Towards an updated national seismic assessment for Australia

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Abstract

Geoscience Australia has produced a draft National Seismic Hazard Assessment (NSHA18), together with contributions from the wider Australian seismology community. This paper provides an overview of the provisional peak ground acceleration (PGA) hazard values and discusses rationale for changes in the proposed design values at the 1/500-year annual exceedance probability (AEP) level relative to Standards Australia's AS1170.4–2007 design maps. The NSHA18 update yields many important advances on its predecessors, including: consistent expression of earthquake magnitudes in moment magnitude; inclusion of epistemic uncertainty through the use of third-party source models; inclusion of a national fault-source model; inclusion of epistemic uncertainty on fault-slip-model magnitude-frequency distributions and earthquake clustering; and the use of modern ground-motion models through a weighted logic tree framework.

In general, the 1/500-year AEP seismic hazard values across Australia have decreased relative to the earthquake hazard factors the AS1170.4–2007, in most localities significantly. The key reasons for the decrease in seismic hazard factors are due to: the reduction in the rates of moderate-to-large earthquakes through revision of earthquake magnitudes; the increase in *b*-values through the conversion of local magnitudes to moment magnitudes, particularly in eastern Australia, and; the use of modern ground-motion attenuation models.

Whilst the seismic hazard is generally lower than in the present standard, we observe that the relative proportion of the Australian landmass exceeding given PGA thresholds is consistent with other national hazard models for stable continental regions.

Keywords: seismic hazard, earthquake magnitude, ground-motion models, AS1170.4

INTRODUCTION

Damaging earthquakes in Australia are considered low probability but high consequence events. Woodside and McCue (2017) provide an excellent synopsis of the history of seismic design and code development in Australia, through to the current Standards Australia *Structural design actions, part 4: Earthquake actions in Australia, (AS1170.4–2007)*. The objective the AS1170.4–2007 is to ‘provide designers of structures with actions and general detailing requirements to protect life and property from earthquakes’ (Standards Australia, 2007). The seismic hazard factor *Z* in the Standard is represented as the peak ground acceleration (PGA) values calculated on rock sites (AS1170.4 Site Class B_e) with a probability of exceedance of 10% in 50 years. This probability level is approximately equivalent to a 1/500-year annual exceedance probability (AEP).

The AS1170.4–2007 seismic hazard factors trace their lineage back to the probabilistic seismic hazard assessment (PSHA) of Gaull *et al.* (1990). This was a landmark study for its time and was developed based on scientific understandings and available data from the late 1980’s. The Gaull *et al.* map was subsequently modified through a process of expert judgement (McCue, 1993) in response to significant Australian earthquakes (notably the M_W 6.2, 6.3 and 6.6 1988 Tennant Creek sequence and the deadly 1989 M_W 5.4 Newcastle earthquake) for inclusion in the then new design standard AS1170.4–1993 (McCue *et al.*, 1993). This assessment, compiled in 1991, reflected the understanding of seismic hazard in Australia at the time and has provided a reliable assessment to guide engineering design since its publication. However, with advances in our understanding of earthquake characteristics in Australia and analogue tectonic regions, we should now consider whether this map reflects our current understanding of ground-motion hazard for Australian earthquakes.

Since the development of the 1991 hazard map, national-scale seismic source models have been developed to support various national and site-specific probabilistic hazard assessments (e.g., Brown and Gibson, 2004; Hall *et al.*, 2007). However, these models were not developed specifically with building codes in mind. In 2012, Geoscience Australia (GA) developed a national seismic hazard assessment that was intended to supersede the 1991 seismic design factors in the Standard (Burbidge, 2012; Leonard *et al.*, 2013; 2014). This assessment used modern probabilistic methods, improved characterisation of tectonic region type and maximum earthquake magnitude (Clark *et al.*, 2012) and included Australian-specific ground-motion models (Somerville *et al.*, 2009; Allen, 2012), in addition to an earthquake catalogue augmented with an additional 20 years of earthquake data (i.e., magnitudes and epicentres). Whilst a significant advance from its predecessor, in terms of methods and data, the Standards subcommittee elected not to adopt the 2012-13 revision of the NSHA to underpin seismic design provisions for AS1170.4 owing to the large uncertainties associated with seismic hazard assessments in Australia (as with any stable continental interior), as well as concerns that it did not reflect the view of the broader Australian seismological community.

Geoscience Australia has embarked on a project to seek broader community engagement and to update the seismic hazard model for Australia through the National Seismic Hazard Assessment (NSHA18) project. This paper summarises the development of the draft NSHA18, as prepared for the consideration of inclusion into the updated Standard, AS1170.4–2018.

THE DRAFT 2018 NATIONAL SEISMIC HAZARD ASSESSMENT

Standards Australia and the BD–06–11 Subcommittee – the subcommittee responsible for the review and revision of the AS1170.4 – indicated a desire to update the 1991-era seismic hazard factors for the forthcoming update to the Standard in 2018. In response to this request, GA initiated a process to update the national seismic hazard model and solicited contributions from the wider earthquake hazard community in Australia. Seismic source model proponents were invited to develop and submit source models to be considered for inclusion in the NSHA18 under the condition that the models were peer reviewed and published through Australian Earthquake Engineering Society (AEES) conference proceedings, or within other reputable literature (e.g., Hall *et al.*, 2007; Leonard, 2008; Cuthbertson, 2016; Dimas *et al.*, 2016; Dimas and Venkatesan, 2016; Griffin *et al.*, 2016; Sinadinovski and McCue, 2016; Mote *et al.*, 2017). This process not only enabled the incorporation of epistemic uncertainty into the seismic source model in a more comprehensive manner, but also provides the community with an opportunity to take ownership of the final model. Through the NSHA18 project, GA also established a Scientific Advisory Panel (consisting of national and international seismic hazard experts) to provide valuable and ongoing feedback during the model's development.

Candidate source models were assessed through an expert elicitation process (e.g., Aspinall, 2010) that weighed the opinion of each expert based on their knowledge and ability to judge relevant uncertainties. In total, 14 independent seismic source models were considered in the draft NSHA18 (Allen *et al.*, 2017). Further seismic source models are intended to be used in the final model development.

Leonard (2017) explores the variability amongst the seismic source models employed in the NSHA18. In this manuscript, 24 sites are examined to determine the centre, body and range of hazard curves resulting from each of the seismic source models. Leonard (2017) suggests that epistemic uncertainty (i.e. uncertainty due to limited data and knowledge) has been comprehensively sampled by the inclusion of the multiple seismic source models in the NSHA18.

