Impact of new industry guidelines and new seismic hazard knowledge on seismic hazard assessments for dams in Australia and New Zealand

Paul Somerville, Jeff Bayless, Andreas Skarlatoudis, Scott Condon

AECOM, Los Angeles, California

This paper describes rapid improvements in the modelling of seismic hazards in Australia and New Zealand and in the appropriate representation of probabilistic hazard results in seismic response analyses following new industry guidelines. We have reviewed site-specific seismic hazard calculations for dam sites in all of the states and territories of Australia and in both the North and South Islands of New Zealand, using updated regulations and seismic source models, and compared them with results using earlier regulations and models at the same site. Changes in the Australian National Committee on Large Dams guidelines (ANCOLD, 2019) including the use of MASW seismic velocity profiling of dam foundations, and the use of time histories spectrally matched to Conditional Mean Spectra in place of probabilistic Uniform Hazard Spectra, have improved the reliability of seismic hazard analyses. The 2014 NGA West 2 ground motion models indicate that the ANCOLD (2019) requirement to provide ground motions for bedrock conditions, for which nonlinear soil response is negligible, can be met at sites with V_{S30} *as low as 600 m/s. Changes in earthquake source models in the Geoscience Australia 2018 National Seismic Hazard Assessment have in almost all cases reduced seismic hazard levels below previously estimated levels at the same dam sites in Australia. The peak acceleration of the Safety Evaluation Earthquake (SEE) at many dam sites in Australia now falls below the notional threshold of 0.1 – 0.15g for the triggering of liquefaction. The strong ground motions recorded from the 21 September 2021 Mw 5.9 Woods Point earthquake provided an unprecedented opportunity to compare recorded ground motions with ground motion models being used in Australia, and are in fairly good agreement with those models. A database of strong ground motion recordings in Australia is being used to select and rank ground motion models, and to validate ground motion simulations for the development of improved models. In New Zealand, impending changes in the GNS Science New Zealand seismic hazard model may also result in significant changes in seismic hazard levels. The first New Zealand Community Fault Model (CFM) was released this year, and a revised New Zealand National Seismic Hazard Model, based on the CFM and replacing the current model developed in 2010, is due to be released later this year. New Zealand has an extensive program of validation of ground motion simulation methods against ground motions recorded from a wide range of earthquake magnitudes for both shallow crustal and subduction earthquakes.*

Keywords: *Distributed earthquake source models, fault source models, foundation shear wave velocity, ground motion models, conditional mean spectrum, seismic hazard.*

Introduction

Rapid improvements are occurring in the modelling of seismic hazards in Australia and New Zealand and in the appropriate representation of probabilistic hazard results in seismic response analyses. In Australia these are generally leading to significant reductions in seismic hazard estimates. In the three years since the release of the 2019 ANCOLD seismic guidelines and the Geoscience Australia National Seismic Hazard Assessment in October 2018 (NSHA18), we have performed seismic hazard analyses for dam sites in every state and territory of Australia, as well as major systems of dams in both the North and South Islands of New Zealand. For all categories of dams, and especially for Extreme Consequence dams, the 2019 ANCOLD guidelines and NSHA18 have brought major changes in the seismic hazard levels used for the design and analysis of dams in Australia. Impending changes in the New Zealand seismic hazard model may also result in significant changes in seismic hazard levels.

Recent changes in seismic hazard estimates and seismic guidelines in Australia and New Zealand were reviewed by Somerville (2019). That paper described NSHA18, reviewed the definitions of MCE and CME, compared near fault ground motion levels in Australia and New Zealand using probabilistic and deterministic methods, and reviewed the impact of ANCOLD (2019) on deterministic assessments of Extreme Consequence dams. The objective of this paper is to update this review using current information.

Distributed Earthquake Source Models

Since its release in 2018, NSHA18 (Allen et al., 2018a) has been documented and assessed by its authors. Allen et al. (2020) summarised the development of the NSHA18, explored uncertainties associated with the hazard model, and identified the dominant factors driving the resulting changes in hazard compared with previous assessments. Allen et al. (2021) showed that the total area (or rate) of ground-motion exceedances of the NSHA18 PGA map for an annual exceedance probability (AEP) of 1:475 as estimated from the last 50 years of seismicity is lower than the stated objective of the NSHA18 (about 10%), so the NSHA18 model is likely to be approximately correct, if not slightly conservative, in estimating historical ground motion exceedances.

There is ongoing debate about earthquake magnitudes and their use in developing earthquake recurrence models of distributed sources in NSHA18, mostly focused on the slope (b value) of the Gutenberg-Richter earthquake recurrence model. As described by Griffin et al. (2020), the 2018 National Seismic Hazard Assessment of Australia incorporated 19 alternative seismic-source models developed by members of the Australian seismological community. A complex logic tree was developed to incorporate the alternative component models into a single hazard model. Expert opinion was drawn upon to weight the alternative logic-tree branches through a structured expert elicitation process. Despite the extensive logic tree implemented in NSHA18, some model choices were made independently of the expert elicitation group, and not included in the epistemic uncertainty addressed through expert elicitation for the development of a single model. Although the results had been reviewed by an external Scientific Advisory Panel that provided guidance on the entire NSHA18 process, the updated catalogue had not yet been published through traditional peer-review mechanisms at the time of the expert elicitation workshops.

Implications of NSHA18 for building codes were described by Allen et al. (2020), and Geoscience Australia is currently making adjustments to NSHA18 (Allen, 2022a, b) for use in revision later this year of Australian Standard AS1170.4-2007 for buildings (Standards Australia, 2007). Allen (2022a) convened a workshop on April 7 and 8, 2022 to plan the update to NSHA18, and convened a workshop on August 26 and 27, 2022 to discuss how to revise the earthquake catalogue used in NSHA18 for the 2022 update of NSHA (Allen, 2022b). During that Workshop, there was discussion of the relationships used to convert ML to M_w magnitudes. The break in the linearity of the ML to M_w relationship for the Australian empirical data suggests that M_w is proportional to 2/3 ML for small earthquakes (Allen et al., 2011; 2018a).

