

## GMCM sensitivity analysis for the 2022 New Zealand National Seismic Hazard

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### Abstract

The New Zealand National Seismic Hazard Model (NSHM) has undergone its first significant revision in 10 years. An expectation of the model was to provide epistemic uncertainty to Building Code decisions and to model appropriately the complexity in both the source and ground motion modelling. An update of all major components was done, including aspects of the Seismicity Rate Model (SRM) and Ground Motion Characterisation Model (GMCM). The SRM was built using multiple datasets and has two components: 1) the inversion-based fault model, jointly fitting multiple datasets; and 2) the hybrid seismicity model based on earthquake catalogue, geodesy and geology with a focus on low-seismicity areas.

In the GMCM, the performance of internationally developed ground motion models (GMMs) was assessed using the newly developed site and ground motion databases. These evaluations were used later to develop backbone models which efficiently model specific ground motion characteristics of NZ. In this study, we evaluate the candidate GMMs in terms of median and aleatory uncertainty comparisons. Subsequently, their impact on the hazard calculations is analysed at certain locations.

**Keywords:** National Seismic Hazard Model, Ground-Motion Characterization Models, Epistemic Uncertainty, New Zealand.

# 1 Introduction

The 2022 New Zealand National Seismic Hazard Model (NZ NSHM) represents a fundamental revision of the NZ NSHM across all components, with a significant change in ground motion characterization modeling compared to the previous NZ NSHM (Stirling et al., 2002 and 2010). In NSHM-2010 (Stirling et al., 2012), epistemic uncertainty in GMM space was not accounted for and a single GMM of McVerry et al. (2006) was used. A detailed summary of the 2020 NSHM model development is presented Gerstenberger et al. (2022a) and a high-level overview of the main components as the Seismicity Rate Models (SRM; Figure 1, left) and Ground Motion Characterisation Model (GMCM) components is presented in Gerstenberger et al. (2022b) and Bradley et al. (2022).

