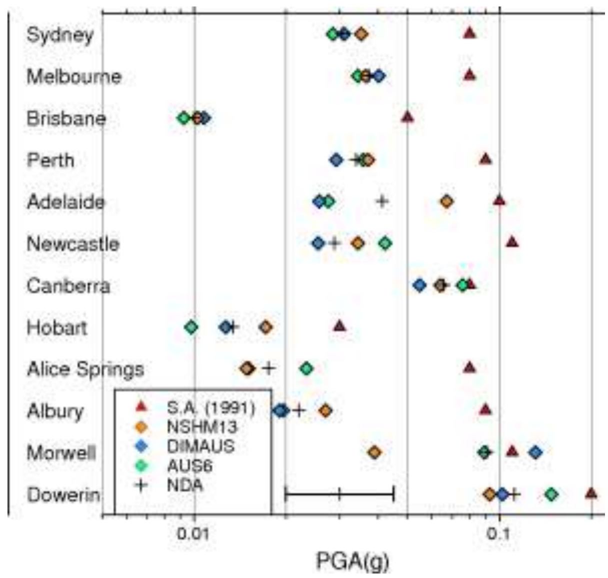

Figure 2 The 1/500-year PGA hazard on Site Class B_e for some Australian cities and towns. The typical $1\sigma_1$ uncertainty range for a reasonably well constrained seismic source model is at the bottom centre. Except for Canberra and Morwell, the 1991 hazard levels represent a greater than $2\sigma_1$ hazard level. NAD is a source model that evenly weights the three source models

For many sites (e.g. Sydney, Melbourne, Perth, Canberra, Brisbane, Toowoomba and Coffs Harbour), the three models produce similar hazard. For other sites (e.g. Adelaide, Hobart, Morwell and Mildura), the three models produce very different hazard values. This does not correlate with quality of the catalogue. The catalogue for the region within a couple of hundred kilometres of Adelaide, Hobart, Melbourne and Sydney are of a similar standard (Leonard 2008). Therefore the differences are not arising from catalogue problems but from different interpretations of the seismicity, geology and tectonics that inform the seismic source models. I consider all three interpretations to be scientifically valid, in which case decreasing this component of the epistemic uncertainty, at sites like Adelaide and Hobart, will be challenging.

For Adelaide, Melbourne and Sydney I have estimated what I consider to be an extreme upper estimate of the 500 year PGA. For the three cities the calculated PGA for the NAD model is 0.041, 0.036 and 0.031 g respectively. Assuming that the revised ML catalogue is the best estimate of the true Mw the PGA increases to 0.043, 0.045 and 0.054 g respectively. Assuming that the most appropriate GMPE for these cities is the Somerville et al. (2009, Yilgarn) the PGA increases to 0.066, 0.069 and 0.082 g respectively. So, even taking this very unlikely MFD-GMPE combination the PGA for Adelaide and Melbourne do not match the AS1170.4 values, with Sydney just matching. To justify these values one has to assume that all the Australian data used to both estimate the local Mw and to constrain or test GMPEs happen to be outliers. Statistically, the probability that this is the case is very small. It also requires evidence from global analogues, such as the difference between ML and Mw and the selection of GMPEs, to be ignored.

Conclusion

The 1991 hazard map, that has been the basis of every version of the AS1170.4, is 3σ above a scientifically valid PSHA for Australia. This equates to a ≥99% quantile map. All five test to assess model uncertainty; four source zone models using method 1 and one source zone model using method 2, give a separation of at least 3σ.

From an engineering and life safety perspective, it might be valid for a building code to reference a hazard map with seismic design levels much greater than scientifically credible PGA values. However, the 1991 map does not represent seismic hazard with a uniform exceedance probability of 1/500-years. For example, based on the NAD model, Adelaide, Melbourne, Sydney, Adelaide, and Mildura AS1170.4(2018) hazard factors are more accurately described as a 1800, 2000, 2300, 70000 year return period hazard factors, respectively. As such, the code should cease referring to it as a 10% in 50 years probability of exceedance hazard map (i.e. 500-year return period) and refer to it as a design PGA map, with typical return periods of greater than 2000 years. Practitioners using the AS1170.4 map, whether for building design or assessing insurance exposure, need to be conscious that it is not a scientifically valid mean probabilistic seismic hazard map.