Experts whose model choices lay outside the single model designed to represent the full range of epistemic uncertainty have been concerned that the b values (slopes) in the earthquake recurrence relations in the NSHA18 earthquake source models are unrealistically high (about 1.2), causing underestimation of the seismic hazard. However, these high b values are for M_w, not ML magnitudes. The equivalent b values for ML magnitudes are about 0.85, the value expected by the concerned experts. This was demonstrated in modelling performed by Trevor Allen (2022c) shown in Figure 1, based on measuring both ML and M_w for a set of simulated earthquake ground motions. While some of the NSHA18 earthquake recurrence models have high b values (above 1.0), these are for M_w, and the equivalent b values of ML are lower, about 0.85, in the range expected for ML. This is in excellent agreement with other theoretical and empirical studies in Australia and elsewhere (e.g., Edwards et al., 2010; Deichmann, 2017). The scaling between ML and M_w can be explained by the interaction of attenuation, stress-drop and the Wood–Anderson instrument response, leading to higher b-values for the M_w scale, reducing the rates of large M_w earthquakes.

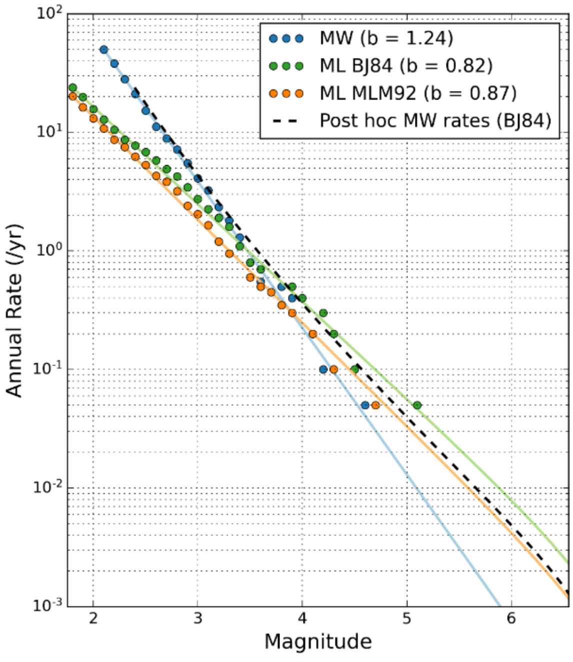

Figure 1. Earthquake recurrence rates using various methods of measuring magnitude: two methods of measuring ML (green and orange) with b values (slopes) of 0.82 and 0.87, and Mw (blue), with a b value (slope) of 1.24. Source: Allen (2022c).

The effects of NSHA18 on seismic hazard estimates in Australia are illustrated in Figure 2. The changes in earthquake magnitudes have the effect of generally reducing earthquake frequency across Australia. This in turn reduces the contribution to the seismic hazard from distributed earthquake sources because they are fundamentally based on earthquake frequencies. The changes in the Australian earthquake catalogue do not impact the hazard from potentially active fault sources, because they only depend on changes in their estimated slip rates. Hence the changes to the hazard due to changes in distributed earthquake frequencies and fault models are independent of each other.

The left side of Figure 2 shows hazard curves for peak ground acceleration in the capital cities of Australia (Allen, 2018). The hazard increases with AEP most rapidly at locations near active faults, including Canberra and Adelaide. At locations where active faults are more distant or less numerous or less active, including Melbourne, Perth, Sydney and Darwin, the hazard increases less rapidly. Brisbane and Hobart have an even slower increase because, in addition to low fault activity, the historical seismicity is also low. The right side of Figure 2 compares the hazard results obtained using the 2018 (Allen et al., 2018) and 2012 (Burbidge et al., 2012) versions of the NSHA at a location in southeastern Australia near active faults. The decrease in hazard level at high values of AEP is relatively large, because that is mainly controlled by the changes in earthquake magnitudes on which the distributed source models are based. However, the decrease in hazard level at low values of AEP is relatively small, because that is mainly controlled by the fault sources, which are independent of changes in earthquake magnitudes.

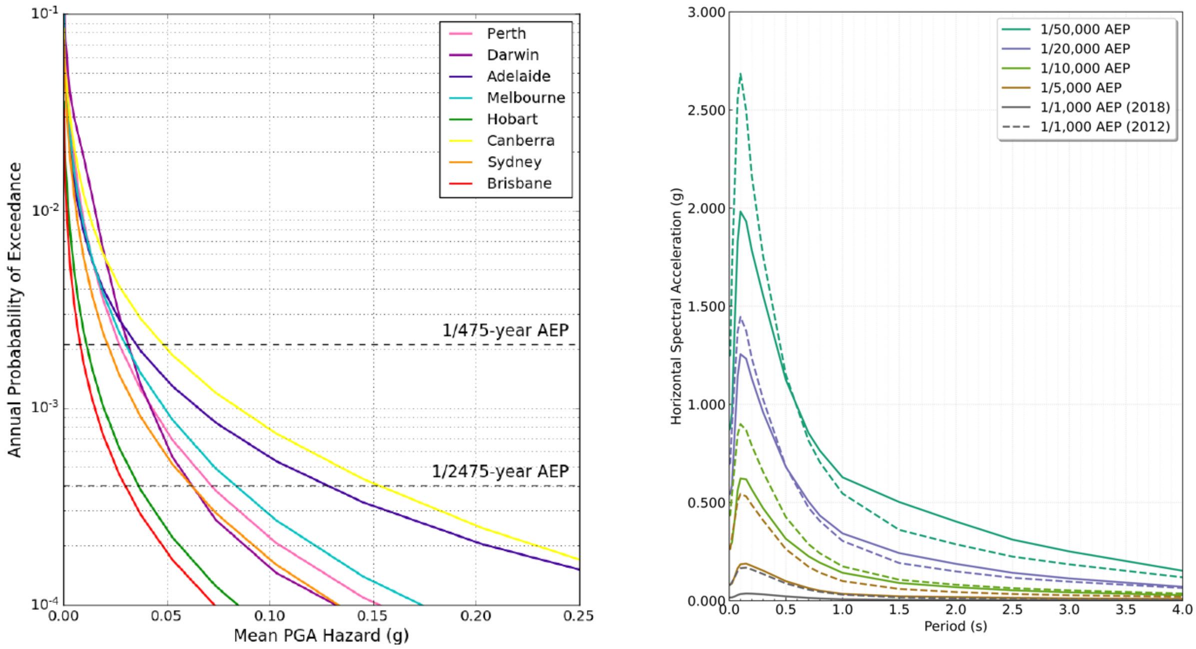

Figure 2. Left: Hazard curves showing the annual probability of exceeding a given PGA level (in g) for Australian capital cities. Source: Allen (2018). Right: Probabilistic mean uniform hazard response spectra at a site in southeastern Australia for a suite of AEP's calculated using the 2012 and 2018 NSHA source models.

