The Ground-Motion Characterization Model for the 2022 New Zealand National Seismic Hazard Model

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ABSTRACT

This article summarizes the ground-motion characterization (GMC) model component of the 2022 New Zealand National Seismic Hazard Model (2022 NZ NSHM). The model development process included establishing a NZ-specific context through the creation of a new ground-motion database, and consideration of alternative ground-motion models (GMMs) that have been historically used in NZ or have been recently developed for global application with or without NZ-specific regionalizations. Explicit attention was given to models employing state-of-the-art approaches in terms of their ability to provide robust predictions when extrapolated beyond the predictor variable scenarios that are well constrained by empirical data alone. We adopted a "hybrid" logic tree that combined both a "weights-on-models" approach along with backbone models (i.e., metamodels), the former being the conventional approach to GMC logic tree modeling for NSHM applications using published models, and the latter being increasingly used in research literature and site-specific studies. In this vein, two NZ-specific GMMs were developed employing the backbone model construct. All of the adopted subduction GMMs in the logic tree were further modified from their published versions to include the effects of increased attenuation in the back-arc region; and, all but one model was modified to account for the reduction in ground-motion standard deviations as a result of nonlinear surficial site response. As well as being based on theoretical arguments, these adjustments were implemented as a result of hazard sensitivity analyses using models without these effects, which we consider gave unrealistically high hazard estimates.

KEY POINTS

- The modeling considerations and adopted ground-motion characterization (GMC) logic tree of the 2022 New Zealand National Seismic Hazard Model (NZ NSHM) are described.
- Nine distinct ground-motion models (GMMs) were adopted with weights assigned based on structured expert elicitation.
- Models were adjusted to include back-arc attenuation and nonlinear site effects on standard deviations.

INTRODUCTION

This article provides a high-level overview of the ground-motion characterization (GMC) model component of the 2022 New Zealand National Seismic Hazard Model (Te Tauira Matapae Pūmate Rū i Aotearoa), herein "2022 NZ NSHM" for brevity. This GMC component of the 2022 NZ NSHM brings together multiple ground-motion models (GMMs) to forecast earthquake-induced ground motions. The intent of this article is to

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describe the process that resulted in the final GMC logic tree, including the underpinning individual models, if and how they were modified, and the adopted logic tree weights. Several aspects of this model development are described in further detail in other articles in this issue, and therefore we largely restrict attention to the overarching intent by which such activities were undertaken, the resulting analysis of data and other key considerations, and the final integration to produce the GMC model.

In a NZ context, the GMC model developed in NSHM 2022 is a significant advancement from prior ground-motion modeling in the past NZ NSHMs (Stirling *et al.*, 2002, 2012), which previously considered only a single GMM based on New Zealand-specific observations from pre-2000 (i.e., McVerry *et al.*, 2006; albeit the Canterbury- and Kaikōura-specific regionalizations of the NZ NSHM, Gerstenberger *et al.*, 2016 did make use of multiple GMMs in a "weights-on-models" logic tree approach). It is also worth noting that the 2010 NZ NSHM update (Stirling *et al.*, 2012) was essentially just an update to the seismic source characterization model since the exact same approach was taken in the GMC model with the singular use of the McVerry *et al.* (2006) model, and also this 2010 update was not formally utilized in any major building code or standard updates (Gerstenberger *et al.*, 2022). Hence, the GMC model development for the 2022 NZ NSHM (which, at the time of writing this article, is already being adopted in a technical specification amendment in the NZ seismic loadings standard) represented the first change in earthquake-induced ground-motion modeling in NZ for ∼20 yr.

Over the past two decades, there have been significant advancements in the state-of-the-art and practice of GMC model development. Naturally, the leading edge is geared more toward site-specific seismic hazard studies for high-importance safety-critical facilities and includes considerations to (1) explicitly relax the ergodic assumption (Anderson and Brune, 1999); (2) improve predictions for seismic scenarios that are poorly constrained from empirical observations alone (by drawing on insights from numerical simulations or seismological theory); and (3) more consistently represent epistemic uncertainty through the use of "backbone" models (e.g., Boore *et al.*, 2022), which explicitly quantify epistemic uncertainty within a given model, as opposed to the traditional logic tree weights on alternative models that implicitly gives rise to between-model epistemic uncertainty. The GMC modeling for various NSHM developments (e.g., Petersen *et al.*, 2020) naturally seeks to follow such contemporary considerations, but is complicated by (1) the consideration of a geographical region, rather than a single site; and (2) the use of model results for informing seismic design codes and standards, which typically are revised on the scale of a decade(s) and users for which often prefer hazard stability over the consideration of leading-edge scientific thinking (given that the scientific process naturally results in "dead ends" as well new advancements). In the development of the 2022 NZ NSHM, we sought to further close the gap between site-specific and conventional NSHM GMC modeling approaches. In addition, we sought to develop some of the foundational datasets and models necessary to facilitate the application of state-of-the-art site-specific hazard analysis in NZ, for example, a new ground-motion database and site characterization that would enable nonergodic site effects to be considered (Baker *et al.*, 2021, chapter 8).

The remainder of this article is ordered into three primary sections. First, we describe the NZ-specific ground-motion database that was developed, the GMMs that were considered, the quantitative performance of the prospective models against this NZ-specific database, and the key features of the alternative models for seismic scenarios that dominate the hazard for major population centers in NZ but cannot be adequately quantified due to a lack of such scenarios in the NZ ground-motion database. Second, the adopted logic tree is then presented and discussed, with an emphasis on the consideration of both the new NZ-specific backbone models and the existing models, how model weights were determined via expert elicitation, and how within-model epistemic uncertainty was additionally applied. Third, the first-order deficiencies in several models, and subsequent adjustments that were applied, are discussed. We also briefly address the consideration of near-fault directivity as well as limitations in the adopted GMC model that were due to both data and time constraints.

NZ-SPECIFIC DATASETS AND PROSPECTIVE MODEL EXAMINATION

NZ ground-motion database

The development of a NZ-specific GMC model for the NZ NSHM naturally requires a region-specific ground-motion database of sufficient data quality and quantity to provide insights into the appropriateness of existing (published) GMMs, as well as a basis for the development of NZ-specific adaptions of general GMM functional forms (Bommer and Stafford, 2020). As elaborated upon by Hutchinson *et al.* (2022, 2023), prior NZ ground-motion databases in the past 15 yr include those by Zhao and Gerstenberger (2010), Bradley (2013), and Van Houtte *et al.* (2017). The database of Zhao and Gerstenberger (2010) was further manipulated in the NZ-specific adjustments leading to the Bradley (2013; hereafter, B13) GMM, whereas Van Houtte (2017) used their 2017 database (Van Houtte *et al.*, 2017) to examine the applicability of NZ-specific and international GMMs for use in NZ hazard analysis. For the 2022 NZ NSHM, we elected to completely redevelop a ground-motion database, building on the most recent work by Van Houtte *et al.* (2017) with two primary motivations. First, to significantly increase the number of events and recordings with a view toward improving the degree to which NZ-specific data could be used in the nonergodic analysis, whether they be site-specific or regional (e.g., Baker *et al.*, 2021; Lavrentiadis *et al.*, 2022). As well as the increase in a number of ground motions available due to the five-year period since the publication of Van Houtte *et al.*

