ABSTRACT: We have developed an earthquake hazard model for Australia specifically for use in loss estimation, which includes industry and insured monetary losses of industrial, commercial, and residential structures caused by shaking and fire-following. The core of our model is the 2012 hazard data developed by Geoscience Australia (GA) to update the Australia national seismic hazard maps and earthquake loading standards. With cooperation from GA personnel, our model was developed simultaneously to theirs and served as independent verification. For purposes of loss estimation, our model incorporates several modifications to the GA model, including: (1) giant (M ≥ 9) earthquakes on the Sunda and New Guinea subduction zones that can contribute to the hazard at longer structural periods, (2) a global set of ground motion prediction equations (GMPEs) in addition to those used by GA to incorporate additional epistemic uncertainty, (3) firm soil instead of rock as the reference site condition in order to reduce uncertainty (i.e., GMPEs are better constrained for soil sites and the majority of property is located on soil, mitigating the need for large site adjustments), and (4) removal of conservatisms introduced in the GA maps for engineering design, although GA also provided a similar alternative model in their final report. We also developed an Australian NEHRP site classification map in order to incorporate site effects in the hazard estimates and we used NEHRP nonlinear site factors to modify the estimated ground motions on soil to represent the local site condition at a property site.

1 INTRODUCTION

Earthquake hazard models for loss estimation and risk management have an inherently different purpose than many seismic hazard models available worldwide, which are constructed typically for the purpose of engineering seismic design requirements in national building codes. The goal of life safety stipulated in building codes often influences the development of the earthquake hazard model on which the engineering design criteria are based, leading to conservative estimates of the ground motion hazard (e.g. Thenhaus et al. 2012). Conservatism, whether intentional or not, is appropriate if the purpose of the hazard model is to protect life safety because of the large uncertainty in the hazard estimate itself, the uncertainty in developing site-specific ground motion estimates from a generalized national hazard map, and the large variety of structure types, construction practices, and building materials to which a building code is intended to apply. On the other hand, the fundamental purpose of earthquake economic loss estimation is to determine an unbiased estimate of damage and loss to the built environment given the expected level of earthquake shaking. For that reason, conservatism in hazard models intended for building codes needs to be identified and removed for use in a loss model.

Geoscience Australia (GA) recently published a new earthquake hazard model for Australia for the purpose of updating building seismic design standards nationwide. This effort was the culmination of three years of intensive research (Burbidge 2012). Our earthquake hazard model for economic loss estimation in Australia was developed during 2012 simultaneously to the GA model and with the full cooperation of GA personnel. We reviewed GA’s hazard model as it was being developed and selected and modified specific elements of this model to better align with our explicit purpose of developing a hazard model for economic loss estimation in Australia. Exchanges of information and professional opinion benefitted the final outcome of both seismic hazard models (Burbidge 2012).
2 SUMMARY OF THE 2012 GA SEISMIC HAZARD MODEL

GA produced alternative formulations of their seismic hazard models in order to evaluate ground motion results relative to engineering practice and to capture modeling (“epistemic”) uncertainty. Accordingly, GA developed three different seismic source models to characterize the Australian ground motion hazard nationwide: a Background model, a Regional model, and a “Hotspot” model. Each source model is independent and mutually exclusive. Each of these source models produces substantially different ground motion hazard distributions throughout Australia. The final ground motion map recommended by Burbidge (2012) for use in the Australian building standards is a composite (robust) map of probabilistic ground motions for a fixed exceedance probability in which the ground motion at a specific location on a 0.1º grid is defined as the maximum ground motion from the Background and Regional models, unless the Hotspot model produces higher ground motion, in which case this maximum is averaged with the ground motion from the Hotspot model (Burbidge 2012). The final results were then smoothed geographically. While this methodology produces a conservative estimate of expected ground motion for seismic design purposes, it does not reflect an unbiased uniform ground motion exceedance probability as required for loss estimation. It should be noted that based on our suggestion, GA did produce an unbiased hazard model that was published in the final report (Burbidge 2012). The three independent GA source models are summarized in the following sections.

