Opportunities to enhance seismic demand parameters for future editions of the AS1170.4

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Abstract

Geoscience Australia has recently released its 2018 National Seismic Hazard Assessment (NSHA18). Results from the NSHA18 indicate significantly lower seismic hazard across almost all Australian localities at the 1/500 annual exceedance probability level relative to the factors adopted for the current Australian Standard *AS1170.4–2007 (R2018)*. These new hazard estimates, coupled with larger probability factors (k_p) for long return periods, have challenged notions of seismic hazard in Australia in terms of the recurrence of damaging ground motions. As a consequence, the new hazard estimates have raised questions over the appropriateness of the prescribed National Construction Code probability level as used in the *AS1170.4* to determine appropriate seismic demands for the design of ordinary-use structures. Therefore, it is suggested that the ground-motion exceedance probability used in the current *AS1170.4* be reviewed in light of the recent hazard assessment and the expected performance of modern buildings for rarer ground motions.

Whilst adjusting the *AS1170.4* exceedance probability level would be a major departure from previous earthquake loading standards, it would bring it into line with other international building codes in similar tectonic environments. Additionally, it would offer opportunities to further modernise how seismic demands are considered in Australian building design. In particular, the authors highlight the following additional opportunities: 1) the use of uniform hazard spectra to replace and simplify the spectral shape factors, which do not deliver uniform hazard across all natural periods; 2) updated site amplification factors to ensure continuity with modern ground-motion models, and; 3) the potential to define design ground motions in terms of uniform collapse risk rather than uniform hazard.

Estimation of seismic hazard at any location is an uncertain science. However, as our knowledge improves, our estimates of the hazard will converge more closely to the actual – but unknowable – (time independent) hazard. It is therefore prudent to regularly update the estimates of the seismic demands in our building codes using the best available evidence-based methods and models.

Keywords: NSHA18, exceedance probability, uniform hazard, uniform risk

1. INTRODUCTION

Geoscience Australia, together with contributors from the wider Australian seismology community, has produced a National Seismic Hazard Assessment (NSHA18; Allen *et al.*, 2018a). The NSHA18 update leverages advances in earthquake-hazard science in Australia and analogue tectonic regions over the last three decades to offer many important advances over its predecessors, including:

- the calculation in a full probabilistic framework using the OpenQuake-engine (Pagani *et al.*, 2014);
- the consistent expression of earthquake magnitudes in terms of moment magnitude, M_W (Allen *et al.*, 2018b);
- inclusion of a national fault-source model based on the Australian Neotectonic Features database (Clark *et al.*, 2016);
- the estimation of epistemic (i.e., modelling) uncertainty through the use of multiple alternative source models (Griffin *et al.*, 2018);

In general, peak ground acceleration (PGA) values at the 1/500 annual exceedance probability (AEP) across Australia have decreased, on average, by 72% relative to the earthquake hazard factors provided for localities in the Australian earthquake loading code, *AS1170.4–2007* (Standards Australia, 2007). Furthermore, NSHA18 PGA values at the 1/500 AEP are approximately half of those in the 2013 National Seismic Hazard Maps (NSHM13; Burbidge, 2012; Leonard *et al.*, 2013), with a decrease of 48% (on average) at *AS1170.4* localities (Table 1). The key reasons for this decrease in seismic hazard factors are:

- the reduction in the rates of moderate-to-large earthquakes (approximately $M_W \geq 4.0$); firstly through the correction of pre-1990 local magnitude M_L estimates, and secondly, through the conversion of M_L to M_W (Allen *et al.*, 2018b);
- increases in Gutenberg and Richter (1944) *b*-values, particularly in eastern Australia, owing to the M_L to M_W conversions, which decrease the rates of rare large earthquakes relative to more commonly observed moderate-magnitude earthquakes, and;
- the use of modern ground-motion attenuation models that predict lower ground-motions and faster attenuation of PGA and other spectral ordinates with increasing distance, and thus forecasting lower ground-motion hazard.

These new hazard estimates, coupled with changes to site-specific probability factors (k_p), which scale the 1/500 AEP hazard factors to different exceedance probabilities, have challenged notions of seismic hazard in Australia in terms of the recurrence times for damaging ground motions. In light of the new results, it is timely to review whether the ground-motion probability level prescribed by the National Construction Code for use in the *AS1170.4* for the design of ordinary-use structures is appropriate.

The *AS1170.4* was recently amended by Standards Australia's BD–06–11 Technical Subcommittee (Standards Australia, 2018). The amended *AS1170.4–2007 (R2018)* retains seismic demands developed in the early 1990's (McCue *et al.*, 1993) and introduces a minimum hazard design factor of $Z = 0.08$ g, partly due to concerns that the new 1/500 AEP hazard factors proposed in the NSHA18 would not assure life safety everywhere. Herein, we discuss opportunities to modernise the standard and allay these concerns, should the BD–06–11 Technical Subcommittee seek to update the earthquake loading code to reflect the latest evidence-based science for future standards.

2. ALTERNATE GROUND-MOTION EXCEEDANCE PROBABILITIES

The selection of the 10% exceedance probability in 50 years for the first United States (US) National Seismic Hazard Maps was originally a rather arbitrary decision and appeared to be a "reasonable" choice to ensure structures "remain operable" following large earthquakes (Algermissen and Perkins, 1976) . This probability level was generally viewed to be appropriate for the average recurrence of large damaging earthquakes in well-studied active tectonic regions such as California, and was also considered suitable for preservation of life. Given that this was best practice for the time, this exceedance probability was also adopted by the National Construction Code of Australia for use in the first edition of the *AS1170.4–1993* (Standards Australia, 1993).