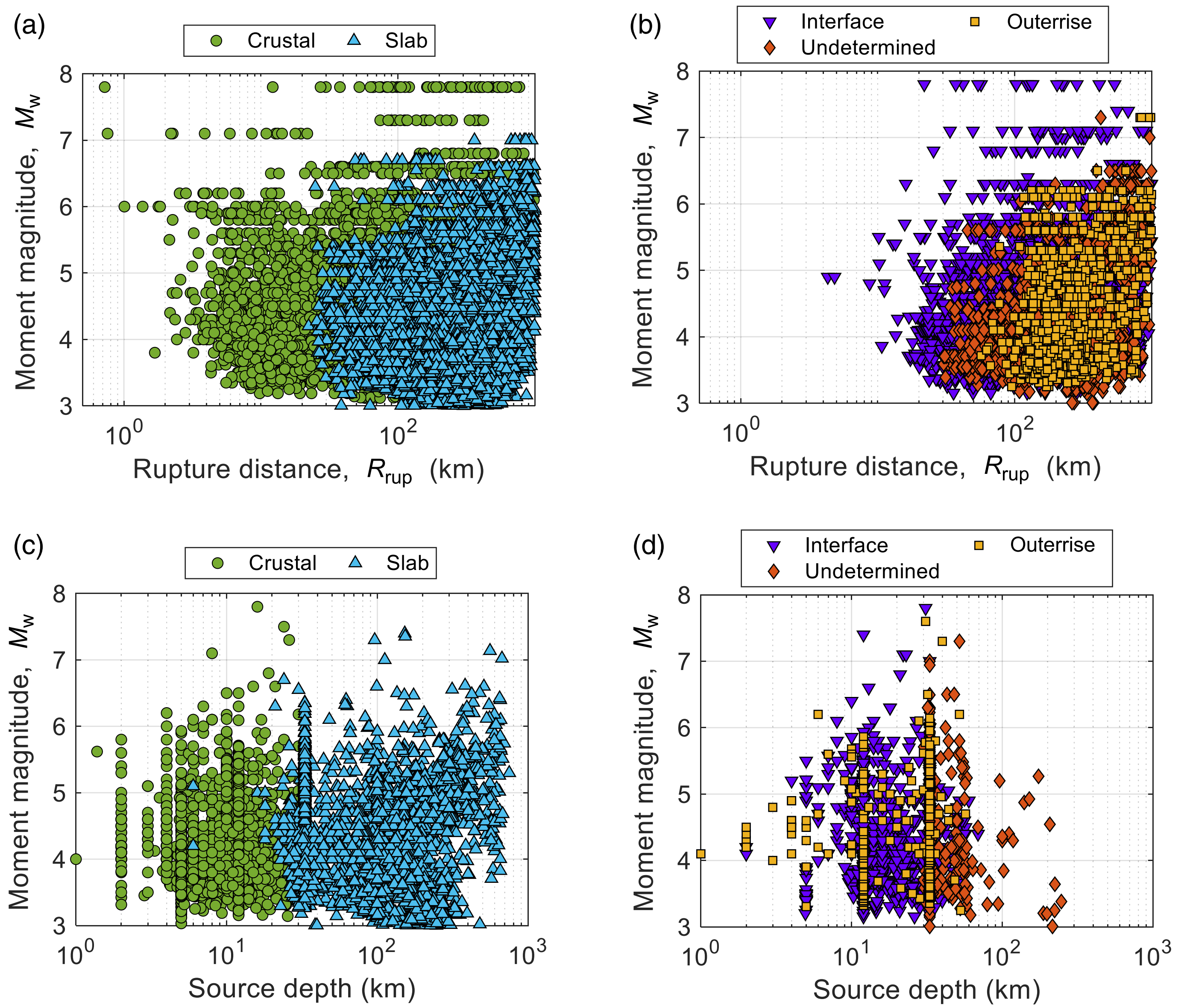

Figure 1. (a,b) Magnitude versus source-to-site distance, and (c,d) magnitude versus source depth distribution of the 2023 New Zealand (NZ) ground-motion database, after Hutchinson *et al.* (2023). The color version of this figure is available only in the electronic edition.

(2017), the principal means of increasing the dataset came from extending the lower magnitude range, and upper source-to-site distance ranges considered. Doing so requires additional care to ensure the quality of these weaker amplitude ground motions, in particular, the maximum and the minimum frequency ranges. Second, significant attention was placed on improving the quality of the event and site metadata.

The developed 2023 NZ ground-motion database (Hutchinson *et al.*, 2023) comprises ground motions from 5067 earthquakes of magnitude **M** > 3, recorded at 359 different instrument locations, giving rise to 32,349 three-component ground-motion time series for which a range of different intensity measures (IMs) are computed. This dataset has been subject to quality assurance and control and represents ~12% of ground motions from an underlying initial database that was extracted from the national GeoNet network. The ground-motion data and associated metadata are stored in a relational database that includes separate tables for source, path, and site metadata; intensity measures of the time series, and phase arrival and station magnitude tables (principally used for improving event-magnitude estimates from automatically computed network values; Hutchinson *et al.*, 2023).

Figure 1 provides a summary of the ground-motion data in terms of its distribution of magnitude, source-to-site distance, and source depth. It is noted that the prior NZ-specific database of Van Houtte *et al.* (2017) included 276 events and 4148 ground motions. Hence, this 2023 database revision represents an increase of eightfold ground motions and 18-fold events.

Although the principal focus of the 2022 NZ NSHM was the development of a GMC model for 5% response spectra, the NZ

TABLE 1
Descriptions and Key Parameter Ranges for Considered Active Shallow Crustal Models

Model	Abbreviation	M*	R_{rup} (km)	V_{S30} (m/s)
McVerry *et al.* (2006)	McV06	5.25–7.5	0–400	—†
Bradley (2013)	B13	3.5–8.5	0–400	180–1500
Abrahamson *et al.* (2014)	AS14	3.0–8.5	0–300	180–1500
Boore *et al.* (2014)	BSSA14	3.0–8.5	0–400‡	150–1500
Campbell and Bozorgnia (2014)	CB14	3.3–8.5	0–300	150–1500
Chiou and Youngs (2014)	CY14	3.5–8.5	0–300	180–1500
Atkinson (2022)	A22	4.5–8.5	0–400	150–1000
Stafford (2022)	S22	4.5–8.4	0–300	180–1500

*Range shown is indicative of the widest range considering all faulting styles.
†McV06 uses alphabet-based site classes.
‡Distance range is formally defined for R_{jb}.

TABLE 2
Descriptions and Key Parameter Ranges for Considered Subduction Interface and Slab Models

		M		R_{rup} (km)		
Model	Abbreviation	Interface	Slab	Interface	Slab	V_{S30} (m/s)
McVerry *et al.* (2006)	McV06	5.25–7.5	5.25–7.5	0–400	0–400	—*
Zhao *et al.* (2006)	Z06	5–8.5†	5–8.5†	0–300†	0–300†	—*
Abrahamson *et al.* (2016)	A16	6–8.8†	5–7.9†	0–300†	0–300†	150–1500†
Abrahamson *et al.* (2018)	A18	5–9.5	5–9.5	0–1000	0–1000	150–1500†
Abrahamson and Gülerce (2020)	AG20	6–9.5	5–8	0–500	0–500	150–1500
Kuehn *et al.* (2020)	KBCG20	5–9.5	5–8.5	10–1000	10–1000	150–1500
Parker *et al.* (2022)	PSBAH22	4.5–9.5	4.5–8.5	20–1000	35–1000	150–2000
Atkinson (2022)	A22	4.5–8.5	4.5–8.5	0–400	0–400	150–1000

*McV06 and Z06 use alphabet-based site classes.
†Approximate applicable parameter range inferred from details in the respective publication since they were not explicitly stated.

ground-motion database includes computed intensity measures for a multitude of additional IMs, including peak ground acceleration, peak ground velocity, cumulative absolute velocity, Arias intensity, significant duration, and Fourier amplitude spectra. Similar to Van Houtte *et al.* (2017), tectonic classification, focal mechanisms, finite-fault geometries, source-to-site distances, and site condition information were also included. Specific details on the site database component of this overall ground-motion database are summarized in Wotherspoon *et al.* (2023).

Despite these advances, as is common globally, the NZ-specific database still lacks a large number of observations at large magnitude and small source-to-site distances (e.g., $\mathbf{M} > 6$, $R_{rup} < 50$ km). As a result, it is still considered infeasible to develop NZ-specific GMMs based solely on NZ data. Therefore, reliance on global data-based models or theoretically based seismological models is necessary to ensure realistic scaling in the magnitude and distance ranges of most importance to hazard, with the potential for NZ-specific adjustments to models in the prediction model space where constraints are possible.

GMMs considered

As elaborated upon in further detail by Lee, Bradley, Manea, *et al.* (2022) and Lee *et al.* (2023), we initially considered GMMs that satisfied suitable criteria for magnitude, source-to-site distance, 30 m averaged shear-wave velocity (V_{S30}), and pseudospectral acceleration (SA) vibration period ranges that make them usable for contemporary seismic hazard analysis in a country of high seismicity. We also restricted the scope to the consideration of models for 5% viscous damped SA. This resulted in the GMMs listed in Tables 1 and 2 for active shallow crustal and subduction sources, respectively, and we use the model abbreviations listed in these tables herein.

For active shallow crustal ground motions, the McV06 model (McVerry *et al.*, 2006) was considered for historical reasons, being the sole model used in the 2010 NZ NSHM, even though it did not satisfy the necessary criteria. Four models from the Next Generation Attenuation (NGA)-West2 project (Bozorgnia *et al.*, 2014) were considered (Abrahamson and Silva, 2008; Boore *et al.*, 2014; Campbell and Bozorgnia, 2014; Chiou and Youngs, 2014, denoted as ASK14, BSSA14, CB14, and CY14 in Table 1), as well as the NZ-specific model of Bradley (2013), which is based on modifications to the Chiou *et al.* (2010) model, which is a precursor to the Chiou and Youngs (2014) model. Finally, the A22 and S22 models (Atkinson, 2022; Stafford, 2022) are NZ-specific models developed during the course of the 2022 NZ NSHM project.

Table 2 illustrates that the considered subduction GMMs, specifically the recently completed NGA-Subduction (Sub) project (Abrahamson and Gülerce, 2020; Kuehn *et al.*, 2020; Parker *et al.*, 2022; Bozorgnia *et al.*, 2022) models, denoted as AG20, KBCG20, and PSBAH22, and the McV06 and A22 models for the aforementioned reasons noted for active shallow crustal sources. Because the NGA-Sub models were not available (in report form and subsequent OpenQuake computational implementation) until approximately the second half of the 2022 NZ NSHM development timeline, we also considered the Z06 (Zhao *et al.*, 2006), A16, and A18 (Abrahamson *et al.*, 2016, 2018) models, which have been commonly used as subduction GMMs in NZ and international settings (e.g., Van Houtte *et al.*, 2017; Petersen *et al.*, 2020). Ultimately, we had sufficient time to examine the NGA-Sub models in the second half of the NSHM project such that we did not consider the McV06, Z06, A16, and A18 models in the final GMC logic tree.