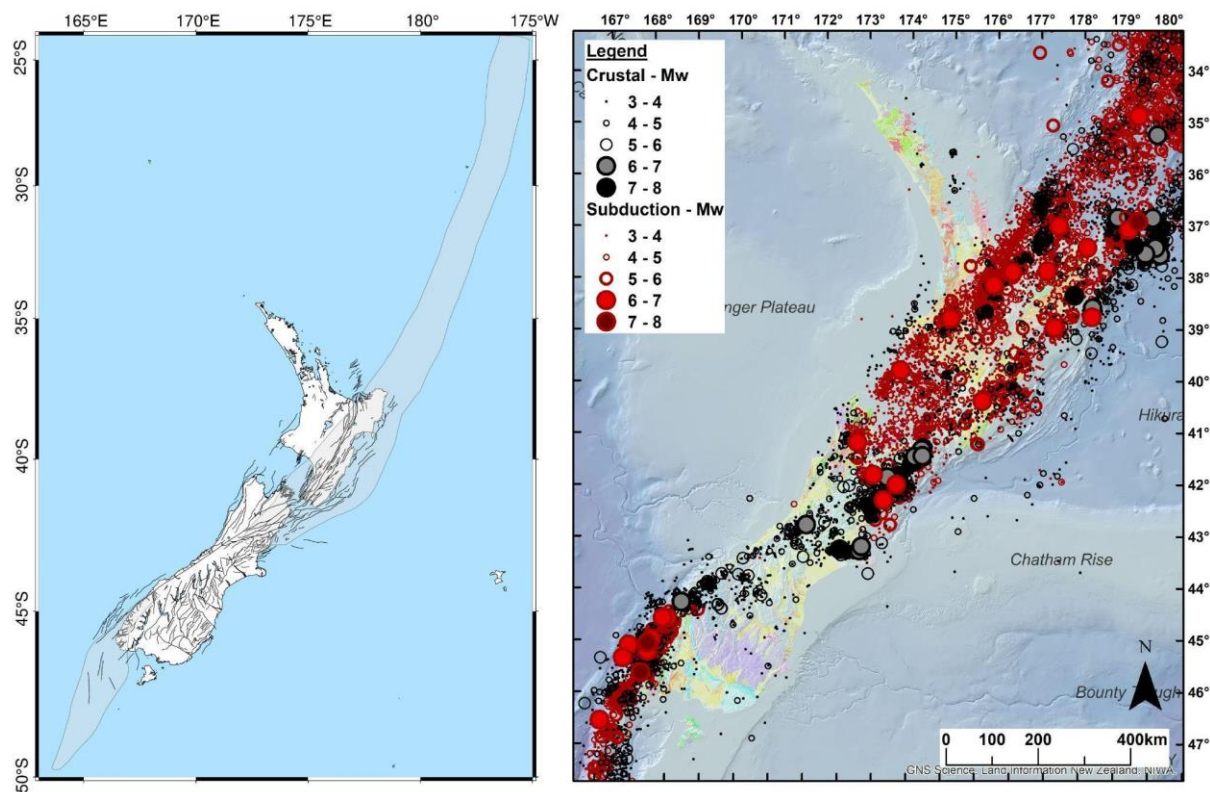


Figure 1. (Left) Community Fault Model V1.0 (Seebeck et al., 2022) and the Hikurangi and Puysegur subduction zones sources (Thingbaijam et al., 2022) (Right) Distribution of the earthquake epicenters with magnitude  $M_w > 3$ , from 2000 - 2022, on the geological map.

In this study, we performed sensitivity analysis for selected ground motion models (GMMs) and two backbone models. For crustal events, we consider four NGA-West2 models namely, Abrahamson et al. (2014), Boore et al. (2014), Campbell and Bozorgnia (2014) and Chiou and Youngs (2014) hereafter referred as ASK14, BSSA14, CB14 and CY14, respectively. In addition to these models, the Bradley (2013) model is also considered for crustal events. Note that the NGA-West2 models are applicable up to  $M 8.5$  while the Bradley (2013) is well constrained by the data from events up to  $M 7.6$ . For subduction-interface events, we consider, recently derived NGA-subduction models namely, Abarhamson and Guelerce (2020), Kuehn et al. (2020) and Parker et al. (2020) hereafter referred as AG20, Kuet20 and Pkret20, respectively. Besides global models, AG20 and Kuet20 have developed NZ-specific regional models for subduction events, which were considered as independent models in the present analysis. The NGA-Sub (interface) models are applicable for scenarios up to  $M 9.5$  while the

intraslab models are applicable up to  $\sim M8-8.5$ . The Atkinson (2022) model is applicable up to  $M7.0$  for both types of sources. We use the acronym GLO and NZ for global and New Zealand specific models of AG20 and Kuet20, respectively. A detailed analysis of all the GMMs applicability, with regard to magnitude and distance limits, and their performance against the recently compiled NSHM strong-motion databases (NZDB; Hutchinson et al., 2021, 2022; Wotherspoon et al., 2022) is presented in Lee et al. (2022). The distribution of the seismic events and their seismic classification within the NZDB is presented in Figure 1 (right). Within NSHM, two new NZ-specific models were developed for crustal and subduction seismicity (Stafford, 2022; Atkinson, 2022), that inherently represent epistemic uncertainty in their modelling framework.

## 2 Evaluation of the candidate GMMs

For crustal sources, we consider five models in addition to the backbone GMMs of Stafford (2022) and Atkinson (2022). Both the backbone GMMs prescribe three branches, lower, central and upper with the intended goal to capture the center, body and range of the epistemic uncertainty. The three branches correspond to 10th, 50th and 90th percentiles of a log-normal distribution. The full response spectra computed using all the selected GMMs are compared with the ones from McVerry et al. (2006) for crustal events  $M6.5$  and  $M7.5$  at a distance  $R_x$  (distance from the site to the surface projection of top-edge of rupture) = 30 km and at sites with VS30 values 250, 400, and 760 m/s and are presented in Figure 2. It can be clearly observed from Figure 2 that all the models (other than the lower and upper branches of backbone models) are clustered together, while the central model of Atkinson (2022) provides higher SA values (mainly for  $M7.5$ ) in the period range ( $\sim 0.5-3.0$ s) in comparison to those from other models. Clearly, for a  $M6.5$  event the response spectral shape is observed to be consistent across all the models, while for a  $M7.5$  event Atkinson (2022) model exhibits a slightly different shape. It is worth mentioning that for the comparison plots we have selected rupture scenarios that are expected to dominate hazard at major urban centers across the country.

For subduction interface events with  $M6.5$  and  $M8.5$ , Figure 3 depicts the full response spectra plots at a fixed distance  $R_x = 30$  km over sites with VS30 values 250, 400 and 760 m/s. For  $M6.5$  events the response spectral shape amongst all the candidate GMMs is observed to be consistent for VS30 760 m/s, while at sites with VS30 values 250 m/s and 400 m/s the SA values from Atkinson (2022) are higher in comparison to the other models between spectral periods  $\sim 0.3-7.0$  s. For the 8.5 event, one can observe a relatively larger spread between the models. Atkinson (2022) backbone model exhibits SA values on the lower side of the range particularly at shorter periods.