In New Zealand, the impending revision of the NZ National Seismic Hazard Model (NSHM) will use a new method (Field et al., 2014, described next) for constructing fault ruptures from identified faults. It is unclear how this will affect the existing distributed source models, which are used to represent earthquakes that do not occur on identified active faults. The new distributed source models will be revised to include the earthquakes that have occurred since the development of the current model (Stirling et al., 2012). They may also contain revisions that are required to accommodate the new Field et al. (2014) method that is being used to represent earthquake ruptures on faults, to avoid double counting of the hazard.

Fault Models

The Australia National Fault Source Model (NFSM), developed as part of NSHA18 (Allen et al., 2018a), provides estimates of fault slip rates as well as fault geometry, and so can be used to make an earthquake forecast, which supplements the earthquake forecast that comes from the distributed earthquake source models described above.

King et al. (2019) studied ten surface rupturing earthquakes that occurred between 1968 and 2018 in the Cratonic crust of Australia, ranging in moment magnitude M_w from 4.7 to 6.6. All of the earthquakes involved co-seismic reverse faulting with varying amounts of strike-slip faulting on single or multiple discrete faults of length longer than 1 km. Nine of the ten earthquakes have surface-rupturing fault orientations that align with prevailing linear anomalies in geophysical data and bedrock structure, indicating strong control of inherited crustal structure on contemporary faulting. However, none of the studied earthquakes have unambiguous geological evidence for preceding surface-rupturing earthquakes on the same faults, and five earthquakes have evidence of the absence of preceding ruptures since the late Pleistocene, indicating the challenge of using mapped active faults to predict future seismic hazards in Australia.

Clark and Allen (2018) concluded that based on their current understanding of earthquake recurrence on neotectonic faults in the Precambrian crust, there appears to be limited advantage to including these features in seismotectonic source models for national-scale seismic hazard analyses. Low implied slip rates, and thus low rates of earthquake recurrence, have little effect on overall seismic hazard calculations at return periods of engineering interest. Consequently, instead of modelling fault sources, they propose that the seismic hazard could be modelled equally well using simple area-based distributed seismic source models. They conclude that potentially greater benefits might be gained from investigations of neotectonic features in Phanerozoic crust, which typically demonstrate higher slip rates and contribute more significantly to estimates of probabilistic seismic hazards at return periods of engineering interest.

The New Zealand Community Fault Model version 1.0 (NZ CFM; Seebeck et al., 2022) is a representation of fault zones associated with the New Zealand plate boundary for which Quaternary activity has been established or deemed probable, and which are considered capable of producing moderate to large-magnitude earthquakes. The NZ CFM builds upon the Litchfield et al. (2014) model, which we have implemented in previous hazard analyses.

The NZ CFM includes information about earthquake recurrence as well as fault geometry, but does not prescribe earthquake ruptures; that will be done in the forthcoming 2022 NZ NSHM described next. The fault sections in the CFM were defined on both geometric grounds (sections of fault that share similar strikes and dips), and kinematic grounds (sections of fault that also share similar slip rates and movement styles).

The 2022 NZ NSHM will for the first time use the method employed in the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3; Field et al., 2014) for constructing the earthquake rupture forecast model. This method will accommodate multi-fault ruptures like that of the 2016 Kaikoura earthquake. An important feature of the UCERF3 process is the "grand inversion" to solve for the rates of occurrence of those ruptures so that they are consistent with fault slip rate, historical seismicity, and geodetic data. The Wellington Fault and many other faults will no longer be represented in the hazard model as a single, segmented earthquake source with a range of possible recurrence intervals and magnitudes, but rather as a suite of compatible sources (encompassing both single-fault and multi-fault ruptures) that span a range of magnitudes and rates, all of which when combined together have of satisfy (to a greater or lesser extent) the various input constraints including fault slip rate, recurrence interval, and historical earthquake magnitude – frequency distributions.

Earthquake activity on faults in the Stirling et al (2012) model was based on estimated recurrence intervals of a characteristic earthquake, an event that ruptures the entire fault. The CFM provides fault slip rates on fault sections, not recurrence intervals of earthquakes. For the Wellington fault, the recurrence interval in Stirling et al. (2012) was about 3,500 years. The central value of the slip rate in the CFM is about 0.8 mm/yr, corresponding to a recurrence interval of about 1,750 years for large earthquakes, about twice the previous frequency. This is reflected in the hazard curves for a site in Wellington shown in Figure 3. While the contributions of background seismicity (distributed sources) and subduction sources have not changed, the contribution from the fault sources has increased. This is due to the approximate doubling of the occurrence rate of events on the Wellington fault, and the incorporation of additional fault sources in the CFM. In the right panel, we have retained the Stirling et al. (2012). approach of using characteristic ruptures on faults.