However, in the late 1990s, concerns were raised by engineers and seismologists in the United States that the anchoring of design hazard values to 1/475 AEP would result in significant disparities in the seismic performance of ordinary-use structures across the country, with regions of low-to-moderate levels of seismicity being considerably more at risk to extreme ground-motion events (e.g., Nordenson and Bell, 2000; Federal Emergency Management Agency, 2004; Wilson *et al.*, 2008). These concerns led to the adoption of seismic design ground-motion demands for a 2% probability of exceedance in 50 years (a 1/2475 AEP) for the *International Building Code* developed in the US. This change in the probability of exceedance level was adopted in the *National Building Code of Canada (NBCC)* shortly thereafter (Heidebrecht, 2003). The 1/2475 AEP level was thought to more closely relate to the probability of structural collapse for regular structures (Bommer and Pinho, 2006). The adoption of this ground-motion exceedance probability leads to several advantages:

- In low-to-moderate seismicity regions, there is a larger difference between 1/475 and 1/2475 AEP ground-motions than in more tectonically active regions. Transitioning to lower exceedance probabilities in the national design provisions reduces the risk in low-to-moderate seismicity regions due to rare extreme ground motions (Leyendecker *et al.*, 2000);
- The rate of attenuation of earthquake ground-shaking is generally lower in stable continental regions (SCRs) like Australia (e.g., Frankel *et al.*, 1990; Bakun and McGarr, 2002). Thus, these provisions protect against rare events that have the potential to affect larger areas than in tectonically active regions;
- Structures in low-to-moderate seismicity regions would be designed with more comparable seismic resistance (combined strength and ductility) to structures in high seismicity regions;
- In many cases, effective seismic resistance for new construction can be achieved at minimal incremental cost (Nordenson and Bell, 2000).

Figure 1 shows a comparison of seismic hazard curves for selected Australian SCR sites as calculated in the NSHA18 relative to hazard curves from a recent assessment of seismic hazard for active tectonic sites in New Zealand (Horspool *et al.*, 2017; Elizabeth Abbott, pers. comm., 2018). By normalising the curves to an arbitrary exceedance probability (Fig. 1b), the difference in the rate of change of the hazard curves between the SCR and active tectonic regions is more clearly expressed. In particular, Figure 1b also demonstrates the difference in the k_p factor (or return period factor R_S or R_U in the *NZS 1170.5-2004*) between the two jurisdictions. The *AS1170.4* currently uses the same return period factors as in the *NZS 1170.5–2004* (Standards New Zealand, 2004), which may not be appropriate for SCR ground-motion probabilities.

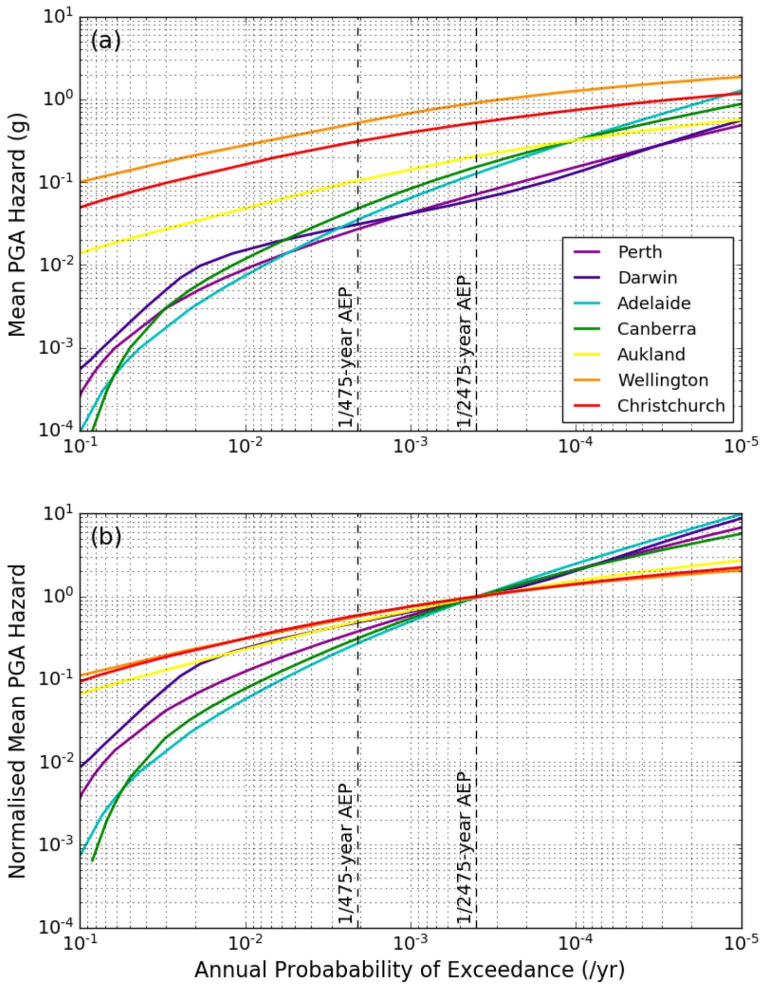

Figure 1: Top panel (a) show NSHA18 PGA hazard curves for representative Australian (Perth, Darwin, Adelaide and Canberra) and New Zealand (Auckland, Wellington and Christchurch) cities. Bottom panel (b) shows the same hazard curves normalised at the 1/2475 AEP to emphasise rate of change of hazard curves versus likelihood between Australian (stable continent) and New Zealand (active tectonic) localities.

Given the arguments presented for adopting lower probability of exceedance ground motions for future editions of the *AS1170.4*, several alternative seismic hazard values are provided in Table 1 for the Australian capital cities, in addition to Morwell, in Victoria's Latrobe Valley. This table compares and contrasts the evolution of 1/500 AEP PGA hazard for these sites, as well as providing alternative ground-motion metrics that could define future seismic demands. The different options include the:

1) 1/500 AEP seismic hazard factors (*Z*) in the *AS1170.4-2007* (McCue *et al.*, 1993);
2) 1/500 AEP hazard design factors[1] in the *AS1170.4–2007 (R2018)* that uses a minimum design PGA of 0.08 g (Standards Australia, 2018);
3) NSHM12 1/500 AEP hazard factors (Burbidge, 2012; Leonard *et al.*, 2013);
4) NSHA18 1/500 AEP hazard design factors on site class B_e;
5) NSHA18 1/2475 AEP hazard design factors on site class B_e, or (MCE ground motions), and;
6) NSHA18 risk-targeted maximum considered earthquake (MCE_R) ground motions (discussed below).