Evaluation of prospective models against observed NZ ground motions

Lee, Bradley, Manea, *et al.* (2022) examined the predictive performance of global and NZ-specific ground motion models against the NZ database discussed in the previous section. As discussed in Lee, Bradley, Manea, *et al.* (2022), additional quality criteria were ultimately applied to the database, such as (1) a moment magnitude estimate based on finite fault or centroid moment tensor modeling; (2) a magnitude-dependent source-to-site distance filter to focus on ground motions of engineering interest; and (3) removal of HH and BH seismometer instrument channels (IRIS, 2012), which exhibit data quality issues. Insights into the predictive capability of the models with respect to the NZ-specific observations were ascertained through mixed-effects regression analysis of the prediction residuals:

$$\Delta = \ln \mathrm{IM}_{\mathrm{obs},es} - f_{es} = a + \delta B_e + \delta S2S_s + \delta W_{es}^0,$$

in which Δ is the total residual given by the logarithmic difference between the observation ($\mathrm{IM}_{\mathrm{obs},es}$) and model prediction ($f_{es}$); a is the total model bias; and δB_e, $\delta S2S_s$, δW_{es}^0 are the between-event, between-site, and remaining residuals with zero mean and variances of τ^2, ϕ_{S2S}^2, and ϕ_{SS}^2, respectively. The total residual variance is obtained from these residual components as $\sigma^2 = \tau^2 + \phi_{S2S}^2 + \phi_{SS}^2$.

Figure 2 summarizes the results of Lee, Bradley, Manea, *et al.* (2022) in terms of the bias, a, and total standard deviation, σ, of the results across all events and ground motions considered. Figure 2a,b illustrates that for crustal events, with the exception of the McVerry *et al.* (2006) model (considered solely for historical reasons, as previously noted), the remaining models that were adopted exhibit similar values for the total model prediction bias, albeit that higher bias values are seen in the S22 model at short periods, and the S22 and A22 models at long periods. In terms of residual total standard deviations, all models are similar, with some deviation for the CY14 and CB14 models at short vibration periods, which is largely due to higher between-event residual standard deviations. Figure 2c–f provides the same results for subduction interface and slab events. As previously noted, the Z06, A16, and A18 models were considered for historical reasons. The figures illustrate that, for interface events, all models have an overall bias typically within 0.5 (natural log) units and residual total standard deviations that are ~0.8–0.9 units across the range of vibration periods. For slab events, there is a wider variation in the residual bias range, with the PSHAB22 and Z06 models both having biases close to ±1.0 for a wide range of vibration periods. The residual total standard deviations are also larger, with values exceeding 1.0 for short vibration periods.

A primary limitation in examining the results from these residual analyses is the distribution of rupture scenario parameters relative to those that are predominant in seismic hazard analysis results for locations in NZ. In this regard, as seen already in the previous section's discussion on the NZ ground-motion database, there is a general lack of large magnitude, small source-to-site distance records. This is even more the case for subduction events and especially slab events. As a result, model performance in these evaluations was primarily considered to determine whether: (1) a model is considered for inclusion, given the limitations of the observed rupture scenarios and uncertainty in metadata values (from which the McV06 and Z06 models were excluded); (2) whether models that have been superseded by more recent additions provide similar or different predictions (from which the A16 and A18 models were excluded); and (3) whether the NZ-specific regionalizations of the NGA-Sub project (AG20 and KBCG20) provided any superior prediction relative to the global models.

We found that the NZ-specific regionalizations of the AG20 and KBCG20 subduction models contained predictor variable dependencies that were subjectively poor-performing and theoretically ill-justified as compared with their corresponding global models (particularly codependencies among source depth and source-to-site distance scaling for subduction slab models). We also had a first-hand understanding of the limitations of the Van Houtte *et al.* (2017) NZ-specific ground-motion database (principally small dataset size and poor metadata quality), which was used in the NGA-Sub project for developing the region-specific versions of these models (as explained in the previous section, such limitations were a primary motivator for the development of a revised database) and is further reinforced by Parker *et al.* (2022) choosing to entirely avoid developing a New Zealand-specific regionalization. Given all of the above, and that the NZ-specific regionalizations did not exhibit better

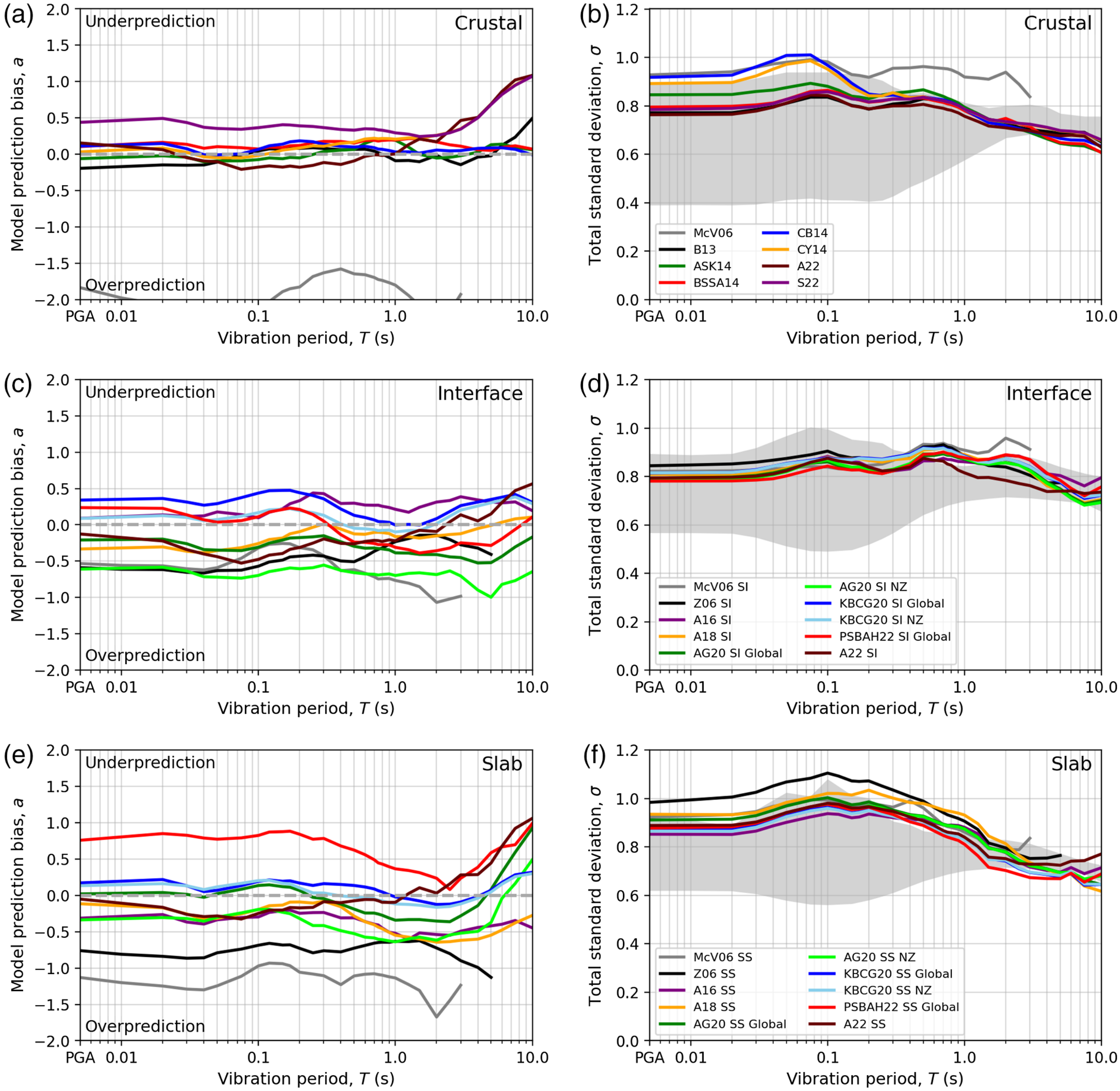

Figure 2. Summary evaluation results for (a) crustal model prediction bias; (b) crustal total standard deviation; (c) interface model prediction bias; (d) interface total standard deviation; (e) slab model prediction bias; and (f) slab total standard deviation. The gray shaded area indicates an approximate range of published model σ based on their development for the models considered and scenarios in the ground-motion database, for each tectonic class, after Lee *et al.* (2023). The color version of this figure is available only in the electronic edition.

performance against the NZ-specific database, as discussed in Lee, Bradley, Manea, *et al.* (2022), we ultimately decided that the global representations were better "base models" for use in the GMC logic tree, rather than the NZ-specific models. As elaborated upon in a later section of this article, we also made further modifications to several models to explicitly account for back-arc anelastic attenuation and nonlinear site response effects on apparent aleatory standard deviation predictions.