For the intraslab events with  $M6.5$  and  $M8$ , Figure 4 depicts full response spectra plots at a fixed distance  $R_x = 30$  km over sites with VS30 values 250, 400 and 760 m/s. For the  $M6.5$  event, the NGA-sub models are observed to be clustered together in terms of values and shape. However, the Atkinson (2022) backbone model exhibits consistently lower SA at periods shorter than  $\sim 0.5$  s. For the event with  $M8.5$ , all the models exhibit significant scatter in terms of values as well as the shape. As also noticed for  $M6.5$ , Atkinson (2022) backbone model exhibits consistently lower SA values for periods shorter than  $\sim 1$ s.

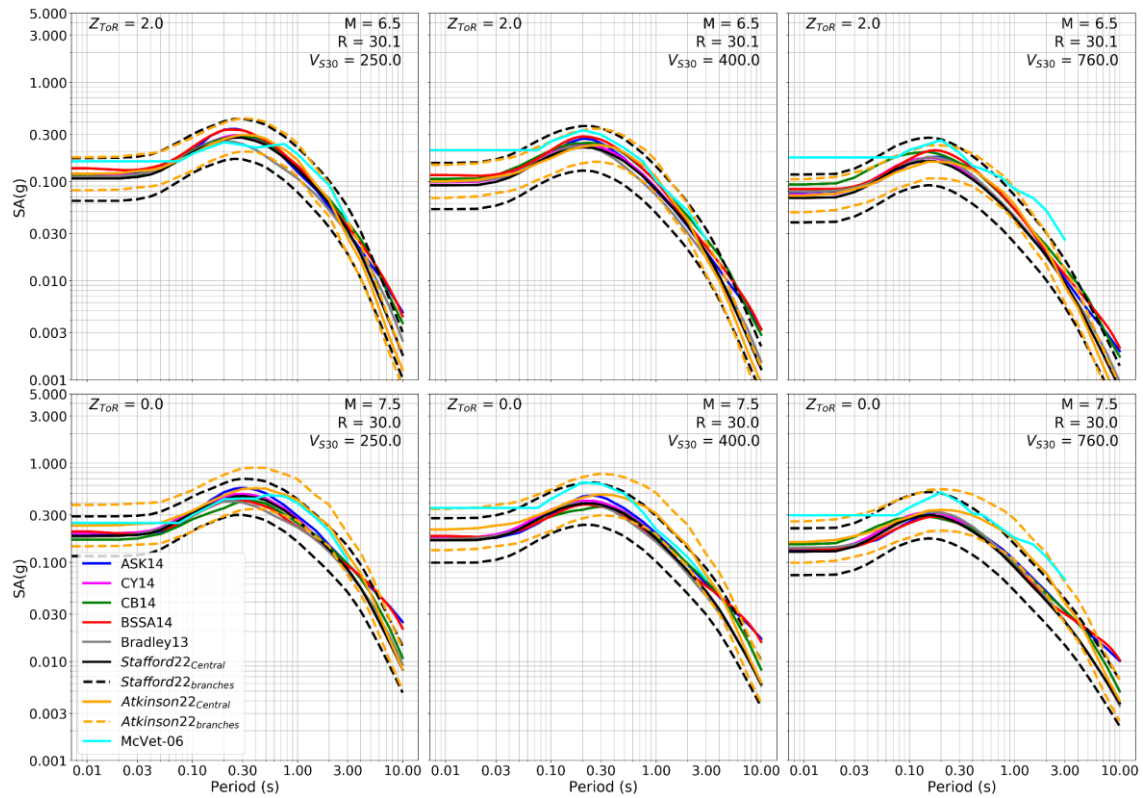


Figure 2. Plots depicting full response spectral plots for crustal GMMs corresponding to M6.5 event (upper panels) and M7.5 (lower panels). The events correspond to strike-slip faulting and the plots are shown for a fixed  $R_x = 30$  km.