One key observation that can be taken from Table 1 is that the NSHA18 MCE ground motions, which consider hazard from rare earthquakes, are greater than those required for seismic design of ordinary-use structures in the new *AS1170.4-2007 (R2018)* for some key

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[1] The AS1170.4–2007 (R2018) now refers to the "hazard factor" as the "hazard design factor" because the parameter no longer reflects a uniform hazard probability.

localities (i.e., Adelaide, Melbourne and Canberra). Should lower exceedance probabilities be adopted for future Standards, structures being designed to seismic demands required by the current Standard could be vulnerable to MCE ground motions from extreme events.

In summary, there is a strong case to transition to lower AEPs (such as 1/2475 AEP) for future construction codes given:

- the significantly diminished 1/500 AEP seismic design values calculated through the NSHA18 relative to the *AS1170.4–2007* values (Allen *et al.*, 2018a);
- designing to 1/500 AEP NSHA18 values would leave new structures potentially vulnerable to earthquakes with longer return periods, which is societally unacceptable;
- structures designed to the hazard design factor prescribed in the *AS1170.4-2007 (R2018)* (including the minimum hazard design factor of Z = 0.08 g) at some localities could be vulnerable to MCE ground motions from extreme events;
- the generally long recurrence times of large Australian earthquakes, noting that known fault sources do not contribute significant hazard at the 1/500 AEP.

Table 1: Seismic design factors, equivalent to PGA (in units of gravity g) for selected localities as provided in different editions of the AS1170.4, in addition to alternate design factors from the NSHM13 and NSHA18.

Locality	AS1170.4-2007 1/500-YR AEP (*Z*)	AS1170.4-2018 Seismic Design Factor	NSHM12 1/500-YR AEP	NSHA18 1/500-YR AEP	NSHA18 1/2475-YR AEP (MCE)	NSHA18 MCE_R
Adelaide, SA	0.10	0.10	0.058	0.036	0.126	0.121
Brisbane, QLD	0.05	0.08	0.043	0.008	0.029	0.028
Canberra, ACT	0.08	0.08	0.060	0.050	0.152	0.137
Darwin, NT	0.09	0.09	0.037	0.032	0.061	0.061
Hobart, TAS	0.03	0.08	0.021	0.011	0.036	0.034
Melbourne, VIC	0.08	0.08	0.059	0.031	0.082	0.075
Perth, WA	0.09	0.09	0.042	0.028	0.071	0.066
Sydney, NSW	0.08	0.08	0.056	0.022	0.061	0.056
Morwell, VIC	0.11	0.11	0.105	0.082	0.274	0.257

3. RISK-TARGETED GROUND MOTIONS

An alternative method to arrive at seismic demands is through risk-targeted ground motions. Traditionally, seismic design codes rely on maps that provide a "constant hazard" assumption where the MCE ground motions used for design are those that assume a uniform exceedance probability (e.g., 2% probability of exceedance in 50 years) that is constant across a spatial region (Douglas *et al.*, 2013). However, Luco *et al.* (2007) suggested it would be more consistent with the final use of seismic design maps to adopt a "constant risk" assumption in which the design ground motions are defined to provide to a certain level of risk, for example, annual probability of collapse, $P[Collapse]$.

The *IBC* has specified so-called risk-targeted maximum considered earthquake (MCE_R) ground motions for designing new buildings and other structures since 2012. If employed for design purposes, MCE_R ground motions lead to the same nominal collapse probability, or a uniform level of risk, over the region of concern (Silva *et al.*, 2014).

Maps that indicate the spatial variability of ground-motion hazard for a uniform exceedance probability provide the basis for seismic design in most jurisdictions around the world. The decision to design structures to a uniform exceedance level sometimes assumes a structure would have the same collapse probability in any locality (Silva *et al.*, 2014). However, constant hazard ground-motion maps do not necessarily lead to uniform estimates of collapse probabilities due to differences in the rate of change of hazard at different exceedance probabilities (see Fig. 1) and uncertainties in collapse capacity (e.g., the acceleration threshold at the structure's fundamental period) for different structures. The collapse capacity for any given structure will be sensitive to several factors as discussed in published literature (Luco *et al.*, 2007; Allen *et al.*, 2015). Furthermore, the uniform hazard assumption can lead to inequitable risks of collapse over a given time period at different localities.

Risk-targeted MCE_R ground motions are based on the "risk integral." The integral takes into account the whole hazard curve across a range of exceedance probabilities rather than simply basing the design ground motions on a single spectral acceleration for a pre-defined return period (Douglas *et al.*, 2013). Consequently, the relative slopes of the hazard curves for each site can have a significant impact on the MCE_R ground motions. The key ingredients for risk-targeted calculations are:

- ground-motion hazard curves that cover a range of exceedance probabilities;
- fragility (or capacity) curves, and;
- a pre-defined uniform collapse risk objective, or the probability of collapse (e.g., 1% in 50 years).

Fragility curves express the conditional probability of failure at a ground motion level a, $P_f(a)$. These curves commonly adopt a lognormal distribution, defined by the mean μ and standard deviation β:

$$P_f(a) = \Phi\{[\ln(a) - \ln(\mu)]/\beta\} \tag{1}$$

where Φ is the standard normal cumulative distribution function. For the 2012 *IBC*, $\beta = 0.8$ was assumed; for the 2018 *IBC*, β was changed to 0.6. For the calculation of the risk integral, the mean of the fragility curve is adjusted such that the collapse risk objective is achieved for fragility having a 10% conditional probability of collapse at the MCE_R ground-motion (Luco *et al.*, 2007; American Society of Civil Engineers, 2010). That is, there is approximately a 10% chance that any structure (built to code) will experience partial or total collapse as a result of its MCE_R design ground-motion.