Draft seismic hazard factors were originally submitted to BD-06-11 in May 2017 to comply with Standards Australia's public comment and publication timelines. There will be continued refinement of these values until the planned completion of the NSHA18 in June 2018.

The draft NSHA18 update yields many important advances over its predecessors, including:

- calculation in a full probabilistic framework (Cornell, 1968) using the Global Earthquake Model Foundation's *OpenQuake-engine* (Pagani *et al.*, 2014);
- consistent expression of earthquake magnitudes in terms of moment magnitude, M_W;
- inclusion of epistemic uncertainty through the use of multiple alternative source models;
- inclusion of epistemic uncertainty on magnitude-recurrence distributions;
- inclusion of a national fault-source model based on the Australian Neotectonic Features database (Clark *et al.*, 2016);
- capturing the epistemic uncertainty on maximum earthquake magnitudes for both fault and area sources through an expert elicitation workshop; and
- the use of modern ground-motion models, capturing the epistemic uncertainty on ground motion through an expert elicitation workshop.

Figure 1 shows the draft peak ground acceleration (PGA) hazard map for a 1/500-year AEP on Site Class B_e as proposed by GA for the AS1170.4–2018. With the exception of small areas in the Western Australian Wheatbelt and in eastern Gippsland, seismic hazard values at the 1/500-year AEP across Australia have decreased relative to the earthquake hazard factors provided in the 2007 Standard – significantly in most localities. In general, the draft seismic hazard values across Australia at the 1/500-year AEP have decreased, on average, by 63% relative to the earthquake hazard factors provided in the 2007 Standard (Allen *et al.*, 2017).

Seismic hazard for lower probability ground-motion exceedances were also calculated for the draft NSHA18. Whilst the seismic hazard for the 1/500-year AEP is generally lower than in the present AS1170.4–2007, the probability factor (k_p), which scales the seismic hazard to different AEPs, is significantly higher than those in the current Standard for lower probabilities of exceedance (Fig. 3). The national average is k_p = 3.3 at the 1/2500-year AEP (compared to k_p = 1.8 in the AS1170.4–

2007), meaning that the relative hazard multiplication factor at lower probabilities will lead to higher design values relative to 1/500-year AEP factors.

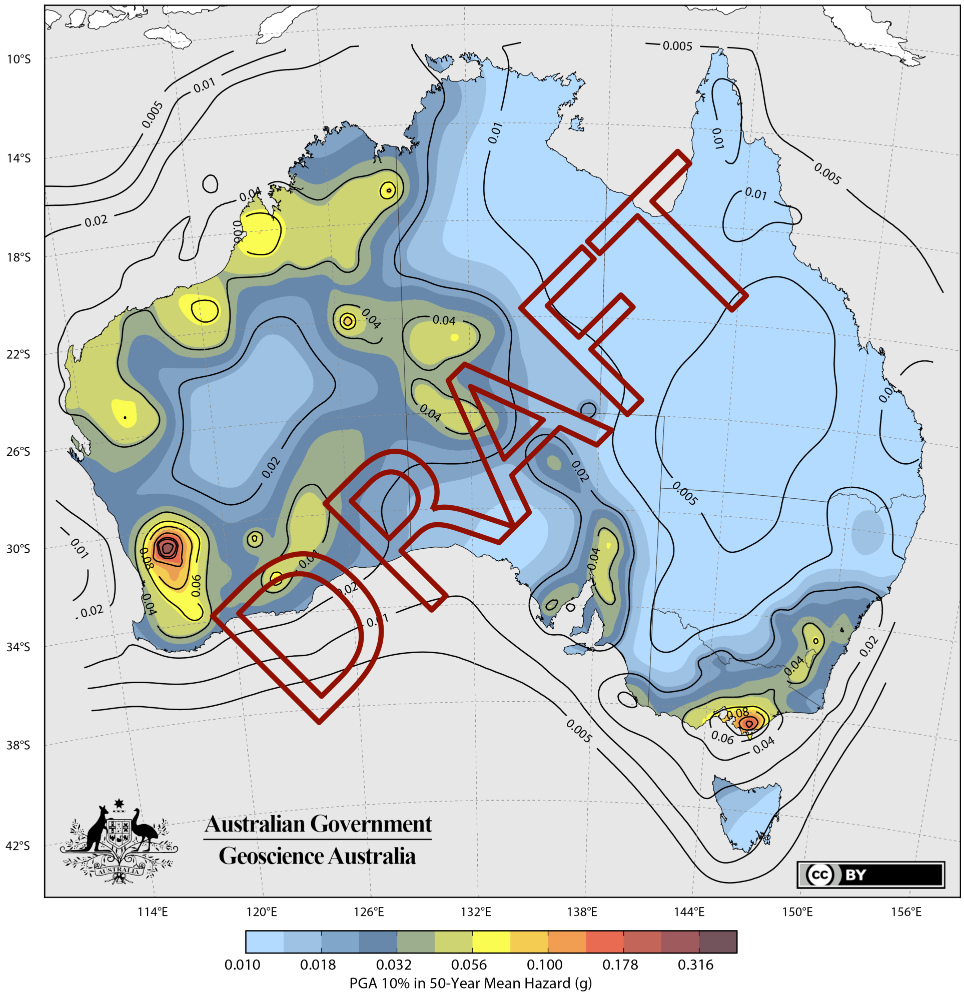

Figure 1: *Provisional peak ground acceleration (PGA) as proposed for the AS1170.4–2018 as of May 2017. Note: values from the NSHA18 within this map are in draft form only and the hazard contours are likely to change prior to the completion of the final model by June 2018.*

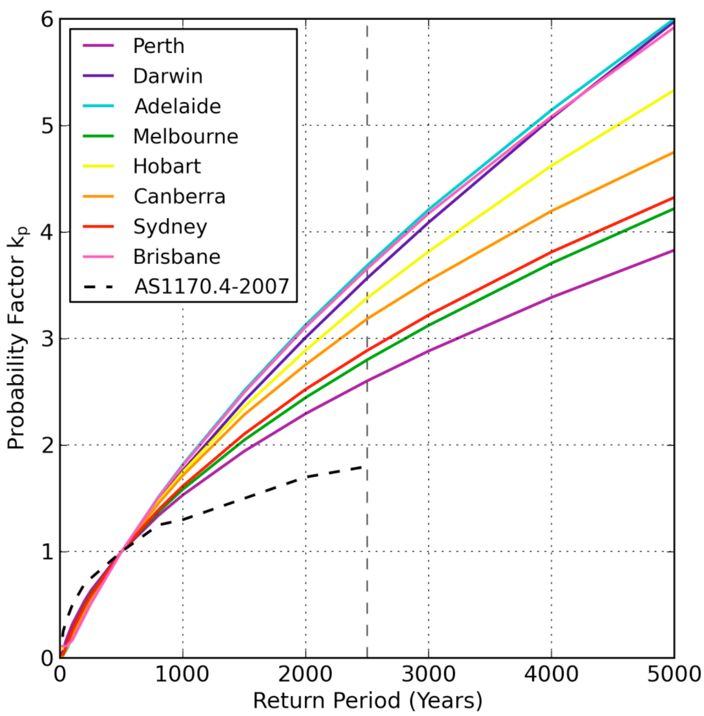

Figure 2: *The probability factor (kp) for the eight capital cities compared to the kp values in AS1170.4-2007 (bold black dashed line). The vertical dashed line indicates the 2,500-year AEP.*