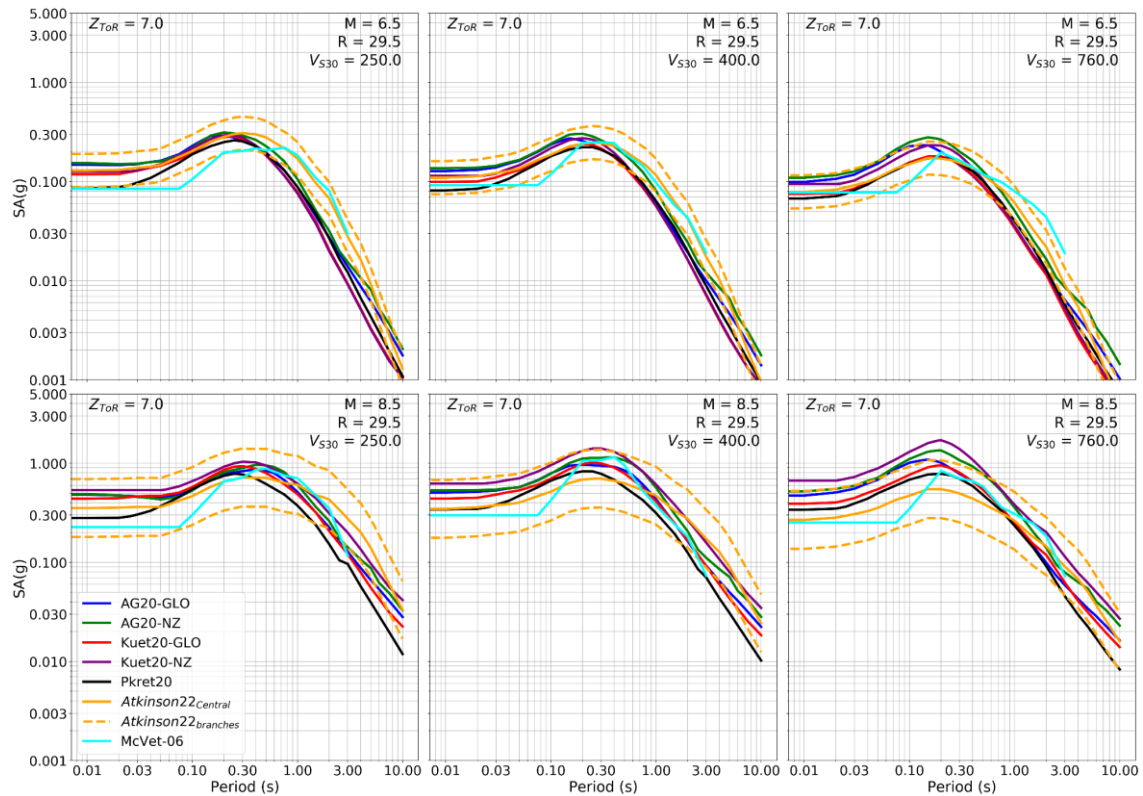


Figure 3. Plots depicting full response spectral plots for subduction interface GMMs corresponding to M6.5 event (upper panels) and M8.5 (lower panels). The events correspond to reverse faulting and the plots are shown for a fixed distance  $R_x = 30$  km.