Via the risk integral, the annual probability of collapse $P[Collapse]$ is calculated by integrating the structural fragility and the hazard curve (i.e., the risk integrand; Fig. 2):

$$P[Collapse] = \int_0^\infty P[Sa(T) > a] \cdot \frac{dP_f(a)}{da}(a)\,\mathrm{d}a \tag{2}$$

where $P[Sa(T) > a]$ is the annual probability of ground-motion spectral accelerations Sa at any period T exceeding the ground motion level a.

The evaluation of this integral requires that the acceptable risk to society be quantified. This is not solely a scientific question and it should be established through the consultation of not only structural engineers, but also politicians, sociologists and other decision makers (e.g., Douglas *et al.*, 2013; Silva *et al.*, 2014). In the US, it was determined by structural engineers that a uniform national collapse risk of 1% in 50 years (about 2×10^{-4} per annum) is an acceptable threshold for use in the *IBC*. This study adopts the same risk objective as used in the *IBC* and makes no attempt to justify the rationale for this decision.

The calculation of the PGA (for example) MCE_R ground motions for Australian localities typically leads to an average hazard reduction factor (or “risk coefficient”) of 0.94 relative to MCE ground motions (Figure 2; Table 1). Risk coefficients of this order are consistent with the MCE_R ground motions in the U.S. design maps (Luco *et al.*, 2015). Nevertheless, it is worth noting that the use of the MCE_R approach using a target collapse risk of 1% in 50 years can provide more conservative (i.e. severe) design ground-motions than would be achieved by using the NSHA18 1/500-year hazard values (see Table 1). This is because the values are not pre-conditioned on the choice of a constant hazard objective, but rather a constant risk objective. Ultimately, the decision to adopt MCE_R ground motions for future editions of the *AS1170.4*, and at what risk level, should be based on broad community consultation.

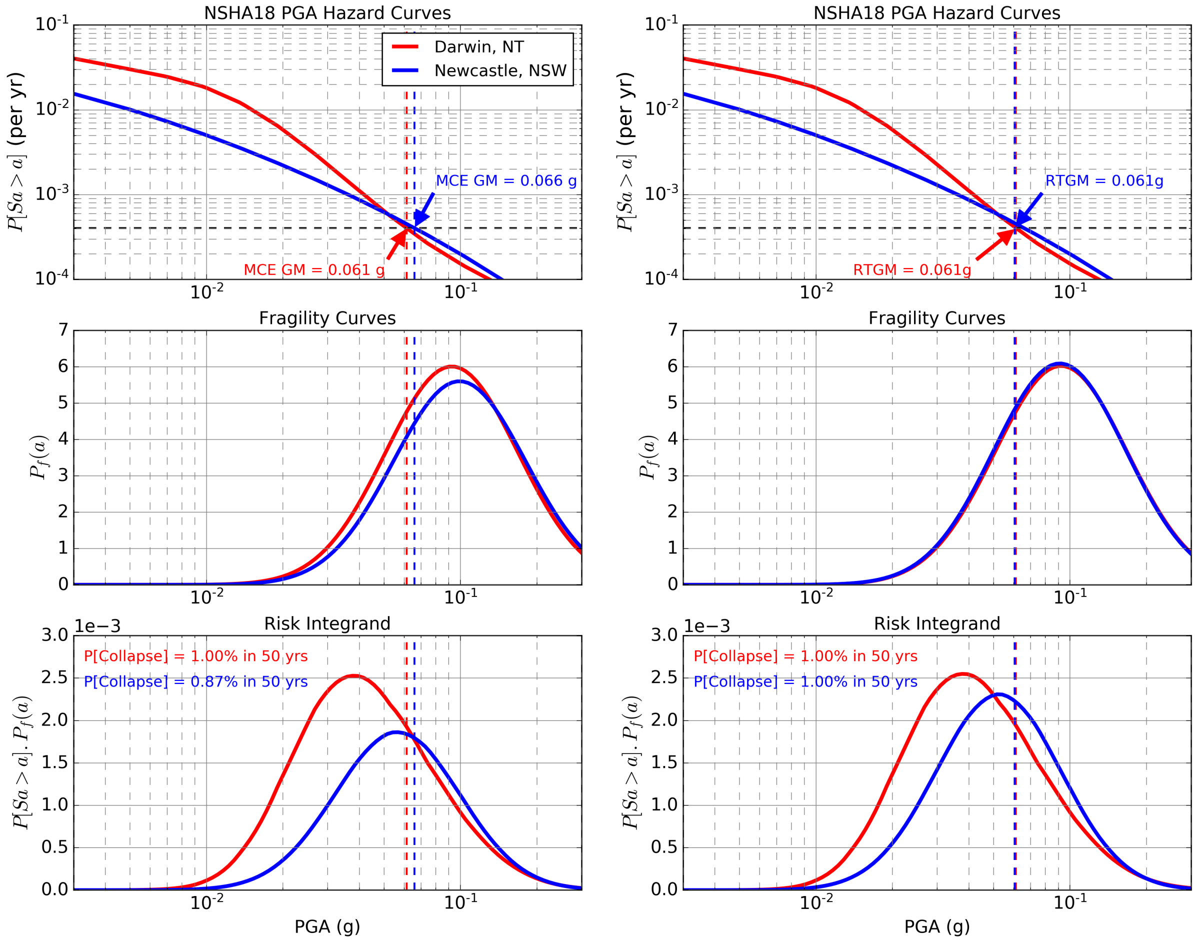

Figure 2: Examples of the risk integral calculation for two Australian localities with similar design ground motions for PGA at the 1/2475 AEP level: Darwin, NT and Newcastle, NSW. The example assesses the probability of collapse of a structure in 50 years in the respective localities. For the two localities, left panels show (top-to-bottom): the NSHA18 hazard curves; fragility curves assuming a 10% probability of collapse under the MCE ground motions, and; the resulting risk integrand over which the integral is calculated. Right panels are analogous to the left-hand panels, but use risk-targeted MCE_R *ground motions to achieve a 1.0% probability of collapse in 50 years. The city of Newcastle would experience a small drop in MCE ground-motion hazard through the application of the risk-targeted procedure, while the city of Darwin remains consistent with the 1/2475 AEP ground motions.*