RATIONALE FOR CHANGES IN SEISMIC HAZARD

The preceding section indicated that the seismic hazard factors estimated from the NSHA18 are significantly lower at the 1/500-year AEP than those used in the AS1170.4–2007 and its predecessors since 1991. In the intervening years, scientists have learned a great deal about earthquake occurrence and their effects in Australia, as well as in analogue tectonic regions. For this reason, it is prudent to update seismic design values in Australia based on the best available science and methods. In this section, we outline the key elements of the NSHA18 that have led to the large differences in seismic hazard relative to the 1991-era hazard map (McCue *et al.*, 1993).

1 Use of a national fault-source model

While hazard values have generally decreased relative to the AS1170.4–2007 hazard values, the introduction of national seismotectonic seismic source models (Griffin *et al.*, 2016) has led to an increase in accelerations relative to pure seismicity-based source models. These effects are particularly pronounced for localities near faults sources that have been assigned neotectonic activity rates (Clark *et al.*, 2016). Figure 3 plots hazard curves for four Australian capital cities having varying contributions of hazard from the seismotectonic source models. It is interesting to note, that while the city of Perth is located near the seismically active Southwest Seismic Zone, it receives very little contribution to total hazard from nearby fault sources. Meanwhile, the cities of Adelaide and Canberra demonstrate significant contributions from the seismotectonic fault source model having an increase of PGA hazard at the 1/475-year AEP of approximately 40% relative to seismic source models based on purely historical seismicity. Because the seismic hazard in Melbourne is affected by the nearby distributed seismicity sources, the relative contribution of fault sources to the total hazard is low (approximately 14%) compared to other localities.

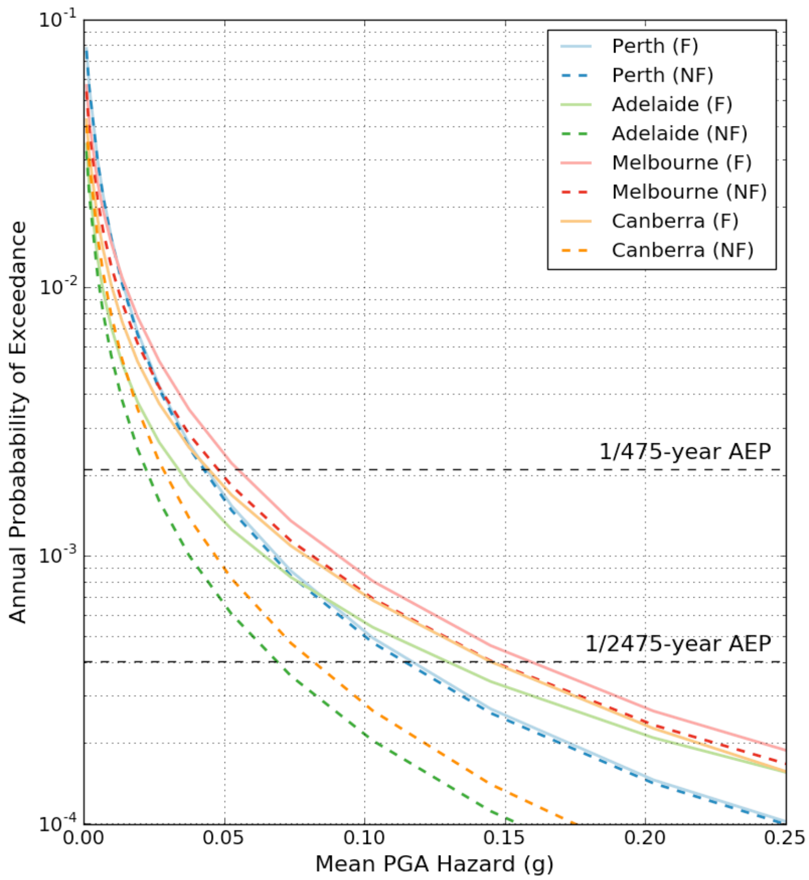

***Figure 3**: Mean PGA hazard curves for four Australian capital cities showing the influence of fault sources. Curves denoted with "F" and "NF" indicate seismic hazard estimates with and without seismotectonic fault-source models, respectively. Note: values from the NSHA18 within this figure are in draft form only and are likely to change prior to the completion of the final model by June 2018.*

2 Adjustment of Local Magnitudes

One reason for the significant drop in seismic hazard is due to adjustments to catalogue magnitudes. Prior to the early 1990's, most Australian seismic observatories relied on the Richter (1935) local magnitude (M_L) formula developed for southern California. At regional distances (where many earthquakes are recorded), the Richter scale will tend to overestimate M_L relative to modern Australian magnitude formulae (Allen, 2010). Because of the likely overestimation of local magnitudes for Australian earthquakes recorded at regional distances (Allen, 2010), there is a need to account for pre-1990 magnitude biases due to the use of inappropriate Californian magnitude formulae. A process was employed that systematically corrected local magnitudes using the difference between the original (inappropriate) magnitude formula (e.g., Richter, 1935) and the Australian-specific correction curves (e.g., Michael-Leiba and Malafant, 1992) at a distance determined by the nearest recording station likely to have recorded any given earthquake (Allen, 2010). This process has largely decreased the magnitudes of those earthquakes recorded at regional distances (approximately > 200 km). By virtue of the sensitivity and density of seismic instrumentation prior to 1990, this process will, more often than not, reduce magnitudes of moderate-to-large earthquakes, thus decreasing the annual occurrence rates of larger events (Fig. 4).