Evaluation of prospective models for hazard-dominating rupture scenarios

Median predictions. As previously noted, the NZ-specific dataset in isolation does not sufficiently cover the large magnitude, small source-to-site distance rupture scenarios that are of prime importance in seismic hazard analysis for an active seismic region such as NZ. Consequently, the residual bias and standard deviation results presented in the previous

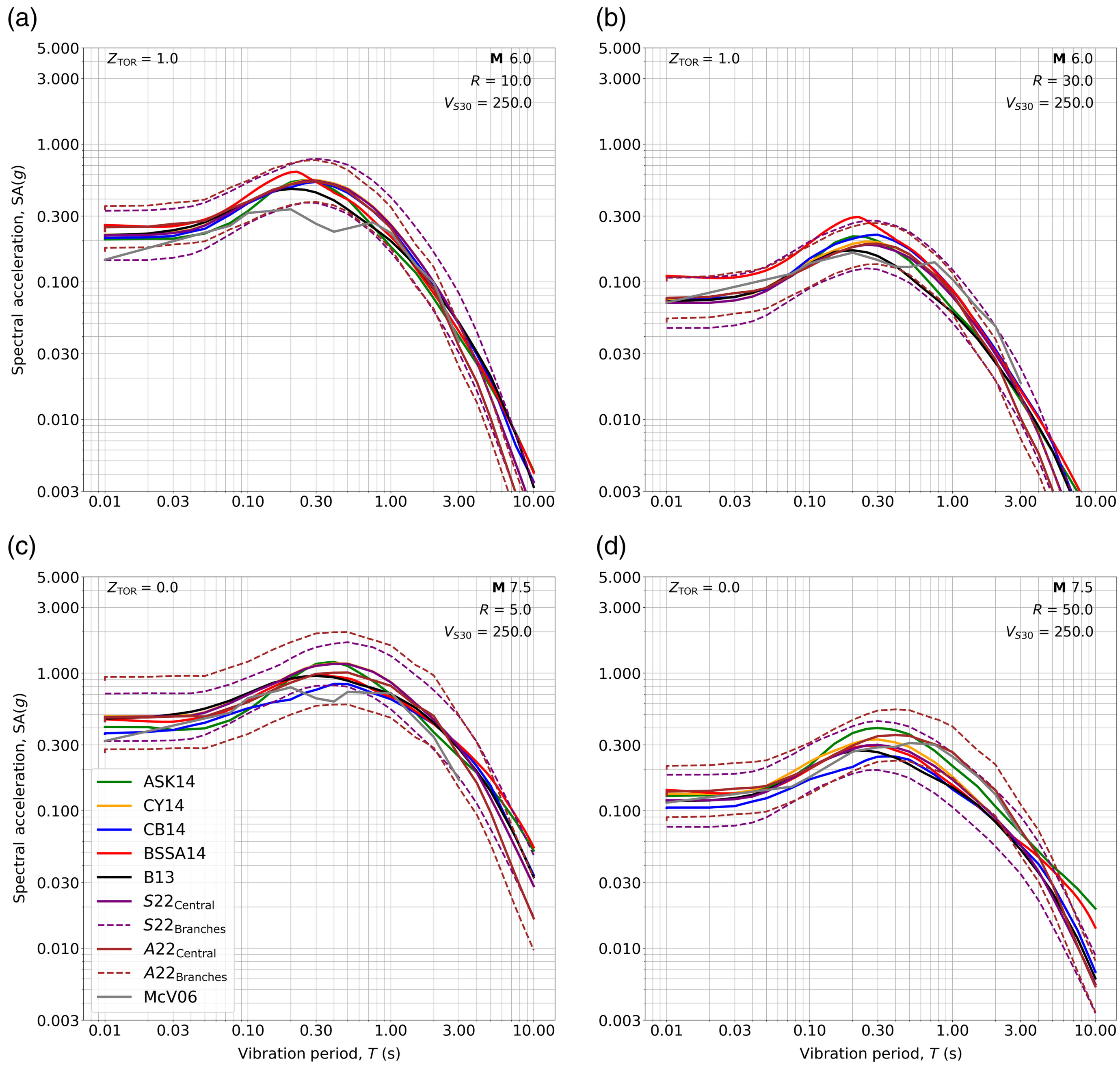

Figure 3. Comparison of median (specifically, exponent of logarithmic mean) predictions of the ground-motion models (GMMs) used in the active shallow crustal ground-motion characterization (GMC) logic tree for four seismic scenarios that typically dominate hazard: (a) **M** 6, $R = 10$ km; (b) **M** 6, $R = 30$ km; (c) **M** 7.5, $R = 5$ km; and (d) **M** 7.5, $R = 50$ km (all for $V_{S30} = 250$ m/s). The McV06 model is shown solely for its historical use in prior New Zealand National Seismic Hazard Models (NZ NSHMs). The 10th and 90th percentiles of the native epistemic uncertainty in A22 and S22 backbone models are also shown. The color version of this figure is available only in the electronic edition.

subsection are insightful, but not sufficient to judge the predictive performance of different models and the model-to-model differences that are observed. Therefore, the considered models were also examined for a wide array of predictor variable combinations that are of interest.

The aim of this examination was to understand the general features of the models in terms of predictor variable scaling, the intermodel differences, and diagnose any features that appeared inconsistent with analyst expectations. This was particularly the case for the NGA-Sub subduction GMMs considered, given that they had only been published in initial reports without blind peer review during the course of the NZ NSHM development and therefore had not been routinely used in site-specific or national-scale seismic hazard analyses (since the completion of the NZ NSHM in September 2022, these models have been subsequently published in archival journals).

Figures 3–5 illustrate the different median (exponent of logarithmic mean) predictions of the alternative models for crustal, interface, and slab tectonic types, respectively. For each

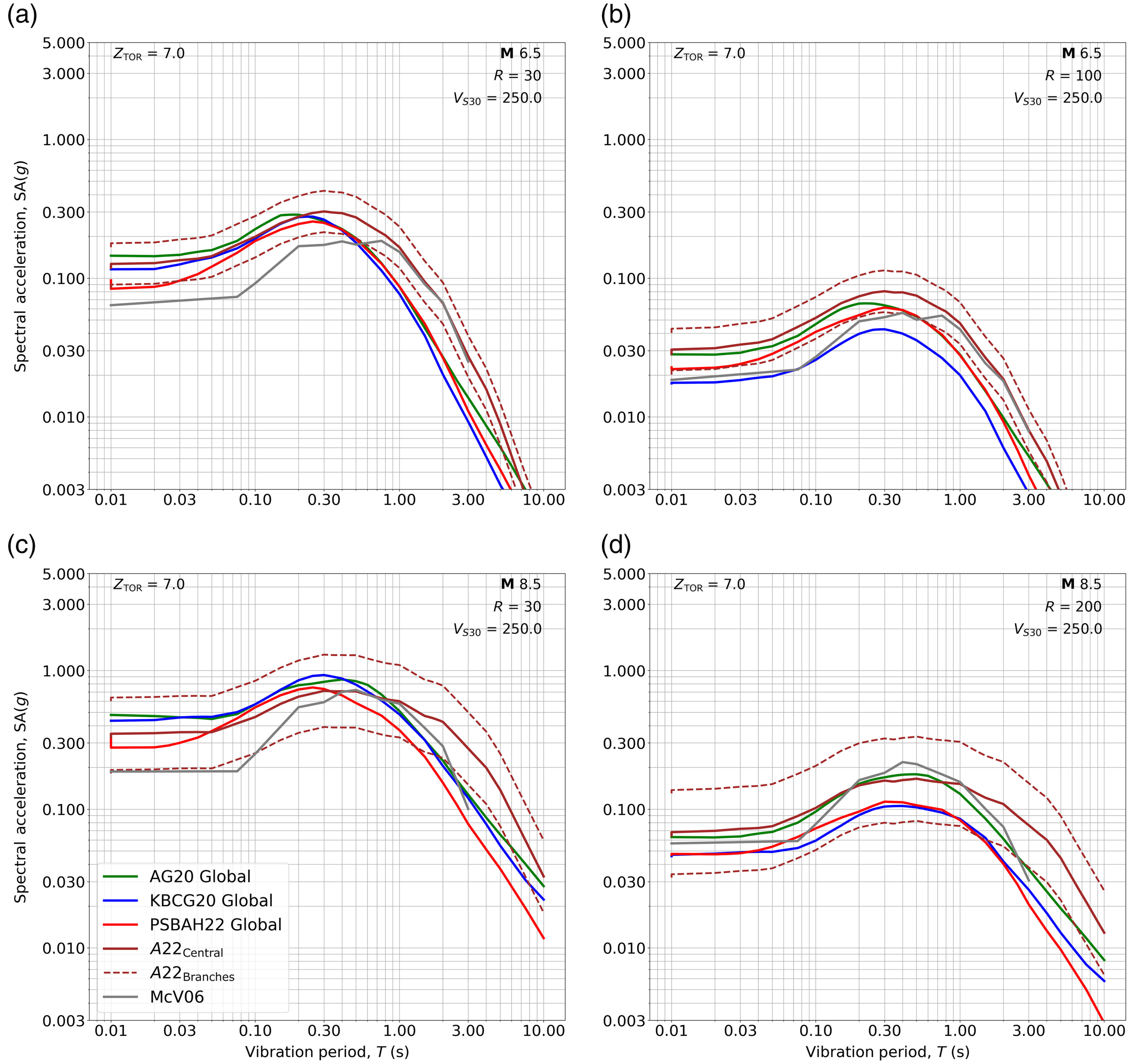

Figure 4. Comparison of median (specifically, exponent of logarithmic mean) predictions of the GMMs used in the subduction interface GMC logic tree for four seismic scenarios that typically dominate hazard: (a) **M** 6.5, R = 30 km; (b) **M** 6.5, R = 100 km; (c) **M** 8.5, R = 30 km; and (d) **M** 8.5, R = 200 km. The McV06 model is shown solely for its historical use in prior NZ NSHMs. The 10th and 90th percentiles of the native epistemic uncertainty in the A22 backbone model are also shown. The color version of this figure is available only in the electronic edition.

tectonic type, the respective figures present four scenarios that are important for hazards in major NZ centers. For the two backbone models (A22 and S22), we also illustrate the 10th and 90th percentile predictions of their native distribution of epistemic uncertainty in the median, as subsequently discussed with respect to the final adopted GMC logic tree.