4. SPECTRAL SHAPE

In the *AS1170.4*, the spectral shape factors translate the seismic hazard factor (anchored at PGA or *Sa*[0.0 s]) to an elastic design spectrum (e.g., Lam and Wilson, 2008). This spectrum can subsequently be used to determine the period-dependent design values at the fundamental period of interest. This general approach allows design provisions to be determined for structures with different fundamental periods in many seismic design codes around the world. However, it is noted that the definition of these spectral shape factors often provides a poor approximation for, in particular, long-period displacement spectra (Bommer and Pinho, 2006). While the shape of the elastic response spectrum can change with seismic site class (e.g., Standards Australia, 2007; Lam and Wilson, 2008), design codes usually do not make provision for changes in spectral shape owing to earthquakes occurring in different tectonic region types with different rupture styles (e.g., McVerry *et al.*, 2006), predominant earthquake magnitude, source-to-site distance (Bommer and Pinho, 2006) and even for different AEPs (Chandler *et al.*, 2001). As a consequence, the standard spectral shape factors will often not deliver uniform hazard/risk across all oscillation periods (McGuire, 1977). The *AS1170.4–2007* introduced some conservatism in displacement-based demands through the adoption of a constant displacement from a second corner period (T_2) in the design spectrum at 1.5 s (Lam and Wilson, 2008).

In Australia, it is recognised that the calculated uniform hazard spectrum (UHS) results in different spectral shapes for different locations across the continent (Leonard *et al.*, 2013; Allen *et al.*, 2018a). A case in point is the UHS for the city of Darwin (Fig. 3), calculated for 11 response spectral periods from $T = 0.0$ s (or PGA) to 4.0 s. The risk of strong earthquake ground motions from the smaller *local* earthquakes near Darwin is relatively low given the low seismicity rates from known nearby seismic sources. Additionally, smaller earthquakes at near-field distances will tend to contribute more ground-motion hazard at shorter oscillation periods. However, much of northern Australia is, at its nearest, approximately 400 km from an active tectonic boundary in the Banda Sea region. Frequent large earthquakes occur in this region and many of these are felt in Darwin (Hearn and Webb, 1984; McCue, 2013). These large distant earthquakes contribute significantly to long-periods in the UHS because the long period ground motions propagate more efficiently over large distances, particularly through old continental crust of the North Australian Craton (Fishwick *et al.*, 2005). Based on Figure 3, the use of standard spectral shapes to determine design ground motions for long-period structures in northern Australia (such as dams) may lead to the assignment of non-conservative design motions.

The *IBC* uses only response periods at 0.2 s (S_S) and 1.0 s (S_1) to define the design seismic spectrum. However, this approach is only appropriate if peak MCE_R response spectral acceleration occurs near 0.2 s and the peak response spectral velocity occurs near 1.0 s for the site of interest (Kircher, 2017). Consequently, defining the design spectrum based only on two spectral periods will be potentially non-conservative if these criteria are not met. For this reason, coupled with dependence of the UHS shape based on a site's location relative to different earthquake sources, the use of a full UHS over a wide range of spectral periods is recommended to determine design spectra for future editions of the *AS1170.4*. This approach is also being adopted by the US *IBC* (Petersen *et al.*, 2018).

5. SITE CLASS FACTORS

In the *AS1170.4–2007*, the site classification scheme is similar to that initially proposed by the National Earthquake Hazard Reduction Program (NEHRP; Building Seismic Safety Council, 2004). However, the *AS1170.4* uses a site's natural period (T_s) as an additional criterion for classification (Lam and Wilson, 2008). The site amplification factors, embedded within the spectral shape factors (Standards Australia, 2007), are based on average short- and mid-period amplifications (F_a and F_v, respectively) with respect to the reference ground condition (e.g., Borcherdt, 1994).

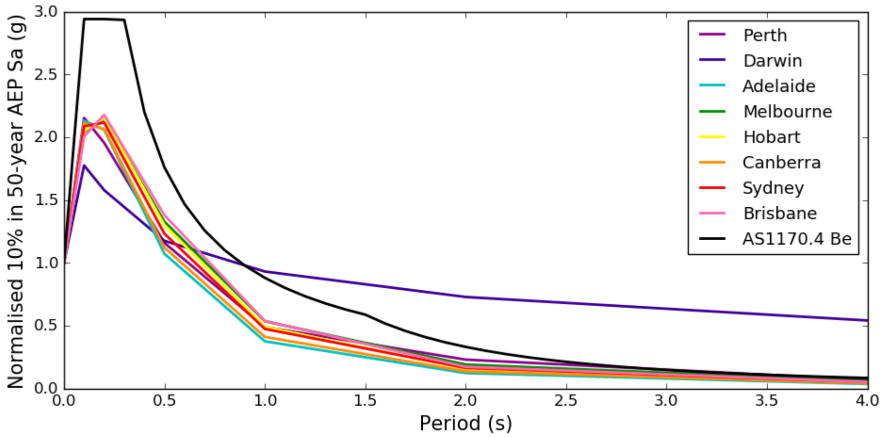

Figure 3: The 1/500 AEP UHS on Site Class B_e for several capital cities from the NSHA18, showing the distinctive long-period behaviour for Darwin due to plate-boundary earthquakes north of Australia. The respective AS1170.4–2007 spectral shape factors anchored to the respective Z values are also shown.