3 M_L-M_W conversions

Another important factor determining the reduction in hazard is the conversion of catalogue magnitudes such that magnitudes are consistently expressed in terms of moment magnitude, M_W. Moment magnitude is the preferred magnitude type for PSHAs because it does not saturate with magnitude (Kanamori, 1977) and all modern ground-motion models (GMMs) are now calibrated to this magnitude type. Relationships between M_W and other magnitude types were developed for the NSHA18 (Ghasemi and Allen, 2017). The most important of these is the relationship between M_L and M_W because of the abundance of local magnitudes in the Australian earthquake catalogue. The preferred bi-linear relationship demonstrates that M_W is approximately 0.3 magnitude units lower than M_L for moderate-to-large earthquakes ($4.0 < M_W < 6.0$). Together, the M_L corrections and the subsequent conversions to M_W, effectively halve the number (and subsequently the annual rate) of earthquakes exceeding magnitude 4.0 and 5.0, respectively (Fig. 4). This further affects the annual occurrence rates of larger earthquakes.

4 Changes to Gutenberg–Richter *b*-value

The secondary effect of the M_L and M_W magnitude conversion is that it tends to increase the number of small-magnitude earthquakes relative to moderate- and large-magnitude earthquakes. This acts to increase the Gutenberg–Richter *b*-value (Gutenberg and Richter, 1944), which in turn further decreases the relative annual rates of larger potentially damaging events (Allen *et al.*, 2017). Ghasemi and Allen (2017) use an idealised earthquake catalogue with a *b*-value of 1.0 to show that the application of the proposed M_L-M_W conversion equation will lead to roughly a 30% increase in *b*, with a subsequent decrease in hazard of around 30-40%. Increases in *b*-value relating to the conversion of M_L to M_W have been observed in other international studies (Edwards *et al.*, 2010; Wiemer *et al.*, 2016; Deichmann, 2017).

5 Impact of combined magnitude adjustments

To test the sensitivity of factors 2-4 from above on seismic hazard estimates, a separate model was generated using the same source zonations and ground-motion logic tree as used in the draft NSHA18. However, the Gutenberg–Richter magnitude-frequency distributions were generated based soley on an earthquake catalogue using original (unmodified) catalogue magnitudes, which is a melange of magnitude types defined here as M_x. Figure 5 (left panel) shows the ratio of this M_x-based hazard map with the draft NSHA18 at the 1/500-year AEP. This map shows that the proposed catalogue modifications contribute to reductions in hazard by factors generally less than a factor of two on a national scale with some areas in central and eastern Australia showing hazard-reduction factors greater than two.

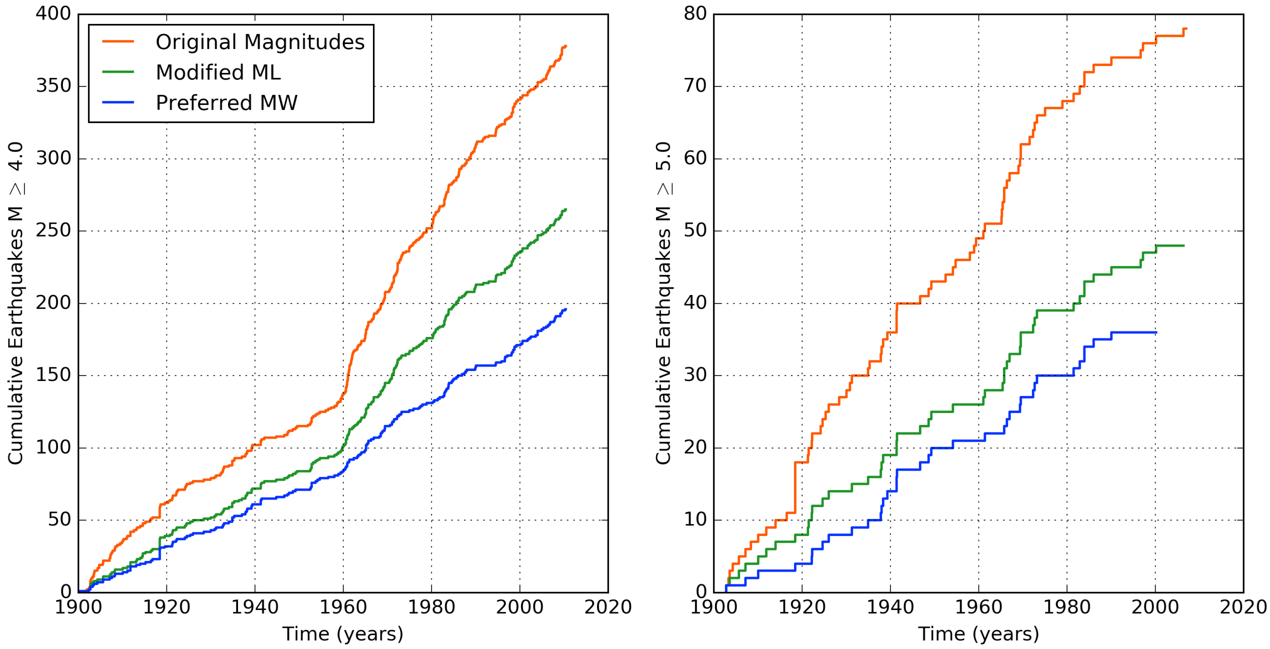

Figure 4: *Cumulative number of earthquakes with magnitudes equal to or exceeding (left) 4.0 and (right) 5.0 for earthquakes in eastern Australia (east of 135°E longitude) from 1900 to 2010. The different curves show different stages of the NSHA18 catalogue preparation: original catalogue magnitudes, modified magnitudes (only local magnitude modified), and preferred* M_W *(for all earthquakes).*