2.1 Background Source Model

Earthquake occurrence in this model is considered to be regionally uniform throughout two large (i.e., cratonic and non-cratonic) continental (onshore) super regions and a third extended margin (offshore) region of Australia (Clark 2011). This model has no expectation that future earthquakes will occur in regionally distributed spatial clusters. Resulting ground motion hazard is smooth and uniformly low on a nationwide basis. Burbidge (2012) suggests such a model could serve as a conservative background “floor” hazard level for building-code purposes in areas of low seismicity, similar to the approach used by the Geological Survey of Canada in the 2012 update of the Canada national seismic hazard map (Thenhaus et al. 2012). All earthquakes in the GA declustered (mainshock) catalogue were used to characterize the occurrence of earthquakes in each of the Background zones.

2.2 Regional Source Model

Earthquake occurrence in this model is considered to occur uniformly within spatial clusters defined by the historical distribution of earthquakes nationwide. Resulting ground motion hazard varies regionally, but is generally constant within each source zone that encompasses a cluster. Burbidge (2012) indicates that this Regional model provides a more accurate representation of the observed distribution of earthquakes than the Background model. All earthquakes in the GA declustered catalogue that occurred within the boundary of a Regional source zone were used to characterize the occurrence of earthquakes in that zone.

2.3 “Hotspot” Source Model

Earthquake occurrence in this model is considered to occur uniformly in relatively small localized zones of relatively intense seismicity. The assumption is that this activity will continue uninterrupted into the future, or at least as long as buildings designed to this hazard will exist. The resulting distribution of seismic hazard is spotty and highly variable with the modeled hot spots showing extremely high ground motion spikes relative to the intervening broad areas of relatively low hazard. All earthquakes, including aftershocks and swarms, were used to characterize earthquake occurrence in these zones. Burbidge (2012) indicates that the modeled hot spots are mostly transient variations of seismicity across the continent that will likely change on a time scale of decades. Consequently, the ground motion hazard portrayed in this model is not stable over moderate-to-long periods of time. Furthermore, the time-dependent nature of aftershock and swarm sequences violates the basic principles underpinning probabilistic seismic hazard analysis (i.e. that earthquakes are independent).

3 REGIONAL HAZARD MODEL FOR LOSS ESTIMATION

For the purpose of obtaining unbiased loss estimates, we removed the inherent conservatism in the GA
source model used to update the Australian seismic loading standards. This was required because our model was developed prior to GA developing an alternative unbiased model. We desired an earthquake hazard model that reflects a uniform probability of ground motion exceedance nationwide, but that also incorporated the current state-of-the-art knowledge on the seismotectonics and seismicity of Australia and Stable Continental Regions (SCRs) worldwide. The GA Background and Hotspot models were judged the least relevant in this context. Research has shown that earthquakes in SCRs such as Australia tend to cluster in areas of persistent long-term earthquake activity (Kafka and Levin 2000; Kafka and Ebel 2011). However, paleoseismic evidence on individual faults in cratonic western Australia also suggests that isolated occurrences of large ($M \geq 6.0$) surface-rupturing earthquakes have average recurrence frequencies on the order of 10,000 to 100,000 years, but unevenly spaced in time (e.g. Crone et al. 2003), making their relevance for the estimation of near-future earthquake hazard relatively insignificant.

Considering the above discussion and observations, we combined the GA Regional source model with a modified background model that eliminated the double-counting of earthquake frequencies inherent in the original GA Regional and Background source models. Furthermore, the Hotspot source model was not used at all due to its conservatism and transient nature. Figure 1 illustrates our seismic source model in comparison to the GA mainshock (declustered) catalogue for Australia and surrounding regions. Minor changes were made to some of the GA Regional source zones to make them spatially contiguous. These minor changes simplified the definition of mutually exclusive background zones that were located around and between the Regional source zones. Seismic sources located north of Australia in Indonesia and Papua New Guinea (PNG) are described in the following section.

**Figure 1: Seismic Source Model of Australia.**

### 4 DISTANT LARGE-EARTHQUAKE SOURCE MODEL

Originally the GA hazard model did not include distant offshore sources that could potentially cause damage in northern Australia (Leonard et al. 2011; McPherson et al. 2011). Based on our suggestion, GA confirmed that large earthquakes from distant sources in Indonesia and PNG could impact intermediate-period ground motion hazard at sites in northern Australia and included several offshore source zones in these areas in the final model (Burbidge 2012). However, GA did not include several seismic sources that we also considered to be important. We included additional sources of great and giant earthquakes from distant tectonic plate boundary zones in Indonesia and PNG. The infrequent great and giant earthquakes on these distant subduction zones were determined to be capable of causing at least some financial losses in extreme northern Australia, depending on the construction type. Figure 2 illustrates our seismic source model for these distant seismic sources.

