Earthquake Hazard Model for Loss Estimation in Australia Using the 2012 GA Hazard Data

P.C. Thenhaus[1], K.W. Campbell[2], D.F. Smith[3] and M.M. Khater[4]

1. Senior Geologist, Model Development Group, EQECAT, Inc., 475 14th Street, Suite 550, Oakland, CA 94612, USA. Email: pthenhaus@eqecat.com

2. Vice President, Model Development Group, EQECAT, Inc., 475 14th Street, Suite 550, Oakland, CA 94612, USA. Email: kcampbell@eqecat.com

3. Senior Vice President, Model Development Group, EQECAT, Inc., 475 14th Street, Suite 550, Oakland, CA 94612, USA. Email: dfsmith@eqecat.com

3. Chief Technical Officer, Model Development Group, EQECAT, Inc., 475 14th Street, Suite 550, Oakland, CA 94612, USA. Email: mkhater@eqecat.com

ABSTRACT

We developed an earthquake hazard model for Australia specifically for use in loss estimation, which includes 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) potentially giant ($\mathbf{M} \geq 9$) 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, and (4) removal of conservatisms introduced in the GA maps for engineering design. We also developed an Australian NEHRP site classification map in order to incorporate site effects in the hazard estimates and used NEHRP nonlinear site factors to represent the local site condition at a property site.

Keywords: seismic, hazard, loss, Australia

INTRODUCTION

Earthquake hazard models for loss estimation and risk management have an inherently different purpose than those constructed 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 is appropriate if the purpose of the 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 to be used in updating building seismic design standards nationwide (Burbidge, 2012). Our model for economic loss estimation was developed simultaneously to the GA model. We reviewed GA's hazard model as it was being developed and modified elements of that model to better align with our needs for modelling economic loss in Australia. Exchanges of information and opinions benefitted the final outcome of both models (Burbidge, 2012).

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 modeling ("epistemic") uncertainty. Accordingly, GA developed three different seismic source models to characterize earthquake hazard nationwide: a Background model incorporating all earthquakes in Australia, a Regional model, and a "Hotspot" model. Each source model is independent and mutually exclusive. Each of the models produces substantially different ground motion hazard distributions. The final ground motion map recommended by Burbidge (2012) for use in the Australian building standards is a composite (robust) map of 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 appropriate for seismic design purposes, it does not reflect an unbiased uniform ground motion exceedance probability nationwide as required for loss estimation. Based on our information exchange, GA did produce an alternative unbiased hazard model in their final report (Burbidge, 2012).

REGIONAL HAZARD MODEL FOR LOSS ESTIMATION

For the purpose of obtaining unbiased loss estimates, we removed the conservatism in the GA source model intended for seismic loading standards. We required an earthquake hazard model that reflects a uniform probability of ground motion exceedance nationwide, but that also incorporates the current state-of-the-art knowledge on the seismotectonics and seismicity of 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 ($\mathbf{M} \geq 6.0$) 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; Clark and McCue, 2003), making their relevance for the estimation of near-future earthquake hazard relatively insignificant.

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 source models. Furthermore, the Hotspot source model was not used at all due to its local conservatism, transient nature, and non-Poissonian distribution. 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.

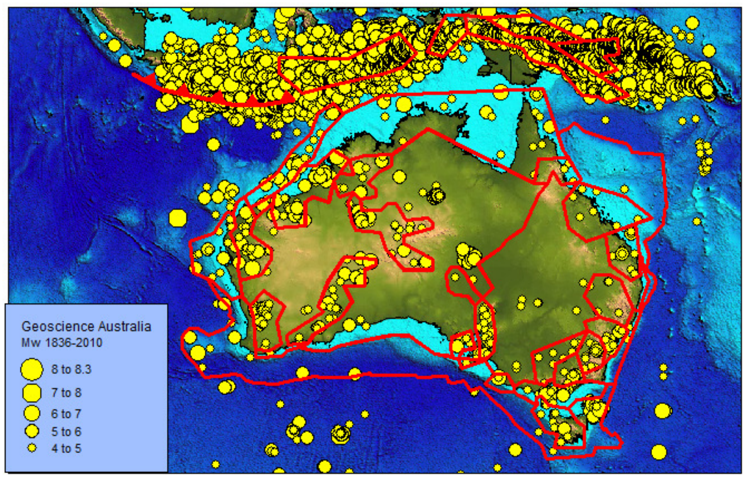

Figure 1: Model of Seismic Sources in Relation to the GA Declustered Catalog.