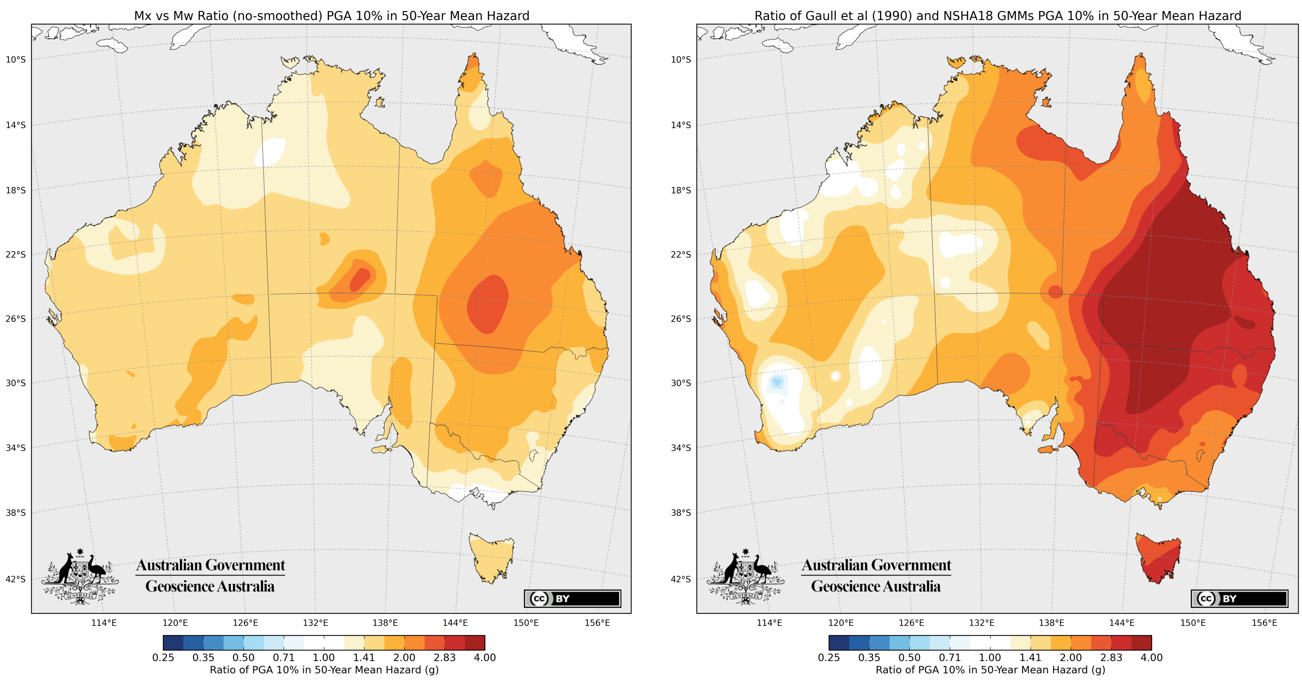

Figure 5: *The ratio of 1/500-year AEP PGA hazard calculated using (left) magnitude frequency distributions (MFDs) calculated using original catalogue magnitudes* M_x *and (right) using the the Gaull et al. (1990) GMMs with the preferred* M_W *catalogue.. In each case the alternative hazard calculations are divided by the preferred NSHA18 assessment (Allen et al., 2017). Values greater than 1.0 (orange-red colours) indicate where either the* M_x*-based MFDs or the Gaull et al. (1990) GMMs predict higher hazard. The colour bar is truncated at 4.0.*

6 Use of modern ground-motion models

The final factor driving the reduction of calculated seismic hazard in Australia is the use of modern GMMs. While seismologists in stable continental regions worldwide recognise the complexity in characterising the likely ground motions from rare large earthquakes, more abundant ground-motion datasets of moderate-magnitude earthquakes are emerging (e.g., Goulet *et al.*, 2014), as are datasets of simulated earthquake ground motions (e.g., Goulet *et al.*, 2015). From these datasets, the characteristics of near-source ground-motion levels and the rates of attenuation are becoming better understood. The hazard levels for the AS1170.4–1993 map (McCue *et al.*, 1993) were based on the contours of the Gaull *et al.* (1990) peak ground velocity (PGV) maps, divided by a factor of 750 to approximate PGA (e.g., Applied Technology Council, 1984). These attenuation relationships were originally derived from the attenuation of macroseismic intensities (e.g., Modified Mercalli Intensity, MMI) using available isoseismal maps for Australian earthquakes (Gaull *et al.*, 1990). The intensity-based attenuation relationships were subsequently converted to PGA and PGV using MMI-to-ground motion conversions based on data from Papua New Guinea (Gaull, 1979).

Questions may arise as to whether modern GMMs used for seismic hazard assessments in stable continental settings are reliable for large-magnitude earthquakes given that they are often developed using simulated data, with few empirical ground-motion records to provide any constraint. In contrast, there is a relative abundance of MMI data from Australian earthquakes (McCue, 2002) and it may be possible for these data – and attenuation models developed from these data (e.g., Gaull *et al.*, 1990) – to guide the selection of GMMs in the Australian context. It is a complex problem that unfortunately does not have a unequivocal solution. This is because it is difficult to readily compare historical macroseismic information with modern ground-motion models in the absence of appropriate MMI-to-peak ground motion conversions that are also based on Australian instrumental ground-motion data (e.g., Cua *et al.*, 2010). Macroseismic intensity data are also susceptible to site effects and are scarcely observed on engineering bedrock (as usually required for building codes). As a consequence, an indirect approach has been taken to assess the utility of the MMI data for benchmarking instrumentally-based GMMs. As a general observation, we find that Australian-specific GMMs are often consistent with active crustal GMMs at mid periods (i.e., those periods that influence MMI assignments; e.g., Frankel, 1994) at distances less than approximately 100 km. It therefore stands to reason that Australian MMI data should be consistent with active tectonic MMI attenuation models (i.e., Allen *et al.*, 2012) within a similar distance range.

Figure 6 shows intensity residuals (observed minus predicted) relative to several intensity prediction equations (IPEs) as a function of moment magnitude for macroseismic observations from Australian earthquakes (McCue, 2002). Intensity observations are limited to distances less than 100 km from the earthquake source in this analysis so that near-source effects can be better assessed. The data have *not* been subdivided into eastern and western subsets. The upper two pannels show residual plots for the Gaull *et al.* (1990) eastern and western IPEs, respectively. These subplots suggest that the Gaull *et al.* (1990) IPEs tend to overestimate near-source intensities for larger-magnitude earthquakes, particularly for the eastern Australian IPE. In contrast, an IPE developed for active tectonic regions (Allen *et al.*, 2012) performs quite well at near-source distances relative to Australian MMI data. The Leonard (2015) IPE, developed for Australian earthquakes, also compares well with the Australian MMI data.

Evaluation of the limited instrumental data indicated that the Gaull *et al.* GMMs also tend to overestimate recorded PGAs from moderate-magnitude Australian earthquakes, for eastern Australia in particular (Ghasemi and Allen, in prep). Based on these analyses of independent datasets and models, it can be inferred that the magnitude scaling and near source attenuation characteristics of modern GMMs as used in the NSHA18 are generally appropriate for use in Australian seismic hazard assessments.