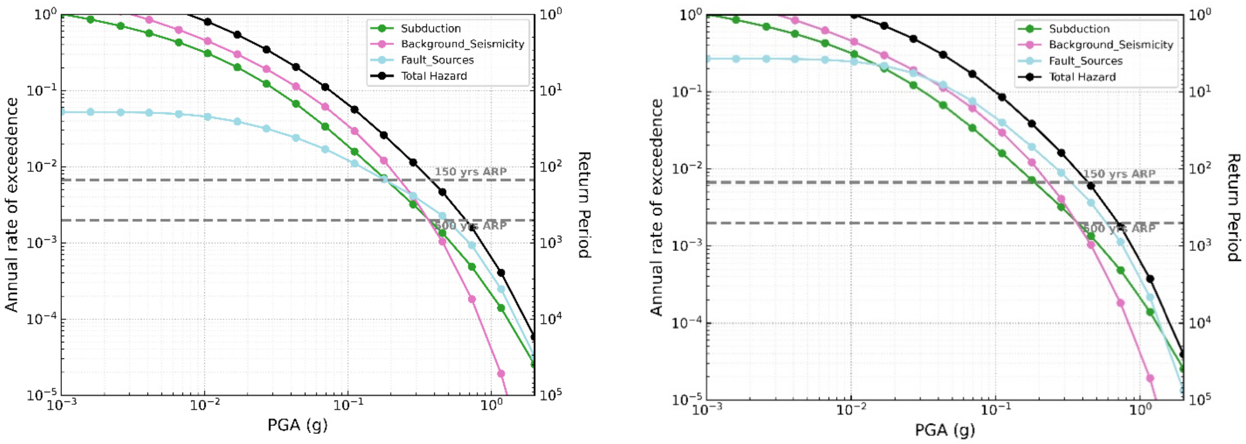

Figure 3. Seismic hazard curves for a site in Wellington using the Stirling et al. (2012) source model (left) and the 2022 CFM combined with Stirling et al. (2012) rupture models on the Wellington – Hutt Valley and Wairarapa faults (right).

The effect of using the UCERF3 method is expected to produce larger maximum magnitudes in some locations, because it allows earthquakes to rupture multiple fault segments in the same event. Assuming no changes in slip rates, this will result in higher Controlling Maximum Earthquake (CME) ground motions in some locations, but is expected to reduce the probabilistic hazard because it distributes the available total slip rate into some larger events, reducing the number of smaller earthquakes that can occur. NZSOLD (2015) does not require the use of the CME for High Potential Impact Classification (PIC) dams, so although higher maximum magnitudes and hence CME's are expected from the 2022 NZ NSHM, this may not have a significant impact on design and evaluation of dams in New Zealand.

The potential for earthquakes to rupture multiple identified fault segments has not been addressed in detail in Australia. If a UCERF3 method were adopted, this could potentially increase the Maximum Considered Earthquake (MCE) in some locations, and then unlike the situation in New Zealand, it would be necessary to base the SEE for Extreme Consequence dams on this MCE if it were to exceed the probabilistic SEE for 1:10,000 AEP when using a deterministic scenario-based approach. The risk-based approach, which is preferred by ANCOLD (2019), does not use the MCE and so would not be affected.

Shear Wave Velocity Profile of the Foundation

If the dam is founded on sediments or deep residual soils (completely weathered rock overlying the bedrock), which are expected to have significant non-linear response, ANCOLD (2019) requires that the ground motions should be specified at the surface of the bedrock beneath the sediments or weathered rock at a depth in the profile having a suitable shear-wave velocity.

All current ground motion models use the parameter V_{S30} to represent the near-surface modification (usually amplification) of ground motions. V_{S30} is defined as the time-averaged shear wave velocity in the top 30 metres of the foundation. Hence it is important to use seismic profiling methods such as MASW or ReMI to obtain measurements of the shear wave velocity of the foundation. These surveys can be done quickly and inexpensively, and reliable contractors are readily available.

Figure 4 shows that, in the 2014 NGA West 2 ground motion models (Gregor et al., 2014), response spectral acceleration (Sa) at 0.2 seconds period decreases linearly with increasing V_{S30} for V_{S30} above 600 m/s for high strain (right side, M7 strike-slip earthquake at 10 km), as well as at low strain (left side, M7 strike-slip earthquake at 100km), indicating that nonlinear soil effects are negligible for V_{S30} greater than 600 m/s. This indicates that using V_{S30} of 600 m/s is consistent with the ANCOLD (2019) requirement to provide ground motions for bedrock conditions, in this case better described as "engineering bedrock," for which nonlinear soil response is negligible. These ground motions can then be propagated through the overlying soil and embankment or structure in a separate nonlinear soil response analysis.

NZSOLD (2015) does not prescribe the measurement of the shear wave velocity of the foundation. However, all current ground motion models use V_{S30} to model the modification of bedrock ground motions by the overlying soil, and it is being used universally in practice.

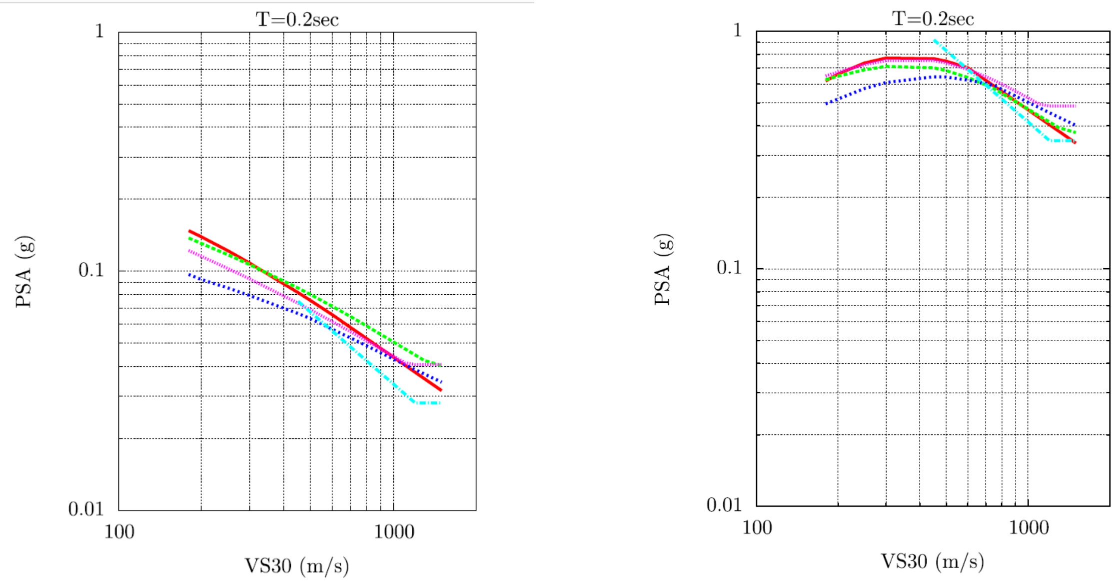

Figure 4. Dependence of low strain (left) and high strain (right) response spectral acceleration at 0.2 seconds period on V_{S30} in the NGA West 2 ground motion models, represented by the alternative line types. Source: Gregor et al. (2014).