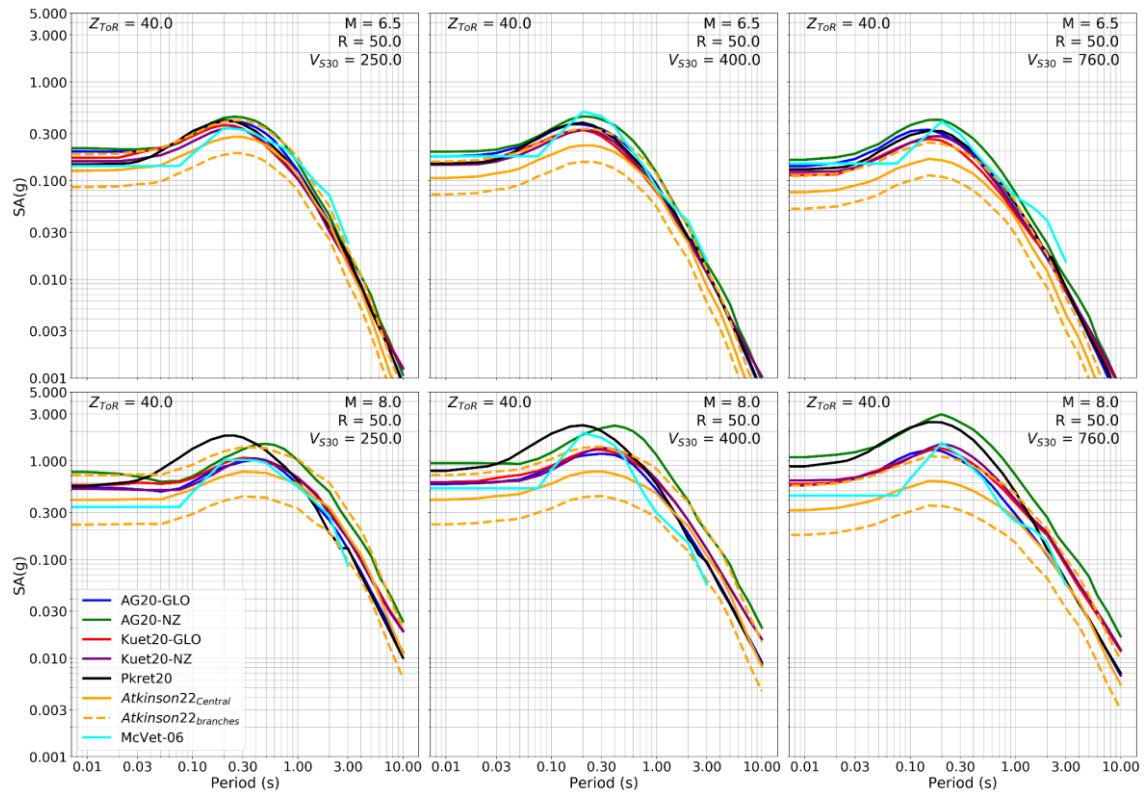


Figure 4. Plots depicting full response spectral plots for subduction intra-slab GMMs corresponding to M6.5 event (upper panels) and M8.0 (lower panels). The events correspond to reverse faulting and the plots are shown for a fixed distance  $R_x = 30$  km.

### 3 Sensitivity Analysis

Current revision of New Zealand NSHM envisages a multi-model approach for GMCM. This involves including recently derived global models and NZ specific GMMs to capture the center, body and range of epistemic uncertainty. In this section, we show the impact of these GMMs on the hazard calculations. Figures 5, 6 and 7 depict hazard curves for Auckland, Christchurch and Wellington, respectively. In these figures, the hazard curves are shown for individual GMM for the three tectonic region types (TRTs) separately. Note that the hazard curves are shown for a single source branch and at a site with  $V_{S30} = 400$  m/s. It is also worth mentioning that these plots show the hazard curves corresponding to the central branch for Stafford (2022) and Atkinson (2022). These plots are important in deciphering relative impact of individual GMMs on the hazard estimates and the range of epistemic uncertainty captured by the (central) models. Both, the level of hazard and associated epistemic uncertainty, vary significantly from location to location depending upon the type of sources dominating the hazard at that location.

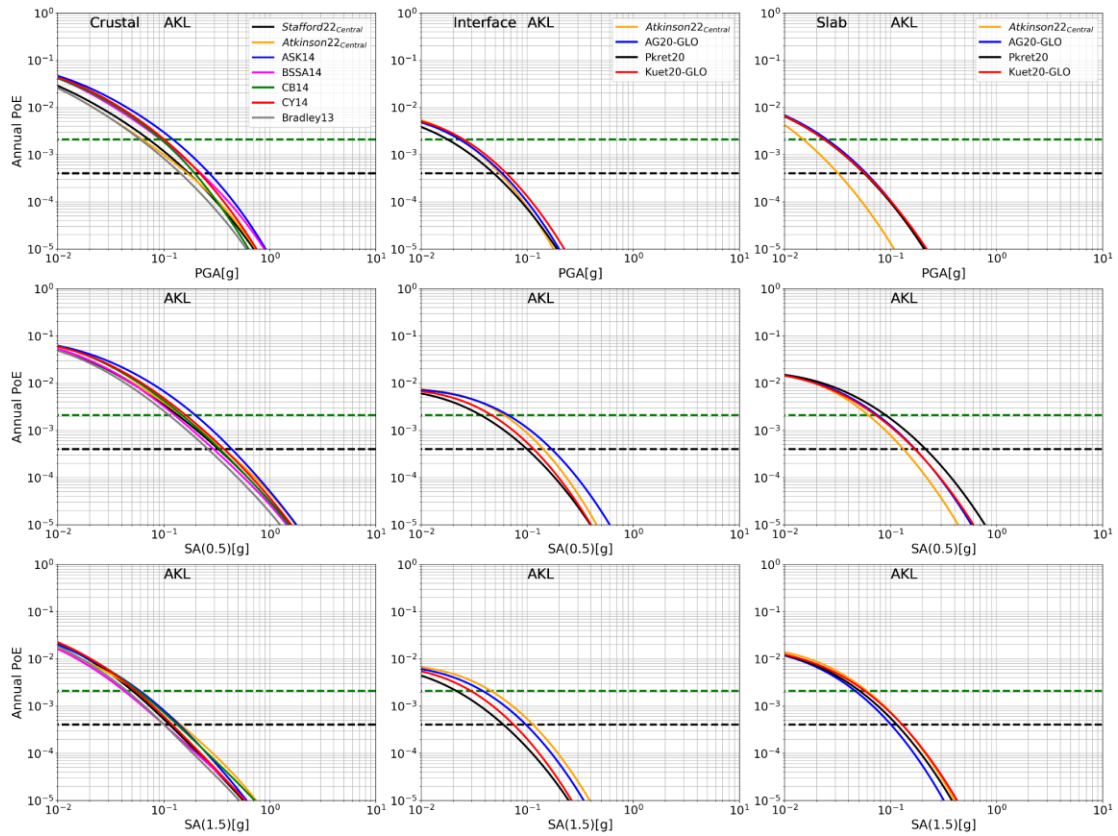


Figure 5. Plots depicting the hazard curves in Auckland for all types of seismicity. The green and black horizontal dashed lines represent annual probability of exceedances (PoEs) corresponding to 10% and 2% PoE in 50 years.