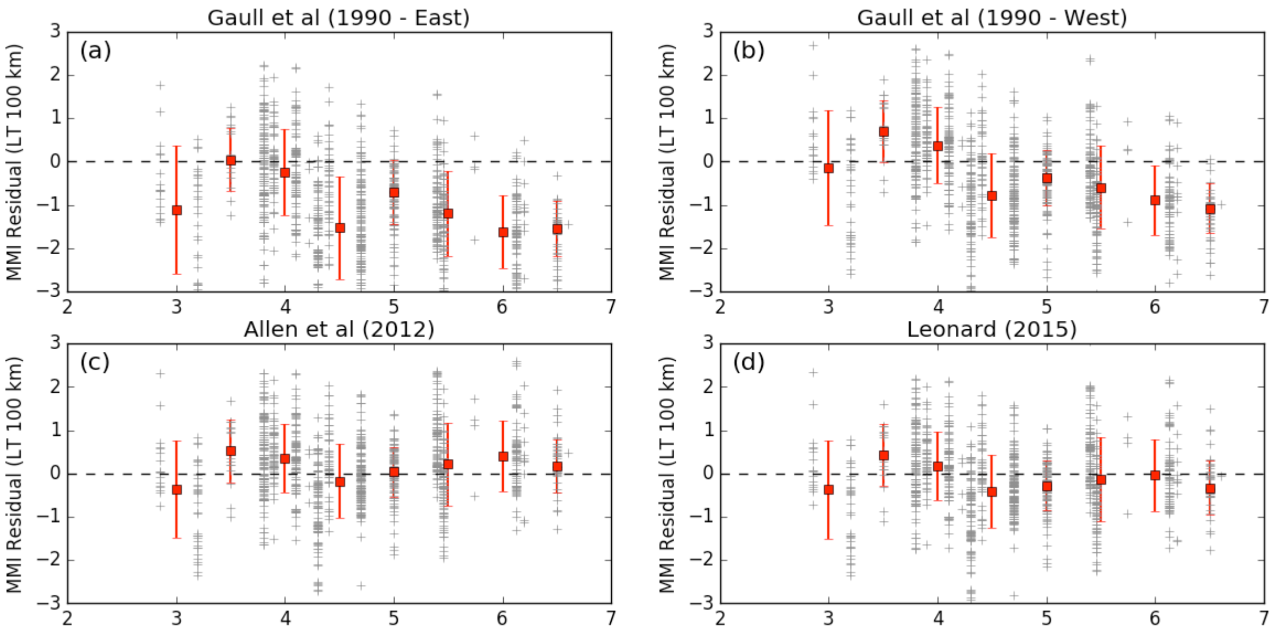

Figure 6: *Macroseismic intensity residuals with respect to moment magnitude for (a) Gaull et al (1990) - Eastern Australia; (a) Gaull et al (1990) - Western Australia; (c) Allen et al (2012) – Active Tectonic, and; (d) Leonard (2015) – Australia. Macroseismic observations are limited to distances less than 100 km (hypocentral distance) from the earthquake source. Magnitudes used in the Gaull et al (1990) IPEs are first converted to* M_L *using the conversions of Ghasemi and Allen (2017).*

The NSHA18 hazard values are consequently based on modern GMMs with improved understanding of instrumental ground-motion source amplitudes and attenuation in Australia, as well as in analogue regions. The PGAs predicted by these modern models, in general, are up to a factor of two lower than the Gaull *et al.* (1990) PGV-based relationships at distances of engineering significance (generally less than 100 km). That said, the Gaull *et al.* (1990) ground-motion model for cratonic Australia generally predicts similar near-source PGAs to candidate GMMs considered for the NSHA18. However, at larger distances, the lower rates of attenuation of each of the Gaull *et al.* (1990) relationships yield accelerations up to factors of 10 higher than most modern GMMs (Allen *et al.*, 2017). This observation should be expected to produce much higher hazard values in regions with low seismicity rates, in particular. Figure 5 (right panel) shows the ratio of the hazard calculated using the Gaull *et al.* (1990) GMMs relative to the preferred GMMs from the draft NSHA18 (Allen *et al.*, 2017). It can be seen that the Gaull *et al.* (1990) GMMs (PGV models converted to PGA as per the AS1170.4–1993 map) result in significantly higher hazard across the vast majority of the Australian landmass, with factors up to and greater than four in regions of eastern Australia. This comparison goes part of the way to explain the differences between the current AS1170.4 design maps and the draft NSHA18 calculations.

A comprehensive suite of sensitivity tests for the aforementioned advances in seismic hazard modelling methods are currently being undertaken (and documented) to test against the approaches taken by McCue *et al.* (1993). However, the resulting reduction in seismic hazard factors at the 1/500-year AEP nevertheless appear to be rational in light of the approaches discussed herein.

COMPARISON WITH OTHER NATIONAL MAPS

Given that this update of the NSHA has seen significant reductions in seismic hazard at the 1/500-year AEP, it is prudent to explore how the new calculations compare to seismic hazard values in analogue tectonic regions at comparable exceedance probabilities. Table 1 shows the relative proportion of land area exceeded by different PGA thresholds with a 1/2475-year AEP for the stable central and eastern component of the United States (CEUS; approximately east of 105°W) based on the U.S. National Seismic Hazard Maps (Petersen *et al.*, 2014). Also shown are the exceedance rates for the draft NSHA18 at the same probability level. In general, the relative areas of ground-motion exceedance are surprisingly consistent at the 1/2475-year AEP level. The proportionally larger areas of ground-motion exceedance at higher PGA thresholds (PGA ≥ 0.2 g) in the CEUS is largely due to the influence of the New Madrid Seismic Zone on the surrounding area; a region that has hosted large historic earthquakes exceeding M_W 7.0 (Boyd and Cramer, 2014) and is modelled to have short recurrence of approximately 500 years (Frankel *et al.*, 2012).

In contrast, the current AS1170.4–2007 design map defined for a higher probability of 1/500-year AEP predicts proportionally higher ground-motion exceedances (in terms of area) than either of the 1/2475-year AEP maps at ground-motion thresholds less than 0.1 g (Table 1). Given the comparable results for the low-probability CEUS (Petersen *et al.*, 2014) and the draft NSHA18, it is of concern that the comparatively high-probability AS1170.4–2007 design map yields higher exceedances at any PGA threshold. Whilst it may provide appropriate design ground motions, this result suggests that the existing AS1170.4–2007 design map may not accurately represent hazard factors with 1/500-year AEP as required by the Standard.

Table 1: *The percentage of land area exceeded by different PGA thresholds with 1/2475-year AEP for the U.S. National Seismic Hazard Maps east of 105°W (Petersen et al., 2014) and the draft NSHA18. Also shown are comparable results for the current AS1170.4–2007 1/500-year AEP design map.*

PGA Levels (g)	Australia % Land Area Exceedance (1/2475 AEP)	CEUS % Land Area Exceedance (1/2475 AEP)	AS1170.4-2007 % Land Area Exceedance (1/500 AEP)*
0.02	88.3	96.1	99.7
0.04	63.7	65.0	83.0
0.06	45.7	43.8	66.5
0.08	30.2	30.5	47.1
0.10	21.6	22.7	18.7
0.14	11.6	13.2	0.6
0.20	2.5	6.8	0.0
0.30	0.6	3.4	0.0
0.40	0.3	1.7	0.0
0.80	0.0	0.5	0.0

** Uses the Global Seismic Hazard Assessment Program gridded seismic hazard (Giardini et al., 1999; McCue, 1999) as a proxy for the AS1170.4 design factors (McCue et al., 1993).*

CONCLUSIONS

This manuscript provides a brief summary of the development of the draft NSHA18, and outlines the rationale for the significant differences between the updated national assessment and that used in the AS1170.4–2007 at the 1/500-year AEP. The new hazard assessment yields many advances on its predecessors and uses the latest data and methods to enable a more comprehensive assessment of Australia's national seismic hazard and its uncertainties. A key attribute of the draft NSHA18 is the inclusion of third-party seismic source models contributed by members of the Australian seismological community.