Ground Motion Models

Significant improvements have recently been made in ground motion models that are applicable in Australia and New Zealand. In particular, a set of ground motion models for subduction earthquakes, suitable for use in New Zealand, have been developed by the NGA Sub Project in 2020 (Abrahamson and Gulerce, 2020; Kuehn et al., 2020; and Parker et al., 2020), supplementing the Bradley (2012) model. The NGA Sub models include regionalisation, and provide models specifically for use in New Zealand. Allen (2022) developed a far-field ground-motion model for the North Australian Craton from plate-margin earthquakes occurring within the subducted slabs of the Sunda – Banda Arc. The NGA-East Project (Goulet et al., 2018) developed ground motion models for tectonically stable regions, and the NGA-West 2 Project (summarised by Gregor et al, 2014) developed models for tectonically active regions. These models supplement the models developed for Australia by Allen (2012) and Somerville et al. (2009).

Geoscience Australia is preparing a strong motion database of Australian earthquakes (Ghasemi, 2022), and are using it to review the selection and ranging of ground motion models for their update of NSHA18 (Allen, 2022). We have been using it to revise the Somerville et al. (2009) model based on broadband strong motion simulations of earthquakes in Australia. Professor Brendon Bradley and his research group at the University of Canterbury, which includes collaboration with the authors, have been conducting an extensive program of validation of ground motion simulation methods against ground motions from a wide range of earthquake magnitudes for both shallow crustal and subduction earthquakes in New Zealand. For example, they simulated broadband ground motions for scenario large earthquakes (Orchiston et al., 2016) on the Alpine fault (Bradley et al., 2017).

The strong ground motions recorded from the 21 September 2021 M_w 5.9 Woods Point earthquake provided an unprecedented opportunity to compare recorded ground motions with ground motion models being used in Australia. Hoult et al. (2021) found that these ground motion models appear to provide reasonably accurate estimates of the recorded ground motion levels and their decrease with distance (Figure 5). The NGA-East model appears to match most of the data, particularly for short periods. The three models developed specifically southeast Australia (Allen, 2012; Somerville et al, 2009, and Tang et al., 2019; A12, Sea09 and Tea19, respectively), also appear to reasonably predict the ground motions, particularly for longer periods. The data appear to be consistent with models that incorporate a flat region of low attenuation in the distance range of 60 to 150 km due to strong postcritical reflections from the Moho discontinuity (Burger et al., 1987; Somerville et al., 1988). The relatively high levels of short period ground motion compared with those at 1 second period at close distances are consistent with the NGA-East model; this is less pronounced at greater distances.

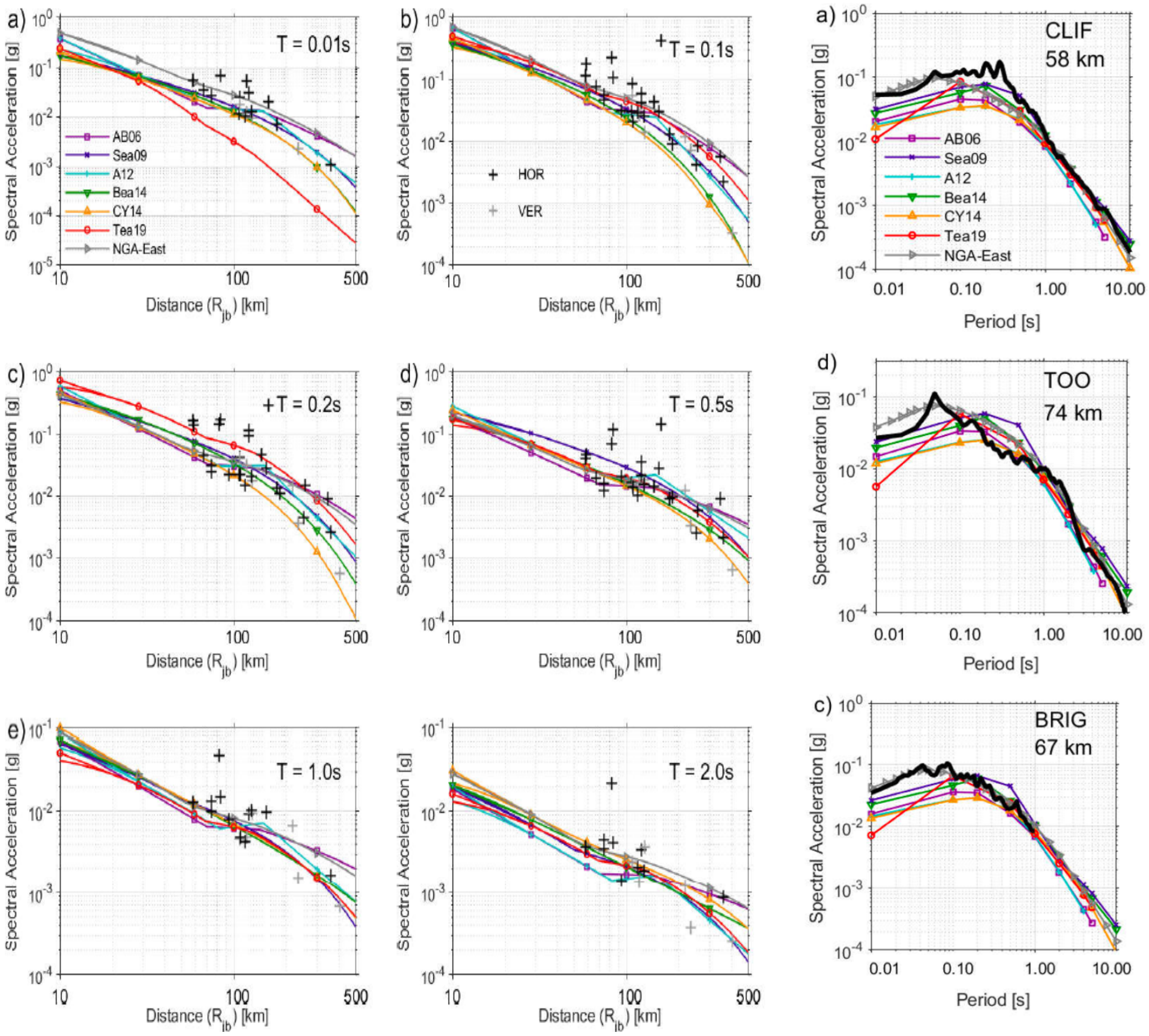

Figure 5. Left two columns: Comparison of recorded and model response spectral acceleration from the Woods Point earthquake for periods ranging from 0.01 to 2 seconds. Right column: Comparison of recorded and model response spectra at three nearby stations: CLIF at 58 km to the south; TOO at 74 km to the west; and BRIG at 87 km to the east. Source: Hoult et al. (2021).