In addition to this general comparison of alternative model predictions, we also sought to specifically compare models against NZ-specific and global observations for magnitude–distance combinations that are of greater interest for seismic hazard results, which are omitted here for brevity and can be found in the NZ NSHM report of Bradley *et al.* (2022). For crustal events, we considered the comparison of model predictions against NZ-specific data, whereas, for subduction events, we felt that the NZ-specific data were so limited that comparison against global observations from the NGA-Sub ground-motion database (Mazzoni *et al.*, 2022) was also undertaken. The most notable feature identified in such comparisons was the need to include explicit back-arc anelastic attenuation factors to the NGA-Sub models, which is further discussed subsequently.

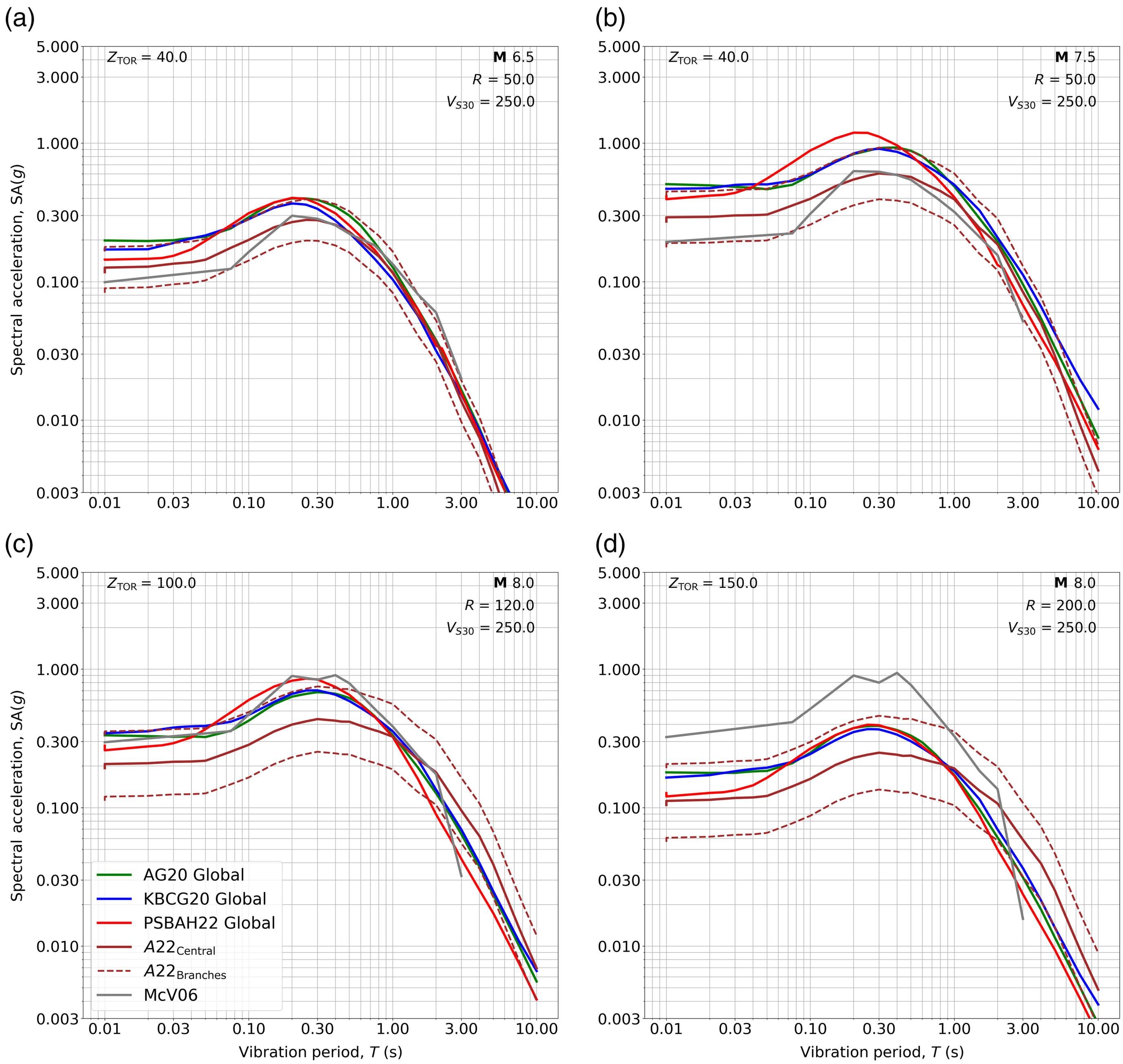

Figure 5. As for Figure 4, but for subduction slab models and scenarios: (a) **M** 6.5, R = 50 km; (b) **M** 7.5, R = 50 km; (c) **M** 8, R = 120 km; and (d) **M** 8, R = 200 km. The color version of this figure is available only in the electronic edition.

Apparent aleatory variability. As well as an examination of model median predictions, attention was equally devoted to the examination of model standard deviations, given its importance on hazard for exceedance probabilities of engineering interest (Bommer and Abrahamson, 2006). Figure 6 illustrates the total standard deviations, σ, of crustal, interface, and slab models as a function of vibration period for three different scenarios of increasing magnitude that are relevant for each tectonic type. Two significant features that are present in Figure 6 include: (1) generally higher σ values for subduction models as compared with crustal models; and (2) crustal models exhibit a notable reduction in σ values at short-to-moderate vibration periods with increasing ground-motion amplitude, which occurs due to the changing magnitude in the three rows of Figure 6. The crustal models, other than the two exceptions noted below, all exhibit a σ dependence that reduces with increasing magnitude, reducing distance, and reducing V_{S30}. The BSSA14 and A22 crustal models are exceptions, with σ models that vary only with vibration period, T, and not with any predictor variables. In the case of subduction zone models, other than the AG20 model, all remaining subduction interface and slab models show either very weak predictor variable dependence on the magnitude, source-to-site distance, and site conditions (e.g., PSBAH20), or no dependence at all (i.e., KBCG20, A22). To illustrate the significance of this, Figure 6a–c illustrates that the AG20 model is relatively similar to

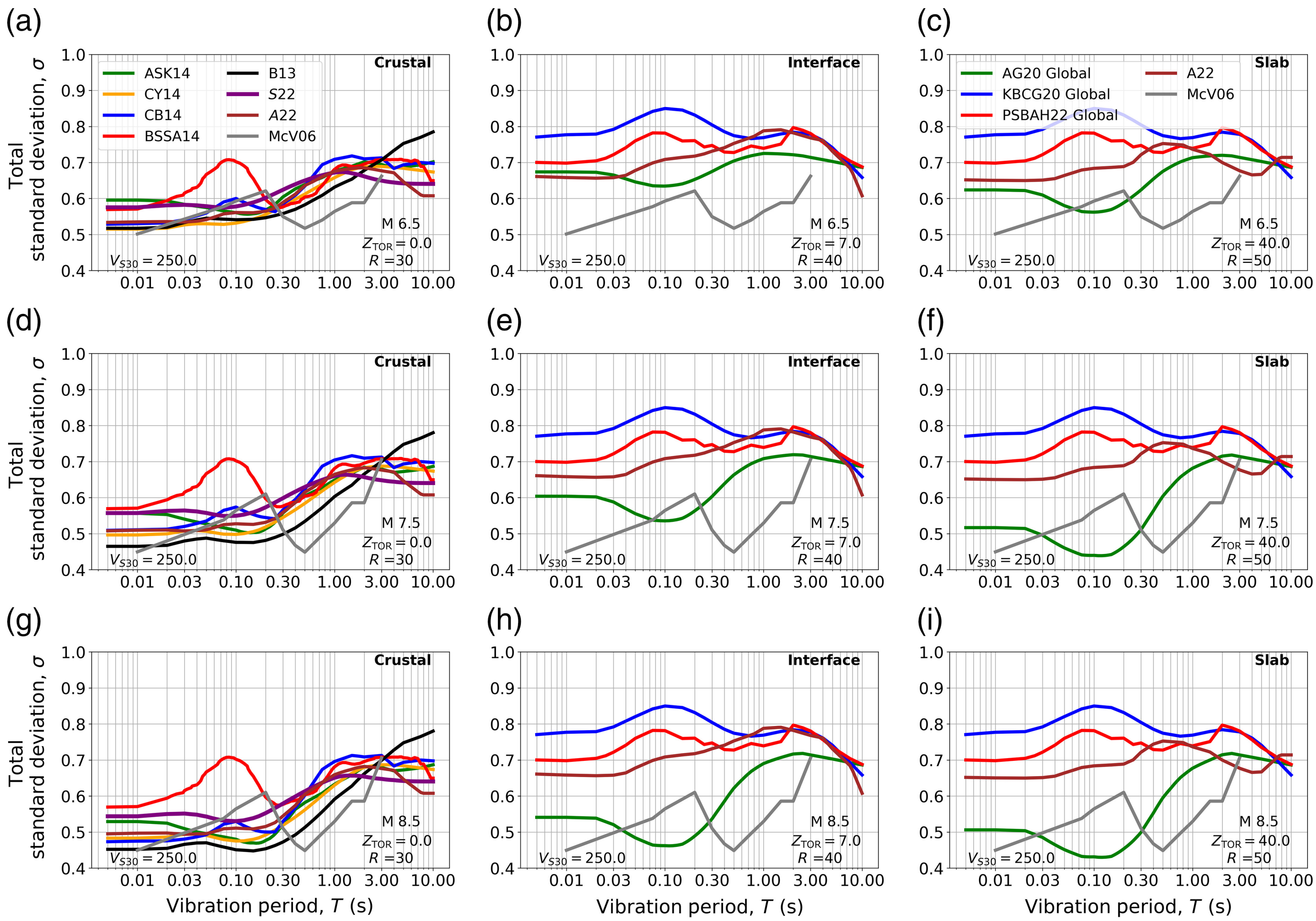

Figure 6. Comparison of aleatory standard deviation predictions of the GMMs used in the GMC logic trees for three seismic scenarios (rows) that typically dominate hazard. (a,d,g), (b,e,h), and (c,f,i) Plots correspond to active shallow crustal, subduction interface, and subduction slab conditions, respectively. The McV06 model is shown solely for its historical use in prior NZ NSHMs. The color version of this figure is available only in the electronic edition.

the remaining models for the **M** 6.5, $R = 40$ km scenario, but then predicts significantly lower σ values for the larger magnitude scenarios at short-to-moderate vibration periods.