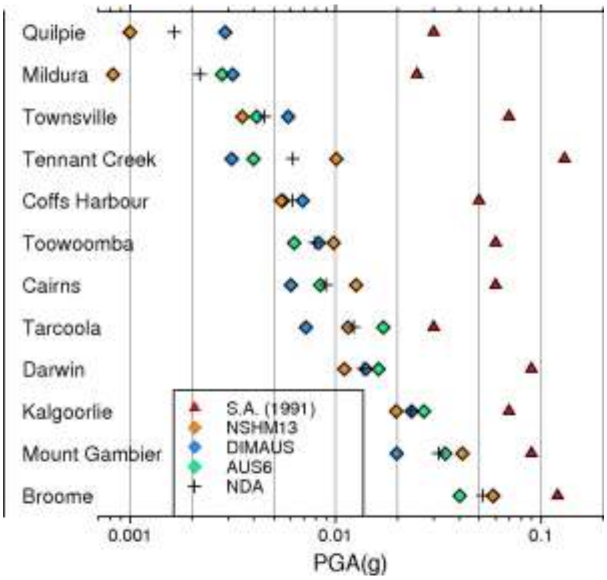

Figure 3 The 1/500-year hazard plot for some Australian cities and towns

Table 1 PGA hazard values for a 1/500-year annual probability of exceedance and the number of standard deviations the 1991 hazard level is from the mean hazard for three models.

Site	*1991*	*NSHM12*	*#*	*AUS6*	*#*	*DIM-*	*#*	*NAD*	*#*
Sydney	0.080	0.035	1.7	0.031	2.0	0.029	2.1	0.032	2.0
Melbourne	0.080	0.037	2.3	0.040	2.0	0.039	2.2	0.039	2.2
Brisbane	0.050	0.010	4.6	0.011	4.4	0.024	2.2	0.015	3.5
Perth	0.090	0.037	2.6	0.029	3.2	0.059	1.2	0.042	2.2
Adelaide	0.100	0.067	1.1	0.026	3.9	0.014	5.7	0.036	3.0
Newcastle	0.110	0.034	3.4	0.026	4.2	0.015	5.7	0.025	4.3
Canberra	0.080	0.064	0.6	0.055	1.1	0.003	*9.4*	0.041	2.0
Hobart	0.030	0.017	1.6	0.013	2.5	0.007	4.1	0.012	2.6
Townsville	0.070	0.004	*8.6*	0.006	*7.1*	0.026	2.9	0.012	5.2
Cairns	0.060	0.013	4.5	0.006	*6.6*	0.020	3.2	0.013	4.4
Toowoomba	0.060	0.010	5.2	0.008	5.7	0.003	*8.5*	0.007	*6.2*
Coffs Harbour	0.050	0.005	*6.4*	0.007	5.7	0.003	*8.2*	0.005	*6.6*
Albury	0.090	0.027	3.5	0.019	4.5	0.040	2.3	0.029	3.3
Mildura	0.025	0.001	*9.8*	0.003	6.0	0.006	4.1	0.003	5.8
Morwell	0.110	0.039	3.0	0.132	-0.5	0.132	-0.5	0.101	0.3
Mount Gambier	0.090	0.041	2.2	0.020	4.4	0.006	7.9	0.022	4.0
Darwin	0.090	0.011	6.1	0.014	5.4	0.019	4.5	0.015	5.2
Tennant Creek	0.130	0.010	7.4	0.003	*10.8*	0.013	6.7	0.009	*7.8*
Alice Springs	0.080	0.015	4.9	0.015	4.8	0.055	1.1	0.028	3.0
Quilpie	0.030	0.001	*9.8*	0.003	*6.7*	0.0031	6.5	0.0021	*6.8*
Tarcoola	0.030	0.012	2.8	0.007	4.1	0.026	0.5	0.015	2.0
Kalgoorlie	0.070	0.020	3.6	0.024	3.1	0.008	6.2	0.017	4.0
Dowerin	0.200	0.093	2.2	0.102	1.9	0.011	*8.4*	0.069	3.1
Broome	0.120	0.058	2.1	0.059	2.1	0.007	8.2	0.041	3.1
Mean of the σ			3.22		3.53		3.36		3.04
σ of the σ (excluded)			1.61		1.73		2.85		1.29

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