Use of Conditional Mean Spectra (CMS) in place of Uniform Hazard Spectra (UHS)

Until recently, it has been almost universal practice to use the probabilistic Uniform Hazard Spectrum (UHS) as the design spectrum. However, the structure will only be subjected to one earthquake at a time, and no single earthquake ground motion has a response spectrum identical to the UHS because the UHS is constructed from the total hazard curves at each spectral period, each of which aggregate exceedance probabilities from all possible earthquakes. For example, the ground motions from a small nearby earthquake may match the UHS at short periods but be much lower than the UHS at long periods. Conversely, the ground motions from a large distant earthquake may match the UHS at long periods but be much lower than the UHS at short periods. The UHS is thus too "broadband" (strong across too broad a period range) to realistically represent the ground motions of individual earthquakes. For this reason, using the UHS is generally an inaccurate and overconservative representation of the hazard. This over-conservatism can be ameliorated using the Conditional Mean Spectrum (Baker and Cornell, 2006; Baker, 2011) in place of the UHS, as described by Somerville et al. (2015).

It is always beneficial to use CMS spectra to develop ground motion time histories, because this provides a more accurate representation of the hazard, and also significantly reduces the seismic demand (Somerville et al., 2015), as shown in the example in Figure 6. The probabilistic UHS (blue) spectrum is the design spectrum, the same in all four panels. The median scenario spectra (green) from the magnitude-distance combinations from deaggregation of the hazard, from which the CMS spectrum was matched to the UHS spectrum at the central period of the CMS, are also shown. ANCOLD (2019) explicitly allows the use of CMS, and it is being used in practice in Australia, especially in cases where the response of the structure is critical, such liquefaction hazard analysis and in the analysis of brittle dams. NZSOLD (2015) does not explicitly endorse the use of CMS, but it is being used in practice to develop ground motion time histories for use in the design and analysis of dams.

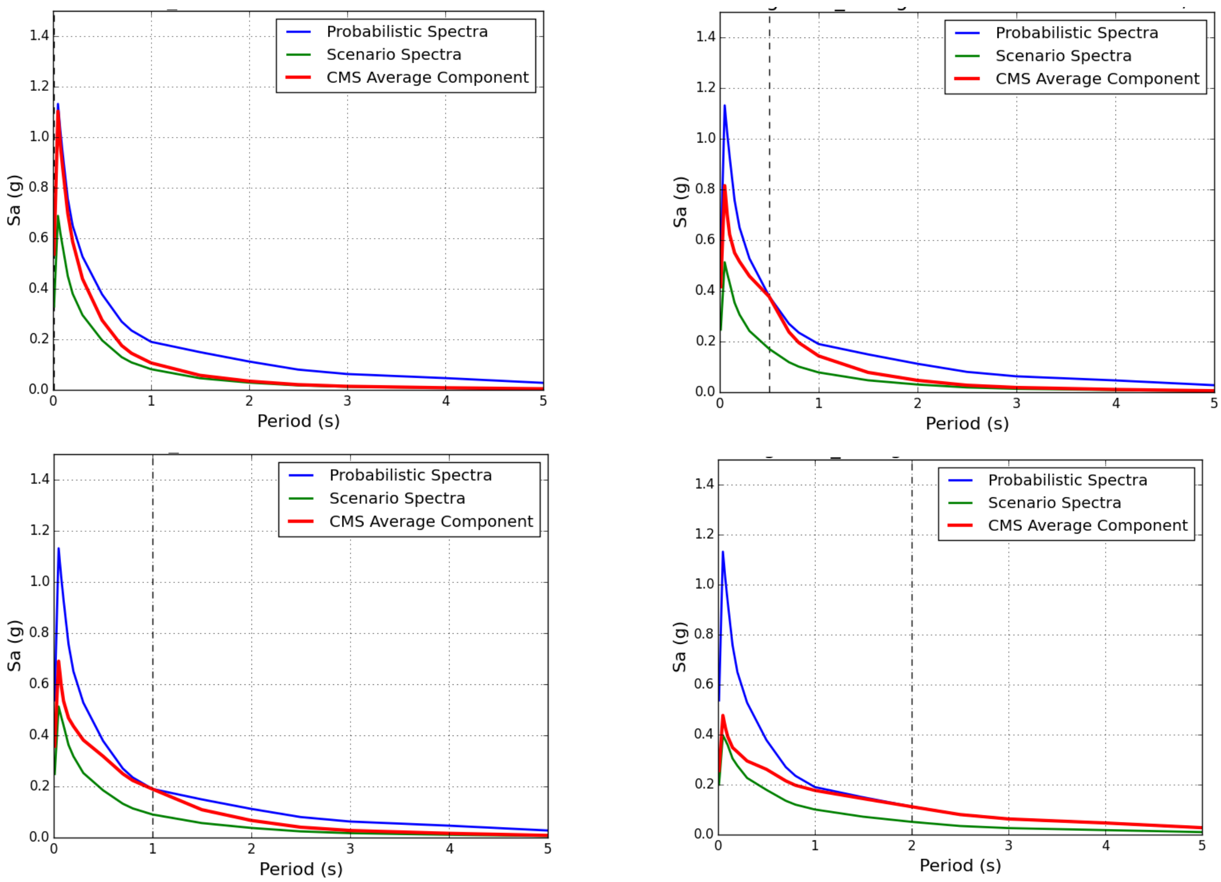

Figure 6. Conditional mean spectra (CMS, red) for response spectral periods of 0.0 sec (PGA, top left), 0.5 sec (top right), 1.0 sec (bottom left), and 2 sec (bottom right) used to represent the probabilistic UHS spectrum; the dashed vertical lines indicate the CMS central periods. Source: Somerville et al. (2015).