The understandings of ground-motion amplification have evolved considerably since the mid-1990s with most ground-motion models (GMMs) now explicitly considering period-dependent amplifications from the effects of near-surface geology and basin amplifications. The augmentation of empirical ground-motion datasets with more abundant data across more diverse site conditions has, to a large degree, facilitated these advancements (e.g., Seyhan and Stewart, 2014).

Figure 4 shows a comparison of the *AS1170.4–2007* amplification factors, anchored to Site Class B_e (Standards Australia, 2007), relative to modern period-dependent amplification factors developed through the Next Generation Attenuation (NGA) – West 2 project (Seyhan and Stewart, 2014). The mapping between *NEHRP* and *AS1170.4* site classes used in this study is shown in Table 2. The amplification factors used in the *AS1170.4–2007* are not dependent on ground-motion intensity and generally appear to be non-conservative for soft-soil sites and low ground motions (where linear amplification is expected) relative to modern amplification models. However, for stronger ground-motions, the *AS1170.4–2007* factors will tend to be conservative and predict stronger amplifications at soil sites owing to expected non-linear behaviour of modern amplification models for short periods, $T < 1.0$ s (Fig. 4). The actual ground-motion amplification will vary from site to site and will depend on the shear-wave velocity profile beneath the site. However, a comparison of the current F_a and F_v amplification factors shows that the modern models of Seyhan and Stewart (2014) demonstrate a much smoother transition between short and long-period amplification, as well as an improved consideration of non-linear shaking effects for strong-ground motions.

Whilst more empirical observations exist from which to base modern amplification factors, it is still very difficult for GMM developers to fully decouple wave-path effects from site effects (including effects from basins). Moreover, it has been recognised that amplification factors vary between GMMs, even those with the same reference site condition. The factors also vary between tectonic region types for which the GMMs were derived (Dowling *et al.*, 2016). Consequently, the use of a single F_a and F_v amplification model anchored to a particular reference site condition could be inconsistent with the GMMs used in modern probabilistic seismic hazard assessments.

Given this likely discontinuity between amplification factors developed for GMMs and the reference site condition in building codes, the *NBCC* is currently calculating seismic design values directly on primary (e.g. A-E) and intermediate (A/B-D/E) seismic site classes (Allen *et al.*, 2019). This approach is also being adopted by the US *IBC* (Petersen *et al.*, 2018). Thus, it is suggested that, for future editions of the *AS1170.4,* seismic hazard be calculated directly for a given site class using amplification models provided by the developers of each of the GMMs used in the ground-motion logic tree.

The adoption of site-class-specific hazard maps would fundamentally simplify the way end users would determine seismic design values for a given location and site class, but would have other technical advantages. Firstly, with the advances in modelling ground-motion attenuation, GMMs now apply V_{S30} as a predictive variable, meaning that ground-motions for a given magnitude, distance and site class can now be directly computed within a GMMs functional form. Secondly, the approach considers the epistemic variability among different GMM amplification models, allowing modellers to better quantify the uncertainty of the design ground motions for each site class. Another advantage of directly computing seismic hazard for a predefined site class is that non-linear ground-motion effects are implicitly considered in the probabilistic hazard framework.

Table 2: Mapping of AS1170.4-2007 and NEHRP Site Class used in this study

AS1170.4-2007 Site Class	Modified NEHRP Site Class	Reference V_{S30} (m/s)
A_e	B	1100
B_e	B/C	760
C_e	C	464
D_e	D	270
E_e	E	150

6. CONCLUSIONS

This contribution has explored several opportunities to modernise how seismic demands are considered in Australian building design for future editions of the *AS1170.4*. Given the significant reduction of the NSHA18 seismic hazard factors across Australia relative to the existing *AS1170.4–2007* factors, there is a strong case for future construction codes to adopt lower-probability ground-motion exceedances, such as 1/2475 AEP. This would ensure an appropriate level of seismic safety for new construction across Australia and its territories. In line with the *AS1170.4–2007* amendment adopted in 2018, minimum base shear design values could apply for the remaining low-hazard jurisdictions (e.g., Humar, 2015).

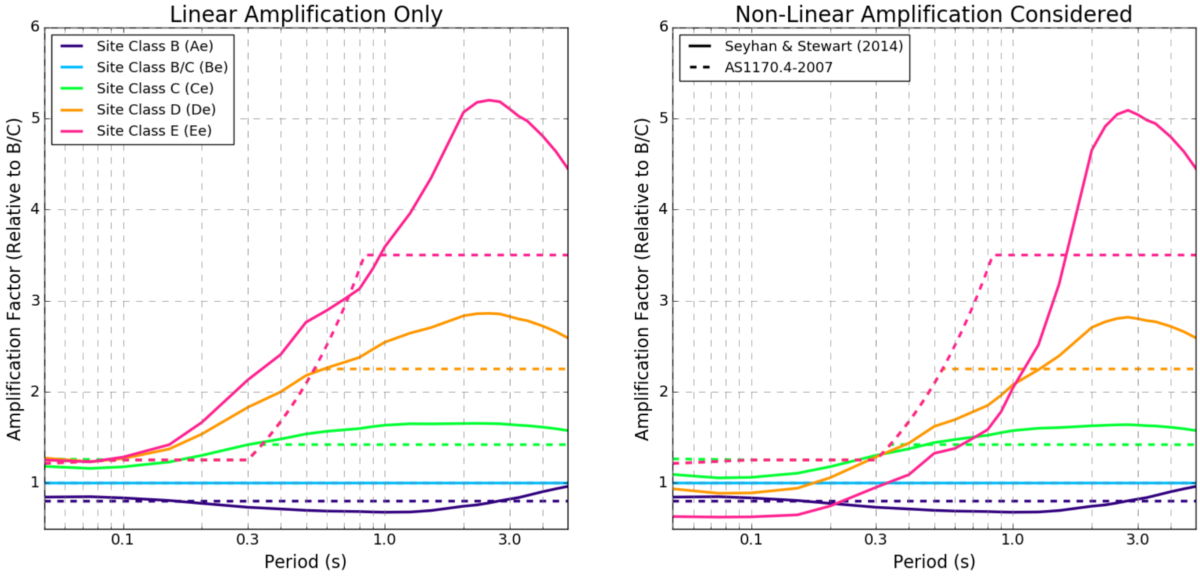

Figure 4: A comparison of the AS1170.4 amplification factors, anchored to an AS1170.4 Site Class B_e (Standards Australia, 2007; dashed lines), relative to modern period-dependent amplification factors developed through the NGA – West 2 project (Seyhan and Stewart, 2014; soid lines). The left panel demonstrates the Seyhan and Stewart (2014) using a PGA_{ref} of 0.1 g (i.e. linear amplification), while the right plot shows amplification with non-linear effects considered using a PGA_{ref} of 0.4 g. The AS1170.4 factors are not dependent on ground-motion intensity.