DISTANT LARGE-EARTHQUAKE SOURCE MODEL

GA confirmed our suggestion that large earthquakes from distant sources in Indonesia and Papua New Guinea (PNG) could impact intermediate-period ground motion hazard at sites in northern Australia and included several offshore source zones in these areas in their final model (Burbidge, 2012). However, we included additional sources of great and giant earthquakes from distant tectonic plate boundary zones in Indonesia and PNG where infrequent large earthquakes were determined to be capable of causing at least some financial losses in extreme northern Australia, depending on the construction type (Fig. 1).

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, our subduction source 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. 1).

RECURRENCE FREQUENCY MODEL

GA earthquake frequencies were area-normalized to maintain the same density of earthquake frequency in each GA Regional source zone that we modified. In addition, the use of mutually exclusive regional background sources appropriately weights the isolated locations of historically large earthquakes that have occurred in these regions with respect to the very long recurrence intervals on individual faults noted by Clark et al. (2011). In the final model (Burbidge, 2012), GA noted the conservatism of its robust building-code hazard model and provided an alternative unbiased Background model.

Frequencies for the GA continental and extended margin Background sources were established independently of the frequencies in the original GA 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 earthquakes in Indonesia and PNG were determined using this same methodology.

GROUND MOTION PREDICTION EQUATIONS

A combination of the ground motion prediction equations (GMPEs) adopted by GA (Burbidge, 2012) and a set of global GMPEs were used with equal weight. 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 for the younger and more deformed non-cratonic eastern Australia and extensional margins.

The GMPEs used by GA are given in Burbidge (2012). The alternative set of GMPEs we selected for use in cratonic western Australia include Frankel et al. (1996), Toro et al. (1997), as adjusted for finite-faulting effects by Toro (2002), Campbell (2003, 2004), Tavakoli and Pezeshk (2005), Atkinson and Boore (2006, 2007), both the 140-bar and 200-bar stress-drop versions, and Silva et al. (2002). 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), each given equal weight.

The same three NGA models used in non-cratonic eastern Australia were used for shallow crustal earthquakes in southern Indonesia and Papua New Guinea. 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 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 southern Indonesia and in PNG.

SITE ADJUSTMENT FACTORS

Although it is common practice in national seismic hazard maps to evaluate GMPEs for a rock reference site condition (e.g., Petersen et al., 2008; Burbidge, 2012), this practice increases uncertainty in ground motions estimated on softer sites where the majority of properties are located for several reasons: (1) GMPEs are not as well constrained for rock site conditions due to a lack of strong motion recordings and (2) additional uncertainty is associated with the site adjustment factors that are required to adjust the rock motion to softer site conditions. For these reasons, we adopted a Soil Based Attenuation (SBA) approach in which we use a reference site condition consistent with NEHRP Site Class D (V_{S30} = 270 m/sec) as defined by the Building Seismic Safety Council (BSSC, 2009). V_{S30} 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 those versions that had already been adjusted to 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 SCR 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 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. 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.

SITE CONDITIONS MAPS

The selection of an appropriate site adjustment factor is based on the local site conditions at any site of interest. We created a high resolution digital (GIS) map of the NEHRP Site Class at any given location in Australia from the national regolith map developed by McPherson and Hall (2007) and references therein. 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. These maps are not able to be shown in this brief summary report. However, the maps replicate the high-resolution analogue map given in McPherson and Hall (2007) to within a few tens of meters.

HAZARD RESULTS

Figure 2 shows seismic hazard curves for Adelaide, Brisbane, Canberra, Hobart, Melbourne, Perth, and Sydney on NEHRP D site conditions as derived from our model. Mid-period, SA 1.0 sec, 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 0.01-0.02 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.