Conclusions

Rapid improvements have been made in the modelling of seismic hazards in Australia and New Zealand and in the appropriate representation of probabilistic hazard results in seismic response analyses following new industry guidelines. Changes in ANCOLD (2019) including the use of MASW seismic velocity profiling of dam foundations, and the use of time histories spectrally matched to Conditional Mean Spectra in place of probabilistic Uniform Hazard Spectra, have improved the reliability of seismic hazard analysis. The 2014 NGA West 2 ground motion models indicate that the ANCOLD (2019) requirement to provide ground motions for bedrock conditions, for which nonlinear soil response is negligible, can be met at sites with V_{S30} as low as 600 m/s. Changes in earthquake source models in NSHA18 have in almost all cases reduced seismic hazard levels below previously estimated levels at the same dam sites we have evaluated in Australia. The peak acceleration of the SEE at many dam sites in Australia now falls below the notional threshold of 0.1 – 0.15g for the triggering of liquefaction. Impending changes in the New Zealand seismic hazard model may also result in significant changes in seismic hazard levels. The first New Zealand Community Fault Model was released this year, and a revised New Zealand National Seismic Hazard Model, based on the CFM and replacing the current model developed in 2010, is due to be released later this year. The strong ground motions recorded from the 21 September 2021 Mw 5.9 Woods Point earthquake provided an unprecedented opportunity to compare recorded ground motions with ground motion models being used in Australia, and are in fairly good agreement with those models.

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References

Abrahamson, N., & Gulerce, Z. (2020). Regionalized Ground-Motion Models for Subduction Earthquakes Based on the NGA-SUB Database. Pacific Earthquake Engineering Research Center. PEER Report 2020/25 https://peer.berkeley.edu/peer-reports.

Allen, T.I. (2012). Stochastic ground-motion prediction equations for southeastern Australian earthquakes using updated source and attenuation parameters. Geoscience Australia Record 2012/069.

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

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

Allen T.I. (2018). The 2018 National Seismic Hazard Assessment for Australia: Data package: Maps and grid values. Geoscience Australia record 2018/33. Canberra, ACT, Australia: Geoscience Australia.

Allen, Trevor I, Jonathan D Griffin, Mark Leonard, Dan J Clark, and Hadi Ghasemi (2020) The 2018 national seismic hazard assessment of Australia: Quantifying hazard changes and model uncertainties. Earthquake Spectra 2020, Vol. 36(S1) 5–43.

Allen, T. I. (2020). Seismic hazard estimation in stable continental regions: Does PSHA meet the needs for modern engineering design in Australia? *Bulletin of the New Zealand Society for Earthquake Engineering*, *53*(1), 22–36. https://doi.org/10.5459/bnzsee.53.1.22-36.

Allen, Trevor (2021). A Far-Field Ground-Motion Model for the North Australian Craton from Plate-Margin Earthquakes. Bulletin of the Seismological Society of America 2021;; 112 (2): 1041–1059. doi: https://doi.org/10.1785/0120210191.

Allen, T. (2022a). Workshop on update of NSHA18. April 7 and 8, 2022.

Allen, T. (2022b). Workshop on NSHA18 earthquake catalogue. July 26 and 27, 2022.

Allen, T. (2022c). Australian Earthquake Catalogue Workshop, Day 2 – Use of Catalogues in Hazard Assessments. Workshop on NSHA18 earthquake catalogue, July 27, 2022.

ANCOLD (2019). ANCOLD guidelines for design of dams and appurtenant structures for earthquake. July 2029.

Baker, J. W. (2011). "Conditional Mean Spectrum: Tool for ground motion selection." Journal of StructuralEngineering,137(3), 322-331. http://dx.doi.org/10.1061/(ASCE)ST.1943-541X.0000215

Baker, J.W. and C. A. Cornell (2006). Spectral shape, epsilon and record selection. Earthquake engineering and structural dynamics, 35, 1077-1095.

Bradley, B.A. (2013) A New Zealand-specific pseudospectral acceleration ground-motion prediction equation for active shallow crustal earthquakes based on foreign models. Bull. Seism. Soc. Am., 103, 1801-1822.

Bradley BA, Bae SE, Polak V, Lee RL, Thomson EM, Tarbali, K. (2017). Ground motion simulations of great earthquakes on the Alpine Fault: effect of hypocentre location and comparison with empirical modelling. New Zealand Journal of Geology and Geophysics. 60(3):188–198.

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

Burger, R.W., P.G. Somerville, J.S. Barker, R.B. Herrmann, and D.V. Helmberger (1987). The effect of crustal structure on strong ground motion attenuation relations in eastern North America, Bull. Seism. Soc. Am., 77, 420-439.

Clark, D. and T. Allen (2018). What have we learnt regarding cratonic earthquakes in the fifty years since Meckering? Proceedings of the Australian Earthquake Engineering Society 2018 Conference, Nov 16-18, Perth.

Deichmann, N. (2017). Theoretical basis for the observed break in ML/MW scaling between small and large earthquakes, Bull. Seism. Soc. Am. 107, 505-520, doi: 10.1785/0120160318.

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

Field, E.H, R.J. Arrowsmith, G.P. Biasi, P. Bird, T.E. Dawson, K.R. Felzer, D.D. Jackson, K.M. Johnson, T.H. Jordan, C. Madden, A.J. Michael, K.R. Milner, M.T. Page, T. Parsons, P.M. Powers, B.E. Shaw, W.R. Thatcher, R.J. Weldon, Y. Zeng (2014). Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) - The Time-Independent Model. *Bulletin of the Seismological Society of America* 2014; 104 (3): 1122–1180. doi: https://doi.org/10.1785/0120130164

Ghasemi, H. (2022). Earthquake Ground Motion Portal (Nonprod). https://nonprod.agmd.ga.gov.au/

Gregor, Nick, Norman A. Abrahamson, Gail M. Atkinson, David M. Boore, Yousef Bozorgnia, Kenneth W. Campbell, Brian S.-J. Chiou, I. M. Idriss, Ronnie Kamai, Emel Seyhan, Walter Silva, Jonathan P. Stewart, and Robert Youngs. (2014) Comparison of NGA-West2 GMPEs. Earthquake Spectra 30:3, 1179-1197.