The larger σ values discussed with respect to Figure 6 resulted in significantly higher hazard estimates obtained using the respective models. As discussed subsequently in the Adjustments for Nonlinear Site Response on Apparent Aleatory Standard Deviations section, we considered that the simplistic treatment of σ modeling within these models made them not appropriate for direct use, and we made first-order adjustments to account for nonlinear site response dependence (but not for a more comprehensive treatment that would also include other predictor variables).

ADOPTED GMC MODEL LOGIC TREES

Logic tree structure

Figure 7 illustrates the adopted logic trees for crustal and subduction zone sources. As previously alluded to, we considered both backbone and conventionally developed GMMs. For the active shallow crustal logic tree (Fig. 7a), this distinction is explicitly noted in the leftmost column of branches because of the consideration of two different backbone models (A22 and S22), whereas we simply compressed this aspect in the subduction GMC logic tree owing to the consideration of only a single backbone model (A22), and the remaining three models do provide their own epistemic uncertainty, so could be partially considered as backbone models (albeit it is not clear the extent to which these within-model epistemic uncertainties simply reflect parametric uncertainty in fitting the regression functional form versus all sources of epistemic uncertainty, for example, fig. 4.31 of Baker *et al.*, 2021). The logic tree treatment of epistemic uncertainty within each model is then depicted in the rightmost column branches of the logic tree, as discussed further subsequently.

There is a general trend in earthquake-induced GMM toward the treatment of epistemic uncertainty through the use of metamodels or colloquially “backbone” models. Such approaches have been advocated for almost a decade (e.g., Atkinson *et al.*, 2014), and seek to overcome some obvious issues with a simple weights-on-models approach (Baker *et al.*, 2021, chapter 4). As a result, we collectively pursued the

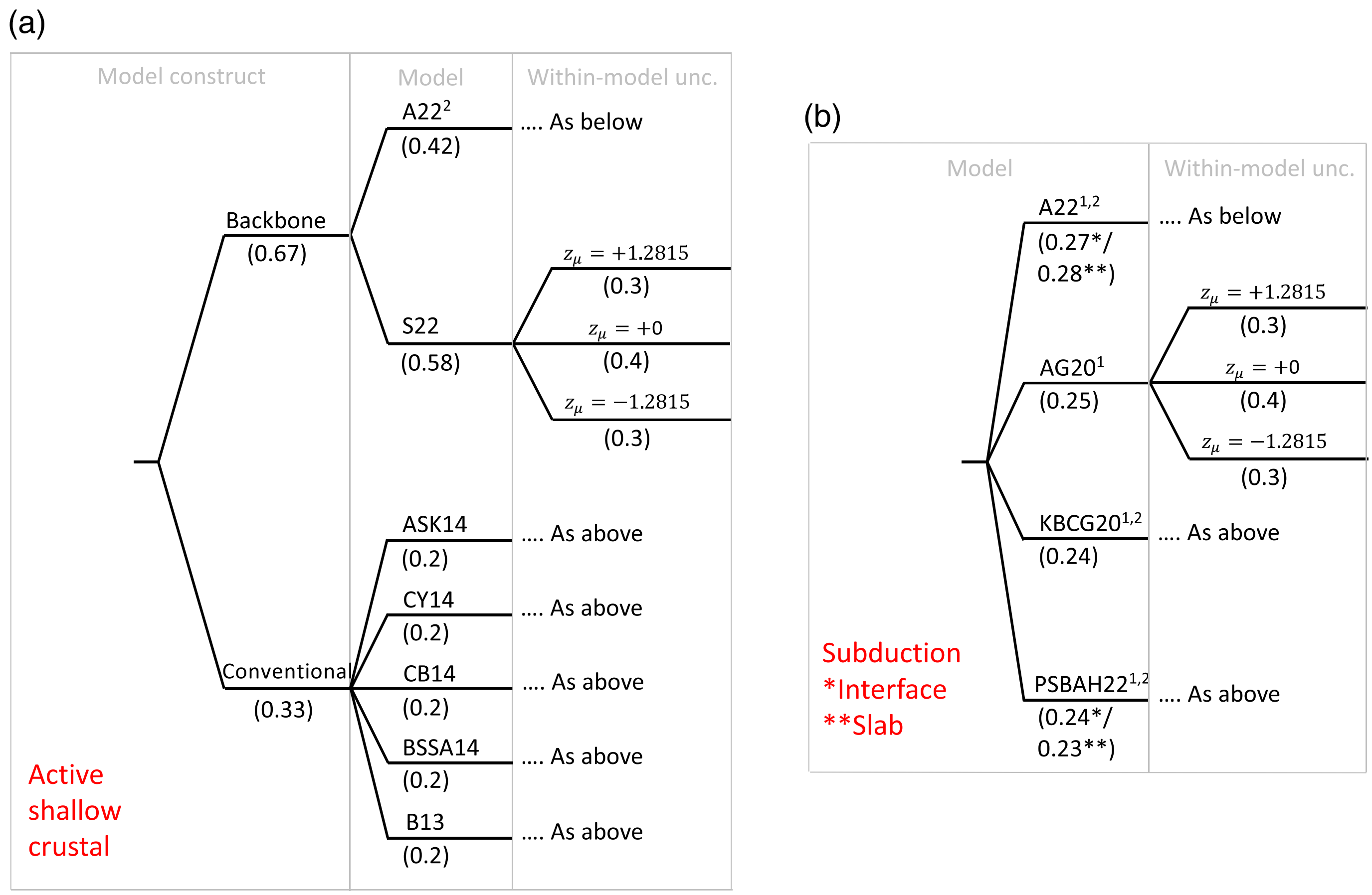

Figure 7. Schematic illustration of the adopted logic trees for (a) active shallow crustal; and (b) subduction interface and slab-induced ground motions. In panel (b), the structure of the logic tree for subduction interface and slab events is the same, with the only difference in the weights denoted with * and **, respectively. For active shallow crustal events, the logic tree is segregated into those models based on a backbone concept in contrast with the conventional models. Both backbone and conventional models had within-model epistemic uncertainty applied as a three-point discrete approximation via the rightmost column of the logic tree. Superscripts "1" and "2" associated with some models indicate that they were modified from their as-published version to include (1) back-arc anelastic attenuation and (2) nonlinear site response dependence in the apparent aleatory standard deviation. The color version of this figure is available only in the electronic edition.

development of NZ-specific backbone models. Conventionally, the use of a backbone model circumvents the need for a GMC logic tree of alternative models, so some explanation for our ultimate logic tree structure is necessary. Despite the conceptual benefits of backbone models we considered the following additional context: (1) backbone models have been almost entirely used for site-specific hazard applications, rather than national/regional applications (the 2015 Canadian NSHM being an exception, Atkinson and Adams, 2013); (2) prior NSHMs have adopted a weights-on-models approach, and NZ, in particular, previously has only used a single GMM in its formalized NSHMs (ignoring "research" studies, such as Bradley *et al.*, 2012, that directly used the 2010 NZ NSHM; or bespoke regional revisions such as Gerstenberger *et al.*, 2014), so we did not want to "jump" too many steps forward in GMC methodology in a single NSHM revision; and (3) the timeline of this NSHM project was such that while logic tree weights could be set near the end of the model development cycle, we were also time constrained to fully explore the hazard implications of the developed backbone models, including how one would select between the two different backbone models developed. As a result of all these factors, we took what may be considered a risk-adjusted strategy of including the backbone models along with the existing convention of weights on models. It seems logical that the future implementations (assuming that the backbone model concepts remain the emerging convention for the next decade, for example) of the GMC for the NZ NSHM would place a greater (or entire) weight on subsequent iterations of backbone models.

The final point on the logic tree structure worthy of note is that we did make several first-order modifications to the adopted GMMs, which are discussed in the next section. Such adjusted models are annotated in the logic trees of Figure 7 via superscripts beside the model acronym.

Model weights via expert elicitation

We used a structured performance-based expert elicitation process to assign weights between the alternative models for the GMC logic tree. Further details of the expert elicitation framework in the context of the 2022 NZ NSHM are described in Christophersen and Gerstenberger (2023). All weights were considered as a constant function of geographic location, site conditions, and SA vibration period due to the national model application requirements and constraints of the adopted software implementation.