Given the significant reduction in seismic hazard factors calculated for the draft NSHA18 relative to the existing AS1170.4 factors, there is a strong case for future construction codes to adopt lower-probability ground-motion exceedances, such as the 1/2475-year AEP as used as the basis for seismic design factors in other national design codes (Canadian Commission on Building and Fire Codes, 2015; Building Seismic Safety Council, 2016). This would ensure an appropriate level of seismic safety for new construction across most of Australia and its territories (minimum design standards could still apply for some low-hazard jurisdictions).

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions made by the Australian seismological community and the participants of the expert elicitation workshops. We also acknowledge the NSHA18 Science Advisory Panel who has offered important ongoing review of the NSHA18. Gregory Brenn, Jane Sexton and an anonymous reviewer are thanked for their thoughtful reviews of this manuscript. This manuscript is published with the permission of the CEO of Geoscience Australia.

REFERENCES

Allen, T., Griffin, J., Clark, D., Ghasemi, H., Leonard, L., and Volti, T. (2017). Towards the 2018 National Seismic Hazard Assessment: Draft design values as proposed for the Standards Australia AS1170.4–2018 Earthquake Design Actions, *Geoscience Australia Professional Opinion 2017/02*, Canberra, 44 pp.

Allen, T. I. (2010). The influence of attenuation in earthquake ground-motion and magnitude estimation: implications for Australian earthquake hazard, *Australian Earthquake Engineering Society 2010 Conference*, Perth, Western Australia

Allen, T. I. (2012). Stochastic ground-motion prediction equations for southeastern Australian earthquakes using updated source and attenuation parameters, *Geoscience Australia Record 2012/69*, Canberra, 55 pp.

Allen, T. I., Wald, D. J., and Worden, C. B. (2012). Intensity attenuation for active crustal regions, *J. Seismol.* Vol 16, pp 409–433, doi: 10.1007/s10950-012-9278-7.

Applied Technology Council (1984). Tentative provisions for the development of seismic regulations for buildings, *Applied Technology Council ATC 3-06 Amended*, Redwood City, CA, 505 pp.

Aspinall, W. (2010). A route to more tractable expert advice, *Nature* Vol 463, pp 294-295, doi: 10.1038/463294a.

Boyd, O. S., and Cramer, C. H. (2014). Estimating earthquake magnitudes from reported intensities in the central and eastern United States, *Bull. Seism. Soc. Am.* Vol 104, No 4, pp 1709–1722, doi: 10.1785/0120120352.

Brown, A., and Gibson, G. (2004). A multi-tiered earthquake hazard model for Australia, *Tectonophys.* Vol 390, pp 25-43, doi: 10.1016/j.tecto.2004.03.019.

Building Seismic Safety Council (2016). NEHRP recommended seismic provisions for new buildings and other structures. 2015 Edition, *FEMA P-1050*, Washington, D.C.

Burbidge, D. R., Ed. (2012). *The 2012 Australian Earthquake Hazard Map*, Geoscience Australia, Record 2012/71.

Canadian Commission on Building and Fire Codes (2015). National Building Code of Canada 2015, *National Research Council of Canada NRCC 56190*.

Clark, D., Leonard, M., Griffin, J., Stirling, M., and Volti, T. (2016). Incorporating fault sources into the Australian National Seismic Hazard Assessment (NSHA) 2018, *Australian Earthquake Engineering Society 2016 Conference*, Melbourne, VIC

Clark, D., McPherson, A., and Van Dissen, R. (2012). Long-term behaviour of Australian stable continental region (SCR) faults, *Tectonophys.* Vol 566-567, pp 1-30, doi: 10.1016/j.tecto.2012.07.004.

Cornell, C. A. (1968). Engineering seismic risk analysis, *Bull. Seism. Soc. Am.* Vol 58, No 5, pp 1583-1606.

Cua, G., Wald, D. J., Allen, T. I., Garcia, D., Worden, C. B., Lin, K., and Marano, K. (2010). "Best Practices" for using macroseismic intensity and ground motion-intensity conversion equations for hazard and loss models in GEM1, GEM Foundation, Pavia, Italy, 57 pp.

Cuthbertson, R. J. (2016). Automatic determination of seismicity rates in Australia, *Australian Earthquake Engineering Society 2016 Conference*, Melbourne, VIC

Deichmann, N. (2017). Theoretical basis for the observed break in M_L/M_W scaling between small and large earthquakes, *Bull. Seism. Soc. Am.* Vol 107, No 2, pp 505-520, doi: 10.1785/0120160318.

Dimas, V.-A., Gibson, G., and Cuthbertson, R. (2016). Revised AUS6 model: Significant changes & approaches to the seismotectonic model, *Australian Earthquake Engineering Society 2016 Conference*, Melbourne, VIC

Dimas, V.-A., and Venkatesan, S. (2016). Seismotectonic model for the Australian Plate – beyond borders, *Australian Earthquake Engineering Society 2016 Conference*, Melbourne, VIC

Edwards, B., Allmann, B., Fäh, D., and Clinton, J. (2010). Automatic computation of moment magnitudes for small earthquakes and the scaling of local to moment magnitude, *Geophys. J. Int.* Vol 183, pp 407–420, doi: 10.1111/j.1365-246X.2010.04743.x.

Frankel, A. (1994). Implications of felt area-magnitude relations for earthquake scaling and the average frequency of perceptible ground motion, *Bull. Seism. Soc. Am.* Vol 84, No 2, pp 462-465.

Frankel, A., Smalley, R., and Paul, J. (2012). Significant motions between GPS sites in the New Madrid Region: implications for seismic hazard, *Bull. Seism. Soc. Am.* Vol 102, No 2, pp 479–489, doi: 10.1785/0120100219.

Gaull, B. A. (1979). Seismic risk at the 20 principal towns of Papua New Guinea, University of Papua New Guinea. **MSc thesis**.