Goulet, C. A., Y. Bozorgnia, N. Abrahamson, N. Kuehn, L. Al Atik, R. R. Youngs, R. W. Graves, and G. M. Atkinson (2018). Central and Eastern North America Ground-Motion Characterization, PEER 2018/08 Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA, 817 pp.

Griffin, Jonathan D., Trevor I. Allen, and Matthew C. Gerstenberger; Seismic Hazard Assessment in Australia: Can Structured Expert Elicitation Achieve Consensus in the "Land of the Fair Go"?. Seismological Research Letters 2020;; 91 (2A): 859–873. doi: https://doi.org/10.1785/0220190186

Hoult, Ryan, Adam Pascale, Abraham Jones, and Trevor Allen (2021). The M_w 5.9 Woods Point Earthquake: A Preliminary Investigation of the Ground Motion Observations. Australian Earthquake Engineering Society 2021 Virtual Conference, Nov 25 – 26.

King, Tamarah, Mark Quigley and Dan Clark (2019). Surface-Rupturing Historical Earthquakes in Australia and Their Environmental Effects: New Insights from Re-Analyses of Observational Data. Geosciences 2019, 9, 408; doi:10.3390/geosciences9100408

Kuehn, N., Bozorgnia, Y., Campbell, K. W., & Gregor, N., (2020). Partially Non-Ergodic Ground-Motion Model for Subduction Regions using the NGA-Subduction Database. Pacific Earthquake Engineering Research Center. PEER Report 2020/04 https://peer.berkeley.edu/peer-reports.

Litchfield NJ, Van Dissen RJ, Sutherland R, Barnes PM, Cox SC, Norris RJ, Beavan RJ, Langridge RM, Villamor P, Berryman KR, et al. (2014). A model of active faulting in New Zealand: fault zone parameter descriptions. Lower Hutt (NZ): GNS Science. 120 p. (GNS Science Report, 2012/19).

Litchfield NJ, Van Dissen RJ, Sutherland R, Barnes PM, Cox SC, Norris RJ, Beavan RJ, Langridge RM, Villamor P, Berryman KR, et al. (2014). A model of active faulting in New Zealand New Zealand Journal of Geology and Geophysics. 57(1):32-56. doi:10.1080/00288306.2013.854256.

NZSOLD (2015). New Zealand Dam Safety Guidelines.

Orchiston C, Davies T, Langridge R, Wilson T, Mitchell J, Hughes M. (2016). Alpine Fault Magnitude 8 hazard scenario. Report commissioned by Project AF8, Environment Southland, Invercargill. P. 45.

Parker, G., Stewart, J., Boore, D., Atkinson, G., & Hassani, B., (2020). NGA-Subduction Global Ground-Motion Models with Regional Adjustment Factors. Pacific Earthquake Engineering Research Center. PEER Report 2020/03 https://peer.berkeley.edu/peer-reports.

Seebeck H, Van Dissen RJ, Litchfield NJ, Barnes PM, Nicol A, Langridge RM, Barrell DJA, Villamor P , Ellis SM, Rattenbury MS, Bannister S, Gerstenberger MC, Ghisetti F, Sutherland R, Fraser J, Nodder SD, Stirling MW, Humphrey J, Bland KJ, Howell A, Mountjoy JJ, Moon V, Stahl T, Spinardi F, Townsend DB, Clark KJ, Hamling IJ, Cox SC, de Lange W, Wopereis P, Johnston M, Morgenstern R, Coffey GL, Eccles JD, Little TA, Fry B, Griffin J, Townend J, Mortimer N, Alcaraz SA, Massiot C, Rowland J , Muirhead J, Upton P, Hirschberg H, Lee JM. (2022). New Zealand

Community Fault Model – version 1.0. Lower Hutt (NZ): GNS Science. 97 p. (GNS Science report; 2021/57). doi:10.21420/GA7S-BS61.

Somerville, P.G., J.P. McLaren, C.K. Saikia, and D.V. Helmberger (1990). The November 25, 1988 Saguenay, Quebec earthquake: source parameters and the attenuation of strong ground motion. Bull. Seism. Soc. Am., 80, 1118-1143.

Somerville, P.G., R.W. Graves, N.F. Collins, S.G. Song, S. Ni and P. Cummins (2009). Source and ground motion models of Australian earthquakes. Proceedings of the 2009 Annual Conference of the Australian Earthquake Engineering Society, Newcastle, December 11-13.

Somerville, P., A. Skarlatoudis, and H.K. Thio (2015). Development of Ground Motion Time Histories for Seismic Design. Proceedings of the Annual ANCOLD Conference, 2015.

Somerville, Paul (2019). Recent changes in seismic hazard estimates and seismic guidelines in Australia and New Zealand. Proceedings of the 2019 ANCOLD/NZSOLD Conference, Rotorua, New Zealand.

Standards Australia (2007). Structural design Actions Part 4. Earthquake actions in Australia, AS1170.4-2007.

Tang, Y., Lam, N., Tsang, H.-H., & Lumantarna, E. (2020). An Adaptive Ground Motion Prediction Equation for Use in Low-to-Moderate Seismicity Regions. Journal of Earthquake Engineering, 1-32. doi:10.1080/13632469.2020.1784810

Stirling, M. W., G.H. McVerry, M. Gerstenberger, N. Litchfield, R. Van Dissen, K. Berryman, P. Barnes, L. Wallace, P. Villamor, R. Langridge, G. Lamarche, S. Nodder, M. Reyners, B. Bradley, D. Rhoades, W. Smith, A. Nicol, J. Pettinga, K. Clark, and K. Jacobs. (2012). National Seismic Hazard Model for New Zealand: 2010 Update. Bulletin of the Seismological Society of America, Vol. 102, No. 4, pp. 1514–1542, August 2012, doi: 10.1785/0120110170.