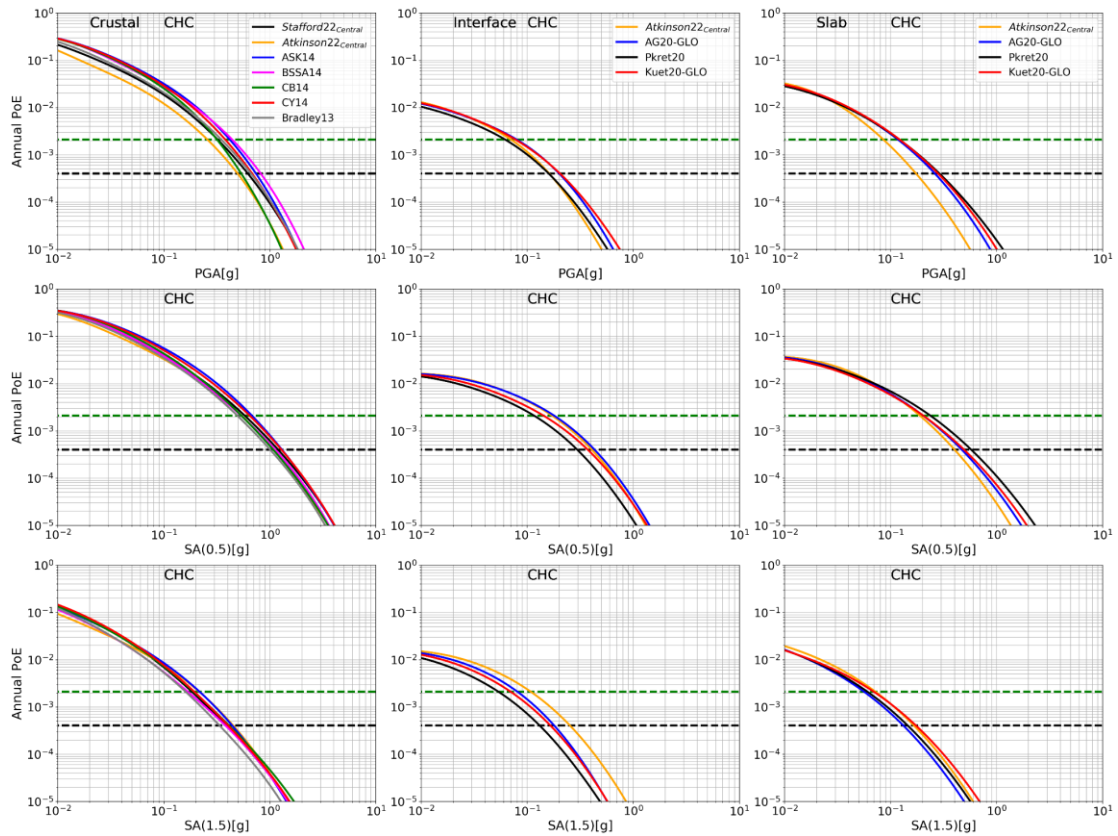


Figure 6. Plots depicting the hazard curves in Christchurch for all types of seismicity. The green and black horizontal dashed lines represent annual PoEs corresponding to 10% and 2% PoE in 50 years.