Gaull, B. A., Michael-Leiba, M. O., and Rynn, J. M. W. (1990). Probabilistic earthquake risk maps of Australia, *Aust. J. Earth. Sci.* Vol 37, No 2, pp 169-187, doi: 10.1080/08120099008727918.

Ghasemi, H., and Allen, T. (2017). Testing the sensitivity of new Australian empirical magnitude conversion equations on seismic hazard analyses, *Australian Earthquake Engineering Society 2017 Conference*, Canberra, ACT

Ghasemi, H., and Allen, T. I. (in prep). Selection and ranking of ground-motion models for the 2018 National Seismic Hazard Assessment of Australia, *Geoscience Australia Record 2018/XX*.

Giardini, D., Grünthal, G., Shedlock, K. M., and Zhang, P. (1999). The GSHAP global seismic hazard map, *Ann. Geofis.* Vol 42, No 6, pp 1225-1230.

Goulet, C. A., Abrahamson, N. A., Somerville, P. G., and Wooddell, K. E. (2015). The SCEC Broadband Platform validation exercise: Methodology for code validation in the context of seismic-hazard analyses, *Seism. Res. Lett.* Vol 86, No 1, pp 17-26, doi: 10.1785/0220140104.

Goulet, C. A., Kishida, T., Ancheta, T. D., Cramer, C. H., Darragh, R. B., Silva, W. J., Hashash, Y. M. A., Harmon, J., Stewart, J. P., Wooddell, K. E., and Youngs, R. R. (2014). PEER NGA-East Database, *Pacific Earthquake Engineering Research Center PEER Report 2014/17*, 97 pp.

Griffin, J., Volti, T., Clark, D., Ghasemi, H., Leonard, M., and Allen, T. (2016). Development of the 2018 Australian National Seismic Hazard Assessment (NSHA), *Australian Earthquake Engineering Society 2016 Conference*, Melbourne, Victoria

Gutenberg, B., and Richter, C. F. (1944). Frequency of earthquakes in California, *Bull. Seism. Soc. Am.* Vol 34, No 4, pp 185-188.

Hall, L., Dimer, F., and Somerville, P. (2007). A spatially distributed earthquake source model of Australia, *Australian Earthquake Engineering Society*, Wollongong, NSW

Kanamori, H. (1977). The energy release in great earthquakes, *J. Geophys. Res.* Vol 82, No 20, pp 2981–2987.

Leonard, M. (2008). One hundred years of earthquake recording in Australia, *Bull. Seism. Soc. Am.* Vol 98, No 3, pp 1458–1470, doi: 10.1785/0120050193.

Leonard, M. (2015). Consistent MMI area estimation for Australian earthquakes, *10th Pacific Conference on Earthquake Engineering*, Sydney, Australia, pp Paper 170.

Leonard, M. (2017). Using hazard curves to examine the sampling of epistemic uncertainty across the Australian continent, *Australian Earthquake Engineering Society 2017 Conference*, Canberra, ACT

Leonard, M., Burbidge, D., and Edwards, M. (2013). Atlas of seismic hazard maps of Australia: seismic hazard maps, hazard curves and hazard spectra, *Geoscience Australia Record 2013/41*, 39 pp.

Leonard, M., Burbidge, D. R., Allen, T. I., Robinson, D. J., McPherson, A., Clark, D., and Collins, C. D. N. (2014). The challenges of probabilistic seismic-hazard assessment in stable continental interiors: An Australian example, *Bull. Seism. Soc. Am.* Vol 104, No 6, pp 3008-3028, doi: 10.1785/0120130248.

McCue, K. (1993). The revised Australian seismic hazard map, 1991, *Proceedings of the 1993 Australian Earthquake Engineering Society Conference*, Melbourne, VIC

McCue, K. (1999). Seismic hazard mapping in Australia, the southwest Pacific and southeast Asia, *Ann. Geofis.* Vol 42, No 6, pp 1191-1198.

McCue, K. (2002). Atlas of isoseismal maps of Australian earthquakes, *Geoscience Australia AGSO Record 2001/??*

McCue, K. c., Gibson, G., Michael-Leiba, M., Love, D., Cuthbertson, R., and Horoschun, G. (1993). Earthquake Hazard Map of Australia – 1991. Canberra, Australian Geological Survey Organisation.

Michael-Leiba, M., and Malafant, K. (1992). A new local magnitude scale for southeastern Australia, *BMR J. Aust. Geol. Geophys.* Vol 13, No 3, pp 201-205.

Mote, T. I., So, M. L., and Pappin, J. W. (2017). Arup NSHM - Australian National Seismic Hazard Model.

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, R., Nastasi, M., Panzeri, L., Simionato, M., and Vigano, D. (2014). OpenQuake Engine: An open hazard (and risk) software for the Global Earthquake Model, *Seism. Res. Lett.* Vol 85, No 3, pp 692–702, doi: 10.1785/0220130087.

Petersen, M. D., Moschetti, M. P., Powers, P. M., Mueller, C. S., Haller, K. M., Frankel, A. D., Zeng, Y., Rezaeian, S., Harmsen, S. C., Boyd, O. S., Field, N., Chen, R., Rukstales, K. S., Luco, N., Wheeler, R. L., Williams, R. A., and Olsen, A. H. (2014). Documentation for the 2014 update of the United States National Seismic Hazard Maps, *U.S. Geological Survey Open-File Report 2014–1091*, 243 pp, doi: 10.333/ofr20141091.

Richter, C. F. (1935). An instrumental earthquake magnitude scale, *Bull. Seism. Soc. Am.* Vol 25, No 1, pp 1-32.

Sinadinovski, C., and McCue, K. (2016). A proposed PSHA source zone for Australia, *Australian Earthquake Engineering Society 2016 Conference*, Melbourne

Somerville, P., Graves, R., Collins, N., Song, S.-G., Ni, S., and Cummins, P. (2009). Source and ground motion models for Australian earthquakes, The Australian Earthquake Engineering Society Conference. Newcastle, The Australian Earthquake Engineering Society.

Standards Australia (2007). Structural design actions, part 4: Earthquake actions in Australia, *Standards Australia AS 1170.4–2007*, 52 pp.

Wiemer, S., Danciu, L., Edwards, B., Marti, M., Fäh, D., Hiemer, S., Wössner, J., Cauzzi, C., Kästli, P., and Kremer, K. (2016). Seismic Hazard Model 2015 for Switzerland (SUIhaz2015), *Swiss Seismological Service*, doi: 10.12686/a2.

Woodside, J., and McCue, K. (2017). Early history of seismic design and codes in Australia, *Australian Earthquake Engineering Society*, 14 pp, http://www.aees.org.au/early-history-of-seismic-design-and-codes-in-australia/.