For the active shallow crustal logic tree, weights were assigned to the two backbone models and the collective weight to the use of the five conventional models. That is, it was agreed on, in advance, that the five conventional crustal models (i.e., ASK14, CY14, CB14, BSSA14, and B13) would each have the same weighting (which has been commonly considered in other NSHMs, e.g., Petersen *et al.*, 2020), and thus it was left to the experts to decide on the relative weight given to this collection of models in comparison to the two adopted backbone models. Figure 7a illustrates that approximately two-thirds of weighting (when rounded to two decimal places) was collectively assigned to the two backbone models, with the remaining one-third weighting assigned to the collection of conventional GMMs.

In contrast to the crustal logic tree development, we did not impose equal weights for the four different GMMs that were considered in the subduction GMC logic tree. The reason was that there was significant discussion throughout the project on the relative applicability of these models for NZ, numerous aspects of their functional form scaling, and the adopted modifications for back-arc attenuation and standard deviation dependence on nonlinear site response, and we wanted to allow greater flexibility. Figure 7b illustrates the resulting weights that were determined for the subduction interface and slab sources. Although we separately developed the weights for interface and slab cases, the weights for the AG20 and KBCG20 models were numerically equal (when rounded to 2 dp), and those for the A22 and PSBAH22 models deviated by only 0.01 units. Even though nonuniform weights were allowed, it is evident that the resulting weights are close to 0.25, likely reflecting that a significant fraction of experts did suggest uniform weights in the elicitation process.

Within-model epistemic uncertainty

In addition to considering multiple GMMs, further epistemic uncertainty was included through "within-model epistemic uncertainty" on the (logarithmic) mean prediction. This is represented through the rightmost column of logic tree branches in Figure 7. In all cases, we adopted the three-point "extended Sawnson-Megill" distribution approximation (Keefer and Bodily, 1983), which uses the (10th, 50th, and 90th) percentiles of the distribution with logic tree weights of (0.3, 0.4, and 0.3), respectively. When the parameter distribution (of the logarithmic mean, in this case) is normal, then these three percentiles correspond to standard normal z values of (−1.2815, 0, +1.2815), respectively, which are used to adjust the prediction mean as follows:

$$\mu^i_{\ln SA|Rup} = E[\mu_{\ln SA|Rup}] + z^i_\mu \times \mathrm{Std}[\mu_{\ln SA|Rup}], \quad (1)$$

in which $E[\cdot]$ and Std[$\cdot$] reflect the mean and standard deviation, respectively, of the distribution of $\mu_{\ln SA|Rup}$; z_μ is the standard normal variate; and the superscript i reflects the ith branch of the logic tree. It is noted that the adopted three-point distribution is consistent with the commonly used (5th, 50th, and 95th) percentiles and weights (0.185, 0.63, and 0.185) from Miller and Rice (1983), but the use of percentiles closer to the median (i.e., 10th and 90th versus 5th and 95th percentiles) ultimately makes the seismic hazard logic tree realizations less influenced by the tails of the distributions.

For the two backbone models (S22 and A22), the distribution of $\mu_{\ln SA|Rup}$ is a native feature within each model. For the remaining (NGA-West2) crustal models we adopted the additional epistemic uncertainty as developed for use in the 2014 US NSHM by Rezaeian *et al.* (2014). Al Atik and Youngs (2014) provided the minimum epistemic uncertainty model for use with the NGA-West2 models, but we chose to retain the larger resulting values from the approach Rezaeian *et al.* (2014) due to the smaller number of NZ-specific observations from moderate- and large-magnitude events, of principal interest for seismic hazard, than for the ergodic NGA-West2 ground-motion dataset. Finally, for the subduction interface and slab events, all four considered models provide their own forms of epistemic uncertainty.

Finally, we only considered within-model epistemic uncertainty in $\mu_{\ln SA|Rup}$, and not in the apparent aleatory variability, $\sigma_{\ln SA|Rup}$, due to its second-order impact on the hazard relative to consideration of epistemic uncertainty in the mean, and the requirement for additional logic tree branches. However, it is noted that such models were available (e.g., the S22 model) and represent an advancement in uncertainty treatment that could be progressed in the future.

FIRST-ORDER ADJUSTMENTS APPLIED TO AS-PUBLISHED MODELS

As alluded to in the previous two sections, we applied multiple modifications to the adopted GMMs in the GMC logic tree from their published versions. Two of the modifications: (1) explicit back-arc attenuation and (2) explicit nonlinear site response modifications to the apparent aleatory standard deviation were based on both theoretical considerations and comparisons with observational data. Finally, we also reduced the epistemic uncertainty in the A22 and S22 backbone models to account for the partial correlation of this uncertainty between different rupture scenarios that are integrated into the hazard calculation. The following three subsections outline each of these modifications.

Adjustments for back-arc modification in subduction models

In subduction zone settings, it is well recognized that seismic waves can take complex ray paths that result in large differences in effective path attenuation. One of the major sources of path-attenuation variation is the difference between wave propagation within the high-quality-factor (low attenuation) slab itself versus that through the low-quality-factor (high attenuation) mantle wedge. Such effects are typically differentiated spatially in what is referred to as "fore-arc" and "back-arc" regions. Specific to NZ, several past GMMs have considered this, in the case of the Taupō volcanic zone (McVerry *et al.*, 2006; Bradley, 2013), and it is also consistent with studies of effective crustal attenuation (Eberhart-Phillips *et al.*, 2015).

Although the adopted NGA-Sub models in the 2022 NZ NSHM consider many of the latest advancements in theoretically based functional forms, large datasets, and additional simulation constraints, one factor that they largely neglected was the consideration of back-arc attenuation effects (the only exception being the KBCG20 region-specific models for Japan, Central America and Mexico and South America, but not their global or NZ-specific models). Those models that did not explicitly consider fore- and back-arc attenuation differences generally restricted the subsets of the NGA-Sub database that they considered to be associated with only fore-arc conditions. In addition, the A22 model developed as part of the NSHM project was not explicitly a fore-arc model, but it was based on NZ-specific observations, which were almost entirely recorded in the fore-arc region (there are more stations in the fore-arc region, and this is further compounded by the high attenuation in the back-arc resulting in a smaller fraction of strong-motion observations from such regions for a given magnitude distance range as compared with fore-arc observations); hence, this model was considered to implicitly also be a fore-arc model.

Initial seismic hazard results undertaken for the purpose of sensitivity studies (e.g., Bora *et al.*, 2023) indicated that, in northwest of the North Island of NZ, the hazard was excessively (in our opinion) dominated by subduction slab sources as a result of initially omitting a back-arc factor in such predictions. As a result of this, modification of the "base" models was undertaken to explicitly include back-arc modification effects.

In examining the literature, we decided to adopt the general features of the back-arc modification of Abrahamson *et al.* (2016, their equation 4), which was applied to all of the considered subduction slab and interface models in the GMC logic tree. The modification is a function of source-to-site distance and spectral vibration period, with the largest reductions for short vibration periods, as expected. The modification also increases with increasing distance beyond $R_{rup} = 85$ km.

Although the number of observations in the back-arc region in the NZ database is relatively small, there were multiple instruments in the back-arc region that had negative site-specific residuals from the analysis of Lee *et al.* (2023). Figure 8a,b illustrates peak ground acceleration (PGA) and SA($T = 0.5$ s) amplitudes of observations in the back arc for the range of magnitudes, source-to-site distances, and site conditions denoted in the figures. For comparison, the median A22 model prediction, with and without the back-arc correction, is also compared along with the binned geometric mean of the observations. It is evident that the inclusion of the back-arc modification improves the similarity of the model with the observational data. Figure 8c,d illustrates the seismic hazard curves for PGA and SA(0.5 s) for a site in Hamilton, and Figure 8e,f illustrates the geographical location of Hamilton as well as the spatial variation in the ratio of the hazard amplitudes for the 10% in 50-year exceedance probability. It is evident that the Hamilton location is approximately where the effect is the largest, with up to a 40% reduction in PGA amplitudes and 25% in SA(0.5) amplitudes. Further results for combinations of geographic location, intensity measure, and exceedance probability are presented in Bora *et al.* (2023).

Clearly, the adopted approach represents a relatively simple treatment of back-arc effects with anecdotal evidence of improvement relative to ignoring this effect but with otherwise little NZ-specific constraint. For example, the back-arc modification is constant for distances less than 85 km, which is likely somewhat region-specific, and the future analyses should seek to further scrutinize this.

Lee *et al.* (2023) and Bora *et al.* (2023) provide further details on the specific geographical region defined for this back-arc factor as well as improvement in station-specific residuals. The specific boundary along the southeastern edge approximately coincides with the 75 km depth contour of the subducted slab in the Hikurangi subduction zone. The southwestern extent of the region is such that back-arc effects are only present in the North Island and not in the upper South Island from the Hikurangi slab or lower South Island from the Puysegur slab. This geographical treatment is also particularly simplified and was focused on achieving a first-order correction for the omission of such effects. Its application in the upper North Island, where subduction slab hazard contributions are otherwise very large, was therefore the primary priority. For other regions in NZ, there is significantly greater hazard contribution from shallow crustal and/or subduction interface sources such that the contribution from slab sources is already relatively lower and therefore was not of primary focus.