The minimum modelled magnitude for distant subduction sources was taken to be $M_{7.0}$, because only the largest earthquakes in these sources are capable of generating sufficient mid-period ground motion to impact northern Australia hazard. Based on the recent past experience of giant earthquakes in Tohoku-oki, Japan ($M_{9.0}$) in 2011 and the Andaman Islands, Indonesia ($M_{9.2}$) in 2004, the subduction models allow for the possible occurrence of giant $M_{9.0}$ earthquakes along the New Britain Trench and $M_{9.3}$ earthquakes along the Sunda megathrust zone (Fig. 2).
Figure 2: Distant Large Earthquake Seismic Sources in Indonesia and PNG.

5 RECURRENCE FREQUENCY MODEL

For every GA Regional source zone that we modified, GA earthquake frequencies were modified on an area-normalized basis in order to maintain the same density of earthquake frequency. This method is consistent with scientific thinking on SCR hazard, because the GA Regional model encompasses the long-term persistent zones of historical earthquake activity observed throughout Australia. The use of a modified background model appropriately weights the isolated locations of historically large earthquakes that have occurred in the background regions with respect to the very long recurrence intervals on individual faults noted by Clark et al. (2012). In the final model (Burbidge 2012), GA noted our concern about the conservatism of its robust building-code hazard model and provided an alternative unbiased Background model based on our approach.

For the background sources that lie around and between the Regional source zones, and for extended margin sources in the offshore and near-shore areas of Australia, earthquake frequencies were established independently of the frequencies in the original GA Background model in order to avoid double-counting seismicity. Our background frequencies were derived from the GA declustered earthquake catalogue after removing those events that contributed to the GA Regional source zones. These earthquakes were fit to a Gutenberg-Richter (exponential) recurrence relation using the method of least squares. The GA declustered earthquake catalogue accounts for the complete reporting times for earthquakes of different magnitudes as determined and reported by GA (Burbidge 2012). Recurrence frequencies for the distant sources of great and giant earthquakes in Indonesia and PNG were determined using the same methodology that we used to derive the background and extended margin recurrence frequencies.

6 GROUND MOTION PREDICTION EQUATIONS

We used a combination of the ground motion prediction equations (GMPEs) adopted by GA (Burbidge 2012) and a set of GMPEs we use globally in order to incorporate additional epistemic uncertainty in our seismic hazard and loss model. Each set of GMPEs was assigned equal weight in our model. We also note that the GMPEs implemented by GA tend to overestimate ground motions for moderate earthquakes at some spectral periods. In order to minimize this embedded conservatism and incorporate additional epistemic uncertainty appropriate for loss modelling, we supplemented the GA GMPEs with GMPEs selected on the basis of Next Generation Attenuation (NGA) and NGA-West2 research (Power et al. 2008; Bozorgnia et al. 2012) and guidance provided by the ground motion component of the Global Earthquake Model (GEM) program (Di Alessandro et al. 2012, Stewart et al. 2012). Similar to the GA model, our model uses a different set of GMPEs for cratonic western Australia than it does for the younger and more deformed non-cratonic eastern Australia and the extensional margins.

Each model was assigned a weight of 12.5% except for Toro (2002), which was given 25% weight. The alternative set of GMPEs selected for use in non-cratonic eastern Australia include Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) with equal weight.

We used two sets of GMPEs for earthquakes occurring on the distant seismic sources in southern Indonesia and Papua New Guinea. The same three NGA models used in non-cratonic eastern Australia were used for shallow crustal earthquakes on these seismic sources. The three subduction zone interface GMPEs of Youngs et al. (1997), Atkinson and Boore (2003, 2008), and Zhao et al. (2006), weighted 25%, 25% and 50%, respectively, were used for earthquakes occurring on the Sunda megathrust interface located south of Java and on the New Britain Trench megathrust interface. The two subduction intraslab GMPEs of Youngs et al. (1997) and Atkinson and Boore (2003, 2008), weighted equally, were used for intermediate-depth (Wadati-Benioff) subduction zone earthquakes occurring within the Banda Arc of western Indonesia and in Papua New Guinea.