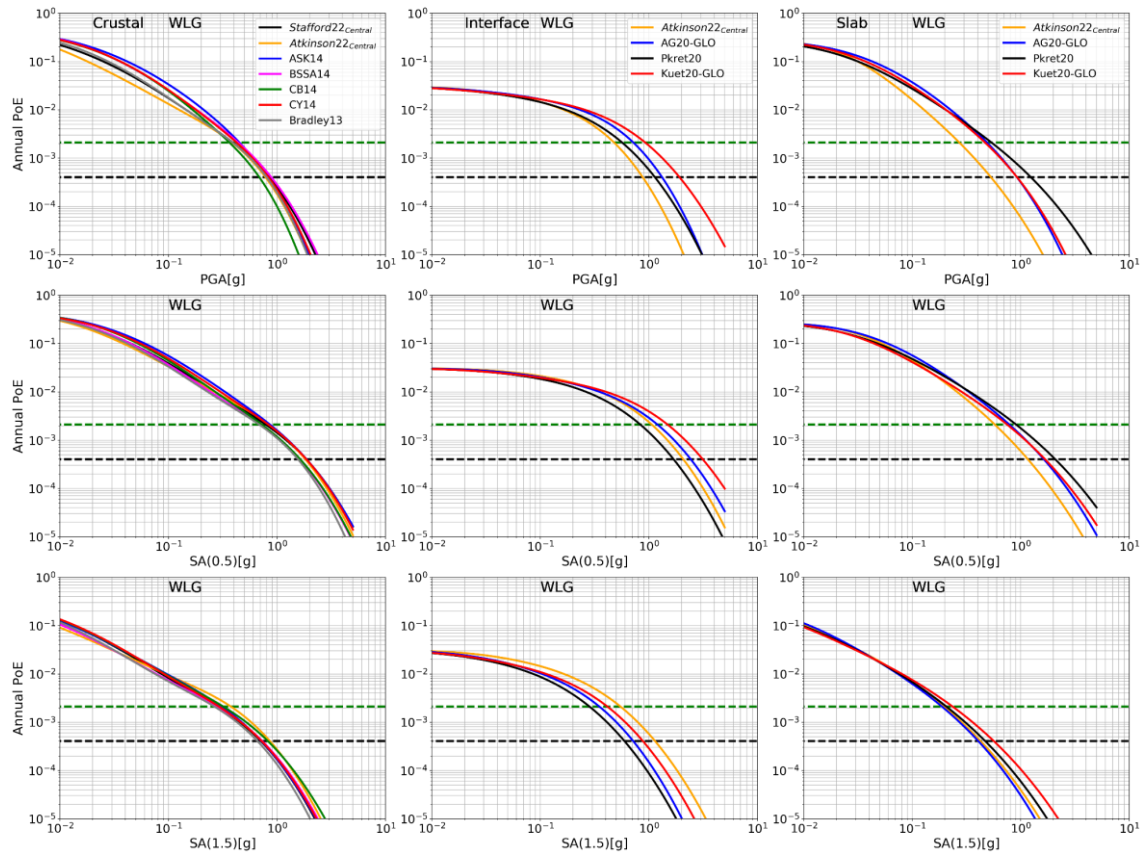


Figure 7. Plots depicting the hazard curves in Wellington for all types of seismicity. The green and black horizontal dashed lines represent annual PoEs corresponding to 10% and 2% PoE in 50 years.

## 4 Conclusions

The NZ NSHM 2022 is a fundamental revision of nearly all components of prior NSHMs in NZ and in this paper, we have presented analysis of hazard sensitivities with respect to a proposed GMCM scheme. The candidate models were assessed by comparing median and aleatory uncertainty components for the rupture scenarios that dominate hazard in high seismicity locations in the north and South Island. Subsequently, a comparative analysis of epistemic uncertainty range was presented across events for selected relevant scenarios. It was clearly observed that the inclusion of the two New Zealand specific backbone GMMs have increased the range of epistemic uncertainty that is being captured across all event types. Furthermore, we also showed how the impact of between-model epistemic uncertainty was reflected in hazard curves at selected key locations in New Zealand using a single branch of the updated SRM.

The full suite of the final hazard results of the 2022 NZ NSHM are available online using the NSHM web application at: <https://nsh.m.gns.cri.nz/>.

All model components are openly available so that results may be reproduced in the OpenQuake engine (Pagani et al., 2014).

## 5 Acknowledgments

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## 6 References

- Abrahamson NA, Silva WJ, Kamai R. 2014. Summary of the ASK14 Ground Motion Relation for Active Crustal Regions. *Earthquake Spectra*. 30(3):1025-1055. doi:10.1193/070913EQS198M.
- Abrahamson, N. A., and Gulerce, Z. (2020). Regionalized Ground-Motion Models for Subduction Earthquakes Based on the NGA-SUB Database (No. PEER Report No. 2020/25) (p. 237).
- Allen, T.I., Griffin, J.D., Leonard, M., Clark, D.J. and Ghasemi, H. (2020). The 2018 national seismic hazard assessment of Australia: Quantifying hazard changes and model uncertainties. *Earthquake Spectra*, 36(1\_suppl), pp.5-43.
- Ancheta T. D. Darragh R. B. Stewart J. P. Seyhan E. Silva W. J. Chiou B. S.-J. Wooddell K. E. Graves R. W. Kottke A. R., and Boore D. M., et al. (2014). NGA-West2 database, *Earthq. Spectra* 30, 989–1005.
- Atkinson, G. M. (2022). Backbone ground motion models for crustal, interface, and slab earthquakes in New Zealand (No. National Seismic Hazard Model report) (p. 61).
- Bradley, B. A. (2013). A New Zealand-Specific Pseudospectral Acceleration Ground-Motion Prediction Equation for Active Shallow Crustal Earthquakes Based on Foreign Models. *Bulletin of the Seismological Society of America*, 103(3), 1801–1822. DOI: 10.1785/0120120021.
- Bradley B.A, Bora S., Lee, R., Manea, E., Gerstenberger, M., Hutchinson, J., van Dissen, R. (2022). Summary of the ground-motion characterisation model for the 2022 New Zealand national seismic hazard model GMCM Summary. Lower Hutt (NZ): GNS Science. (GNS Science report; 2022/46). doi:10.21420/9BMK-ZK64.
- Boore DM, Stewart JP, Seyhan E, Atkinson GM. (2014). NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes, *Earthquake Spectra*. 30 1057-1085.
- Campbell, K.W., and Y. Bozorgnia (2014). NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra, *Earthquake Spectra*. 30 1087-1115.
- Chiou, B.S.-J., and R.R. Youngs (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra, *Earthquake Spectra*. 30 1117-1153.
- Gerstenberger MC, Van Dissen RJ, Rollins C, DiCaprio C, Chamberlain C, Christophersen A, Coffey GL, Ellis SM, Iturrieta P, Johnson KM, et al. (2022). The Seismicity Rate Model for the 2022 New Zealand National Seismic Hazard Model. Lower Hutt (NZ): GNS Science. (GNS Science report; 2022/47). doi:10.21420/2EXG-NP48.