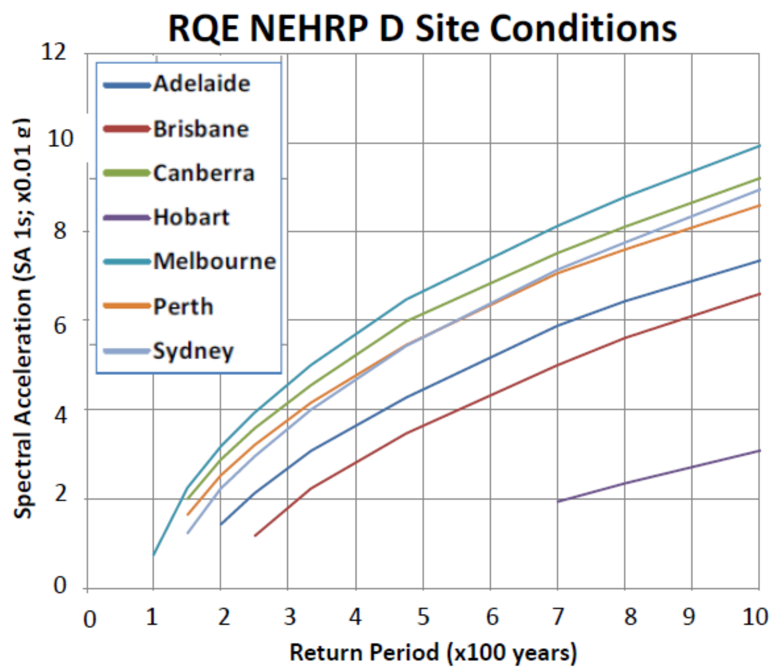

Figure 2: Seismic Hazard Curves for Firm-Soil Site Conditions.

REFERENCES

Atkinson, G. and Boore, D. (2003) Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions, Bull Seismol Soc Am, Vol 93, pp 1703-1729.

Atkinson, G. and Boore, D. (2006) Earthquake ground-motion predictions for eastern North America, Bull Seismol Soc Am, Vol 96, pp 2181-2205.

Atkinson, G. and Boore, D. (2007). *Erratum to* Earthquake ground-motion prediction equations for eastern North America, Bull Seismol Soc Am, Vol 97, pp 1032.

Atkinson, G. and Boore, D. (2008) *Erratum to* Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions, Bull Seismol Soc Am, Vol 98, pp 2567-2569.

Boore, D. and Atkinson, G. (2008) Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, Earthq Spectra, Vol 24, pp 99-138.

Bozorgnia, Y., Abrahamson, N., Campbell, K., Rowshandel, B. and Shantz, T. (2012) NGA-West2: A comprehensive research program to update ground motion prediction equations for shallow crustal earthquakes in active tectonic regions, Proc, 15th World Conf Earthq Eng, Lisbon, 24-28 September 2012, Paper No. 2572.

BSSC (2009) NEHRP recommended provisions for seismic regulations for new buildings and other structures (FEMA P-750), 2009 edition, National Institute of Building Sciences, Washington, D.C.

Burbidge, D. (2012) The 2012 Australian earthquake hazard map, Geoscience Australia Record 2012/71.

Campbell, K. (2003) Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America, Bull Seismol Soc Am, Vol 93, pp 1012-1033.

Campbell, K. (2004) *Erratum to* Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground motion (attenuation) relations in eastern North America, Bull Seismol Soc Am, Vol 94, pp 2418.

Campbell, K. and Bozorgnia, Y. (2008) NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s, Earthq Spectra, Vol 24, pp 139-171.

Chiou, B. and Youngs, R. (2008) An NGA model for the average horizontal component of peak ground motion and response spectra, Earthq Spectra, Vol 24, pp 173-215.

Clark and McCue (2003) Australian paleoseismology: towards a better basis for seismic hazard estimation, Annals of Geophysics, Vol 45, pp 1087-1105.