7 SITE ADJUSTMENT FACTORS

Although it is common practice to evaluate GMPEs for a rock reference site condition when producing national seismic hazard maps (e.g. Petersen et al. 2008; Burbidge 2012), this will result in increased uncertainty when estimating ground motion on softer sites, where the majority of properties are located. This increased uncertainty is caused by the fact that GMPEs are not as well constrained for rock site conditions due to a lack of strong motion recordings on these sites and the fact that there is additional uncertainty associated with the site adjustment factors that are required to adjust the rock motion to softer site conditions. For this reason, we adopted a Soil Based Attenuation (SBA) approach in which we use a reference site condition consistent with NEHRP Site Class D ($V_{30} = 270$ m/sec) as defined by the Building Seismic Safety Council (BSSC, 2009). $V_{30}$ is the time-averaged shear-wave velocity in the top 30 m of a site. The BSSC describes this site class as firm soil. All of the empirical GMPEs were directly evaluated for this reference site condition. Those that were developed from stochastic or kinematic models were adjusted from NEHRP B/C site conditions (Petersen et al. 2008) to this reference site condition using the site adjustment factors in BSSC (2009).

Site adjustment factors are used to convert the ground motion on the SBA reference site condition to the local site condition at a property location according to its NEHRP Site Class (BSSC, 2009). To be consistent with our vulnerability (damage) models, the ground motion parameter used for estimating the hazard is the mid-period response spectral acceleration (SA). For the extended margins and non-cratonic eastern Australia, site adjustment factors were taken directly from the mid-period site factors given in BSSC (2009). For cratonic western Australia, a slightly revised version of these site factors was used based on a site-response study for the central and eastern United States (CEUS) by Hwang et al. (1997). CEUS is considered to be a tectonic analogue to western Australia.

The site adjustment factors given in BSSC (2009) and Hwang et al. (1997) were renormalized from the reference NEHRP B Site Class used by these authors to our SBA reference site condition. This allowed the application of the site factors directly to the SA values estimated from the SBA-based GMPEs. The renormalized site factors reflect the amplitude-dependent (nonlinear site response) characteristics of the original NEHRP site factors. Although the nonlinearity only applies to the softer (lower $V_{30}$) site conditions, normalizing to NEHRP D site conditions transfers these nonlinear effects and any additional epistemic uncertainty to the estimation of the harder site conditions. It was also necessary to adjust the input ground motion amplitude listed at the top of the NEHRP table from NEHRP B to NEHRP D site conditions using these same renormalized site factors.

8 SITE CONDITIONS MAPS

The selection of an appropriate site adjustment factor is based on the site classification, or local site conditions, at the site of interest. We created a digital map of the NEHRP Site Class at any given location in Australia for the purpose of applying site adjustment factors. The source data for these site conditions maps are geologic maps with resolutions that vary according to population density. There is no digital site data for Australia that are publically available in electronic format (John Schneider, personal communication). However, there is a high-resolution analogue version of an Australian
national site conditions map, or what GA refers to as a regolith map, that was developed by McPherson and Hall (2007). These authors used geomorphic, geologic, site profile, and shear-wave velocity data throughout Australia to develop a map of NEHRP Site Classes at two different map scales.

For the more rural parts of Australia, McPherson and Hall (2007) used a map scale of 1:2,500,000 to develop their NEHRP site conditions map. In the metropolitan areas, a higher-resolution scale of at least 1:100,000 or larger was used. We used the references and the high-resolution analogue Australian national regolith map given in McPherson and Hall (2007) to produce a high-resolution digital (GIS) version of the Australian NEHRP Site Class map (Fig. 3). The larger-scale metropolitan site conditions maps are not shown in this brief summary report. These maps replicate the high-resolution analogue map given in McPherson and Hall (2007) to within a few tens of meters.

Figure 3: High-Resolution NEHRP Soil Classification Map for Australia.

9 HAZARD RESULTS

Figure 4 shows a mid-period SA 2500-year return-period (2% probability of exceedance in 50 years) ground motion hazard map generated using our Australia earthquake model for SBA (firm soil) reference site conditions. Seismic hazard curves for Adelaide, Brisbane, Canberra, Hobart, Melbourne, Perth, and Sydney are shown in Figure 5. SA values are given in fractions of gravity (g). Melbourne is seen to exhibit the highest ground motion hazard, approaching 0.1 g for a return period of 1000 years, followed closely by Canberra, Perth and Sydney. The hazard for Adelaide and Brisbane is around 0.01 g less than these higher-hazard cities. The hazard for Hobart is considerably lower than the other cities and is representative of other low-hazard regions in Australia.

Figure 4: 2500-Year Seismic Hazard Map of Mid-Period SA in Australia for Firm-Soil Site Conditions.
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