- Hutchinson, J., Bradley, B. A., Lee, R. L., Wotherspoon, L. M., Dupuis, M., Schill, C., Motha, J., et al., 2022. 2021 New Zealand ground motion database (No. National Seismic Hazard Model report) (p. 52).
- Hutchinson J., Bradley B.A., Lee R., Schill C., Dupuis M., Motha J., van Houtte C., Kaiser A.E., Manea E.F., Wotherspoon L. (2022). Insights from the 2021 New Zealand Strong Ground Motion Database. Proceedings of the 2022 New Zealand Society for Earthquake Engineering Annual Technical Conference
- Kuehn, N. M., Bozorgnia, Y., Campbell, K. W., and Gregor, N., 2020. Partially Non-Ergodic Ground-Motion Model for Subduction Regions using the NGA-Subduction Database (No. PEER Report 2020/04) (p. 187).
- Lee, R. L., Bradley, B. A., Manea, E., and Hutchinson, J., 2022. Evaluation of empirical ground-motion models for New Zealand application (No. New Zealand National Seismic Hazard Model report) (p. 153).
- McVerry, G. H., J. X. Zhao, N. A. Abrahamson, and P. G. Somerville. 2006. Response spectral attenuation relations for crustal and subduction zone earthquakes, Bull. New Zeal. Soc. Earthquake Eng. 39, 1–58.
- Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L. and Simionato, M., 2014. OpenQuake engine: An open hazard (and risk) software for the global earthquake model. Seismological Research Letters, 85(3), pp.692-702.
- Parker, G. A., Stewart, J. P., Boore, D. M., Atkinson, G. M., and Hassani, B., 2020. PEER 2020/03 August 2020 NGA-Subduction Global Ground-Motion Models with Regional Adjustment Factors (No. PEER Report 2020/03) (p. 131).
- Petersen, M.D., Shumway, A.M., Powers, P.M., Mueller, C.S., Moschetti, M.P., Frankel, A.D., Rezaeian, S., McNamara, D.E., Luco, N., Boyd, O.S. and Rukstales, K.S., 2020. The 2018 update of the US National Seismic Hazard Model: Overview of model and implications. Earthquake Spectra, 36(1), pp.5-41.
- 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. (With data repository available at: <https://doi.org/10.21420/NMSX-WP67>)
- Stafford, P. J., 2022. A model for the distribution of response spectral ordinates from New Zealand crustal earthquakes based upon adjustments to the Chiou and Youngs (2014) response spectral model (p. 122).
- Stirling, M., McVerry, G., Gerstenberger, M., Litchfield, N., Van Dissen, R., Berryman, K., Barnes, P., et al., 2012. National seismic hazard model for New Zealand: 2010 update. Bulletin of the Seismological Society of America, 102(4), 1514–1542. DOI: 10.1785/0120110170.

- Thingbaijam KKS, Gerstenberger MC, Rollins C, Christophersen A, Williams CA, Ristau J, Rastin SJ, Fraser J, Van Dissen RJ. 2022B. A seismogenic slab source model for New Zealand. Lower Hutt (NZ): GNS Science. 27 p. (GNS Science report; 2021/50). doi:10.21420/CDMK-3F30.
- Wotherspoon LM, Kaiser AE, Manea EF, Stolte AC. 2022. National Seismic Hazard Model: Site Characterisation Database summary report. Lower Hutt (NZ): GNS Science. (GNS Science report; 2022/28). doi:10.21420/363X-CK83.