Clark, D., McPherson, A. and Collins, C. (2011) Australia's seismogenic neotectonic record: A case for heterogeneous intraplate deformation, Geoscience Australia Record 2011/11.

Crone, A., De Martini, P., Machette, M., Okumura, K. and Prescott, J. (2003) Paleoseismicity of two historically quiescent faults in Australia: Implications for fault behaviour in stable continental regions, Bull Seismol Soc Am, Vol 93, pp 1913-1934.

Di Alessandro, C., Bozorgnia, Y., Abrahamson, N., Akkar, S. and Erdik, M. (2012) GEM-PEER global ground motion prediction equations project: An overview, Proc, 15th World Conf Earthq Eng, Lisbon, 24-28 September 2012, Paper No. 2437.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S. & Hopper, M. 1996. National seismic hazard maps: Documentation June 1996. U.S. Geol. Survey Open-File Report 96-532.

Hwang, H., Huijie, L. and Huo, J. (1997) Site coefficients for design of buildings in eastern North America, Soil Dyn Earthq Eng, Vol 16, pp 29-40.

Kafka, A. and Levin, S. (2000) Does the spatial distribution of smaller earthquakes delineate areas where larger earthquakes are likely to occur? Bull Seismol Soc Am, Vol 90, pp 724-738.

Kafka, A. and Ebel, J. (2011) Proximity to past earthquakes as a least-astonishing hypothesis for forecasting locations of future earthquakes, Bull Seismol Soc Am, Vol 101, pp 1618-1629.

McPherson, A. and L. Hall (2007) Development of the Australian national regolith site classification map, Geoscience Australia Record 2007/7.

Petersen, M., Frankel, A., Harmsen, S., Mueller, C., Haller, K., Wheeler, R., Wesson, R., Zeng, Y., Boyd, O., Perkins, D., Luco, N., Field, E., Wills, C. and Rukstales, K. (2008) Documentation for the 2008 update of the United States national seismic hazard maps, U.S. Geol. Survey Open-File Report 2008-1128.

Power, M., Chiou, B., Abrahamson, N., Bozorgnia, Y., Shantz, T. and Roblee, C. (2008). An overview of NGA project, Earthq Spectra, Vol 24, pp 3-21.

Silva, W., Gregor, N. and Darragh, R. (2002). Development of regional hard rock attenuation relations for central and eastern North America, Pacific Engineering and Analysis, El Cerrito, California.

Stewart, J., Douglas, J., Di Alessandro, C., Bozorgnia, Y., Abrahamson, N., Boore, D., Campbell, K., Delavaud, E., Erdik, M. and Stafford, P. (2012). Selection of a global set of GMPEs for the GEM-PEER global GMPEs project, Proc, 15th World Conf Earthq Eng, Lisbon, 24-28 September 2012, Paper No. 2320.

Tavakoli, B. and Pezeshk, S. (2005) Empirical-stochastic ground-motion prediction for Eastern North America, Bull Seismol Soc Am, Vol 95, pp 2283-2296.

Thenhaus, P., Campbell, K., Gupta, N., Smith, D. and Khater, M. (2012) A consistent cross-border seismic hazard model for loss estimation and risk management in Canada, Proc., 15th World Conf Earthq Eng, Lisbon, 24-28 September 2012, Paper No. 0077.

Toro, G., Abrahamson, N. and Schneider, J. (1997) Model of strong ground motions from earthquakes in central and eastern North America: Best estimates and uncertainties, Seismol Res Lett, Vol 68, pp 41-57.

Toro, G. (2002) Modification of the Toro et al. (1997) attenuation equations for large magnitudes and short distances, Risk Engineering, Inc., Boulder, Colorado.

Youngs, R., Chiou, S., Silva, W. and Humphrey, J. (1997) Strong ground motion attenuation relationships for subduction zone earthquakes, Seismol Res Lett, Vol 68, pp 58-73.

Zhao, J., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H., Somerville, P., Fukushima, Y. and Fukushima, Y. (2006) Attenuation relations of strong ground motion in Japan using site classification based on predominant period, Bull Seismol Soc Am, Vol 96, pp 898-913.