While the NSHA18 estimates of hazard have generally decreased on the national scale at the 1/500 AEP, there are some localities where the *AS1170.4–2007 (R2018)* may underestimate earthquake risk relative to the NSHA18. Should future editions of the *AS1170.4* transition to lower ground-motion exceedance probabilities (as used in the US and Canada), the design levels currently used for many cities may not provide adequate seismic protection for possible MCE ground-motions.

Alternatively, rather than modifying the ground-motion exceedance probabilities using a "constant hazard" assumption, the *AS1170.4* could move towards ground-motion design values that target a uniform collapse probability. Benefits of using the so-called risk-targeted MCE_R ground motions include the explicit consideration of whole hazard curves across a range of exceedance probabilities, quantification of collapse prevention objectives and mainstreaming the consideration of collapse risk into earthquake engineering practice.

Finally, the combined adoption of site specific UHS and the direct calculation of hazard at varying seismic site classes using the full suite of GMM amplification factors would replace the need to have a separate spectral shape factors and would sample the epistemic uncertainty associated with ground-motion amplification modelling more comprehensively. Consequently, this will enable end users to simply define their location and site class (or V_{S30}) to return the seismic design values of interest. Overall, this would be a significant advance in developing seismic design values for future editions of the *AS1170.4*, and it would simplify how end users interface with seismic demand parameters in the code.

The opportunities to update earthquake loading provisions presented herein use modern approaches and models and follow global best practices and evidence-based science for determining seismic demands at a given site. Consequently, a robust discussion among Standard Australia's Technical Subcommittee, hazard practitioners and end users is suggested to consider alternative hazard and/or risk objectives for future editions of the *AS1170.4*.

7. AKNOWLEDGMENTS

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8. REFERENCES

Algermissen, S. T., and Perkins, D. M. (1976). A probabilistic estimate of maximum accelerations in rock in the contiguous United States, *US Geological Survey Open-File Report 76-416*.

Allen, T., Griffin, J., Leonard, M., Clark, D., and Ghasemi, H. (2018a). The 2018 National Seismic Hazard Assessment for Australia: model overview, *Geoscience Australia Record 2018/27*, Canberra, doi: 10.11636/Record.2018.027.

Allen, T., Kolaj, M., Mayfield, R., and Adams, J. (2019). A new ground-motion and site-class modelling framework for the 6th Generation Seismic Hazard Model of Canada, *12th Canadian Conference on Earthquake Engineering*, Quebec City, QC, pp (abstract submitted).

Allen, T. I., Leonard, M., Ghasemi, H., and Gibson, G. (2018b). The 2018 National Seismic Hazard Assessment for Australia: earthquake epicentre catalogue, *Geoscience Australia Record 2018/30*, Canberra, doi: 10.11636/Record.2018.030.

Allen, T. I., Luco, N., and Halchuk, S. (2015). Exploring risk-targeted ground motions for the National Building Code of Canada, *11th Canadian Conference on Earthquake Engineering*, Victoria, Canada, pp Paper 93781.

American Society of Civil Engineers (2010). Minimum design loads for buildings and other structures, *American Society of Civil Engineers ASCE/SEI 7–10*, 209 pp.

Bakun, W. H., and McGarr, A. (2002). Differences in attenuation among the stable continental regions, *Geophys. Res. Lett.* Vol 29, No 23, pp 2121, doi:10.1029/2002GL015457.

Bommer, J. J., and Pinho, R. (2006). Adapting earthquake actions in Eurocode 8 for performance-based seismic design, *Earthq. Eng. Struct. D.* Vol 35, pp 39-55, doi: 10.1002/eqe.530.

Borcherdt, R. D. (1994). Estimates of site-dependent response spectra for design (methodology and justification), *Earthq. Spectra* Vol 10, No 4, pp 617-653.

Building Seismic Safety Council (2004). NEHRP Recommended Provisions for seismic regulations for new buildings and other structures, 2003 edition, *Federal Emergency Management Agency 450*, Washington, D.C., 338 pp.

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

Chandler, A. M., Lam, N. T. K., Wilson, J. L., and Hutchinson, G. L. (2001). Response spectrum modelling for regions lacking earthquake records, *Electron. J. Struct. Eng.* Vol 1, No 1, pp 2-14, http://www.ejse.org/Archives/Fulltext/200101/05/20010105.htm.

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, Victoria

Douglas, J., Ulrich, T., and Negulescu, C. (2013). Risk-targeted seismic design maps for mainland France, *Nat. Hazards* Vol 65, pp 1999–2013, doi: 10.1007/s11069-012-0460-6.

Dowling, J., Finn, W. D. L., Ventura, C. E., Bebamzadeh, A., and Fairhurst, M. (2016). An alternative approach to site factors for NBCC 2015, *Can. J. Civ. Eng.* Vol 43, pp 1017–1024, doi: 10.1139/cjce-2015-05.

Federal Emergency Management Agency (2004). NEHRP Recommended Provisions for seismic regulations for new buildings and other structures, Part 2: Commentary, *Federal Emergency Management Agency 450-2 / 2003 Edition*, Washington, D.C., 385 pp.

Fishwick, S., Kennett, B. L. N., and Reading, A. M. (2005). Contrasts in lithospheric structure within the Australian craton—insights from surface wave tomography, *Earth Planet. Sci. Lett.* Vol 231, pp 163– 176, doi: 10.1016/j.epsl.2005.01.009.

Frankel, A., McGarr, A., Bicknell, J., Mori, J., Seeber, L., and Cranswick, E. (1990). Attenuation of high-frequency shear waves in the crust: measurements from New York State, South Africa, and southern California, *J. Geophys. Res.* Vol 95, No B11, pp 17,441-17,457.

Griffin, J., Gerstenberger, M., Allen, T., Clark, D., Cummins, P., Cuthbertson, R., Dimas, V.-A., Gibson, G., Ghasemi, H., Hoult, R., Lam, N., Leonard, M., Mote, T., Quigley, M., Somerville, P., Sinadinovski, C., Stirling, M., and Venkatesan, S. (2018). Expert elicitation of model parameters for the 2018 National Seismic Hazard Assessment: Summary of workshop, methodology and outcomes, *Geoscience Australia Record 2018/28*, Canberra, doi: 10.11636/Record.2018.028.

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

Hearn, S. J., and Webb, J. P. (1984). Continental-scale felt effects of the large Banda Sea earthquake of 4 November 1963, *Bull. Seism. Soc. Am.* Vol 74, No 1, pp 349-351.

Heidebrecht, A. C. (2003). Overview of seismic provisions of the proposed 2005 edition of the National Building Code of Canada, *Can. J. Civ. Eng.* Vol 30, No 2, pp 241-254, doi: 10.1139/l02-068.

Horspool, N., Abbott, E. R., Canessa, S., Van Houtte, C., Gerstenberger, M., Huso, R., and King, A. (2017). Challenges and opportunities in developing a national seismic hazard and risk model with OpenQuake for New Zealand, *16th World Conference on Earthquake Engineering*, Santiago, Chile, pp Paper Number 2987.

Humar, J. (2015). Background to some of the seismic design provisions of the 2015 National Building Code of Canada, *Can. J. Civ. Eng.* Vol 42, pp 940–952, doi: 10.1139/cjce-2014-0385.

Kircher, C. A. (2017). New site-specific ground motion requirements of ASCE 7-16, *2017 SEAOC Convention*, San Diego, CA

Lam, N. T. K., and Wilson, J. L. (2008). The new response spectrum model for Australia, Vol Special Issue: Earthquake Engineering in the Low and Moderate Seismic Regions of Southeast Asia and Australia, pp 6-24

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.

Leyendecker, E. V., Hunt, R. J., Frankel, A. D., and Rukstales, K. S. (2000). Development of maximum considered earthquake ground motion maps, *Earthq. Spectra* Vol 16, No 1, pp 21-40, doi: 10.1193/1.1586081.

Luco, N., Bachman, R. E., Crouse, C. B., Harris, J. R., Hooper, J. D., Kircher, C. A., Caldwell, P. J., and Rukstales, K. S. (2015). Updates to building-code maps for the 2015 NEHRP Recommended Seismic Provisions, *Earthq. Spectra* Vol 31, No S1, pp S245-S271, doi: 10.1193/042015EQS058M.

Luco, N., Ellingwood, B. R., Hamburger, R. O., Hooper, J. D., Kimball, J. K., and Kircher, C. A. (2007). Risk-targeted versus current seismic design maps for the conterminous United States, *SEAOC 2007*

McCue, K. (2013). Darwin Northern Territory – an earthquake hazard, *Australian Earthquake Engineering Society 2013 Conference*, Hobart, Tasmania

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

McGuire, R. K. (1977). Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response, *Earthq. Eng. Struct. D.* Vol 5, No 3, pp 211–234, doi: 10.1002/eqe.4290050302.

McVerry, G. H., Zhao, J. X., Abrahamson, N. A., and Somerville, P. G. (2006). New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone attenuation relations for New Zealand earthquakes, *Bull. N.Z. Nat. Soc. Earthq. Eng.* Vol 39, No 1, pp 1-58.

Nordenson, G. J. P., and Bell, G. R. (2000). Seismic design requirements for regions of moderate seismicity, *Earthq. Spectra* Vol 16, No 1, pp 205-225, doi: 10.1193/1.1586091.

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., Shumway, A. M., Powers, P. M., Mueller, C. S., Frankel, A. D., Rezaeian, S., Moschetti, M. P., McNamara, D. M., Thompson, E. M., Boyd, O. S., Luco, N., Hoover, S. H., and Rukstales, K. S. (2018). Preliminary 2018 National Seismic Hazard Model for the conterminous United States, *Proceedings of the 11th National Conference in Earthquake Engineering*, Los Angeles, CA, Earthquake Engineering Research Institute

Seyhan, E., and Stewart, J. P. (2014). Semi-empirical nonlinear site amplification from NGA-West 2 data and simulations, *Earthq. Spectra* Vol 30, No 3, pp 1241–1256, doi: 10.1193/063013EQS181M.

Silva, V., Crowley, H., and Bazzurro, P. (2014). Risk-targeted hazard maps for Europe, *Second European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey

Standards Australia (1993). Structural design actions, part 4: Earthquake actions in Australia, *Standards Australia AS 1170.4–1993*, Homebush, NSW.

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

Standards Australia (2018). Structural design actions, part 4: Earthquake actions in Australia, *Standards Australia AS 1170.4–2007 (R2018)*, Sydney, NSW.

Standards New Zealand (2004). Structural design actions, part 5: Earthquake actions – New Zealand, *Standards New Zealand NZS 1170.5:2004*, Wellington, NZ, 76 pp.

Wilson, J. L., Lam, N. T. K., and Pham, L. (2008). Development of the New Australian Earthquake Loading Standard, *EJSE Special Issue* Vol Earthquake Engineering in the low and moderate seismic regions of Southeast Asia and Australia (2008), pp 25-31.