Adjustments for nonlinear site response on apparent aleatory standard deviations

The effects of nonlinear site effects on ground-motion amplitudes are well recognized and are considered in the mean prediction of all credible GMMs intended for large-amplitude motions on soil sites. However, it is still not commonplace for similar attention to be given to the important effect of nonlinear site response on the apparent aleatory standard deviation. Al Atik and Abrahamson (2010) provide a discussion on the theoretical reasons why this standard deviation reduces due to the presence of nonlinear site response and evidence of its presence in empirical GMM development.

All considered crustal GMMs, except for BSSA14 and A22 models, explicitly consider the effect of nonlinear site response

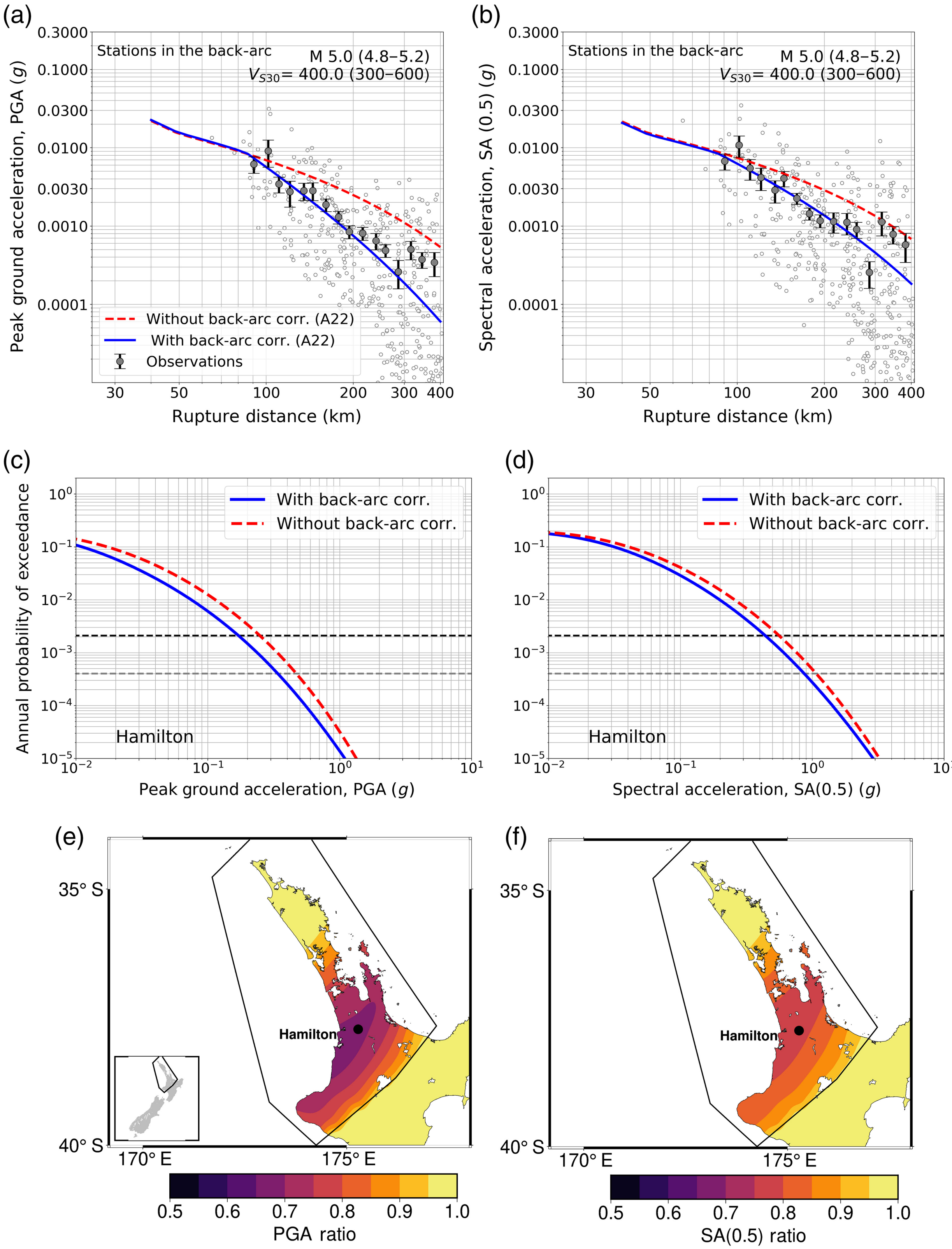

Figure 8. Effect of back-arc correction on predicted A22 median ground-motion amplitudes for **M** 4.8–5.2 events, resulting hazard curves for Hamilton, and variation in ground-motion intensity for the 10% in 50-year exceedance probability. (a,c,e) Correspond to peak ground acceleration (PGA), and (b,d,f) correspond to spectral acceleration SA(0.5 s). The inset map in panel (e) indicates the location of the depicted region in the context of the New Zealand landmass. The color version of this figure is available only in the electronic edition.

in the standard deviation model. In contrast, for subduction interface and slab events, only the AG20 model considers it. The effect of ignoring this dependence becomes significant for regions of high seismicity, where ground motions for exceedance rates of engineering interest (e.g., 10% or 2% in 50 yr) result from high-epsilon (Baker *et al.*, 2021, chapter 7) ground-motion amplitudes at the tails of the ground-motion prediction distribution. Initial hazard calculations with default GMMs illustrated that hazard, on soil sites typical of NZ urban areas (e.g., $V_{S30} = 200$–300 m/s), was being excessively dominated by subduction events, and that hazard curves were significantly flatter than in regions where subduction events were less prevalent. Further interrogation illustrated that this was being driven by the large standard deviation values of the subduction GMMs (as shown in Fig. 6), which did not account for nonlinear site-effect dependence, with the AG20 model providing a useful reference point as a model that did explicitly account for this effect.

Because the methodology of Al Atik and Abrahamson (2010) to account for nonlinear site effects on standard deviation uses analytical error propagation, it was then easily applied to the remaining models that did not initially account for this explicitly. Equations 5.7–5.10 of Abrahamson and Gulerce provide a detailed account of how the between- and within-event variances can be computed when explicitly accounting for nonlinear site response. The only aspect that varies between the considered models is the functional form for nonlinear site response in the median ground motion. In all implementations, we adopted the period-to-period correlation equations for the between- and within-event residuals from table 5.4 of Abrahamson and Gulerce, and the variability in site amplification, $\phi_{\text{Amp}} = 0.3$ from Abrahamson and Silva (2008).

Figure 9 provides a comparison of the total standard deviation of models with the inclusion of explicit nonlinear site response effects versus without the correction (i.e., the original model). The AG20 model is also shown for comparison, which natively includes this effect. To illustrate the size of the reductions, for the *M* 8.5 subduction interface scenario, the PGA standard deviations reduce by ∼0.18, 0.09, and 0.11 units for the KBCG20, PSBAH22, and A22 models, respectively. The resulting standard deviations for these models all lie in the range of 0.55–0.61, which is consistent with the ∼0.55 value of the AG20 model that already includes this effect. It is noted that the A22 model adopted the same σ model for crustal, interface, and slab tectonic types, and hence the reduction for the A22 crustal predictions is also shown.

Figure 10 illustrates the direct effect of the added dependence of the total standard deviation on nonlinear site response. Both Wellington and Napier are high-hazard locations, with ∼75% of the hazard in Wellington being due to subduction sources and ∼90% in Napier. It is seen that the effect of the nonlinear dependence on σ is predominant only at short-to-moderate vibration periods, and that it is also more pronounced for the 2% in 50-year exceedance probability (∼a 15% reduction in the PGA values) compared with that for the 10% in 50-year probability (∼a 10% reduction in PGA values). Further results for combinations of geographic location, intensity measure, and exceedance probability are presented in Bora *et al.* (2023).

Partial correlation of epistemic uncertainty in backbone models

As illustrated in the rightmost column of the GMC logic trees in Figure 7, within-model epistemic uncertainty was applied to all mean predictions of the GMMs. Because of the constraints of hazard software implementations, and for computational efficiency reasons, it is common to consider epistemic uncertainty in the mean GMM via alternative logic tree branches as done here (i.e., a three-branch approach). However, the drawback of this logic tree treatment of epistemic uncertainty in the mean is that it assumes that all sources in the hazard computation will produce ground motions that are perfectly correlated with respect to this epistemic uncertainty (e.g., in Fig. 7, for the hazard calculation using the "upper" logic tree branch, all seismic sources produce ground motions that have a realized mean, which is $z_\mu = 1.2815$ standard deviations above the distribution mean) In reality, this ground-motion uncertainty will be partially correlated.

Bradley *et al.* (2022) describe an exploratory analysis to examine the degree to which a simple reduction factor could be applied to this source of epistemic uncertainty, to account for this partial correlation, via an analysis of the inherent correlation structure that exists within the NGA-West2 GMMs for active shallow crustal conditions. They identified that such a reduction factor typically ranges from 0.85 to 1.0 and is a function of the disaggregation distribution (namely the range of sources that contribute significantly to the hazard), as well as the degree to which the different predictions vary relative to each other for different earthquake scenarios.

Because of the computational implementation constraints of the OpenQuake engine used for the 2022 NZ NSHM hazard calculations, we adopted a single reduction factor for this epistemic standard deviation, with the number being determined via expert elicitation with options of 0.85, 0.90, and 0.95, ultimately adopting a factor of 0.90. It is noted that these different options ultimately result in a minor variation in the overall epistemic uncertainty of the hazard curves and are not expected to have any material impact on the mean hazard itself.

NEAR-FAULT DIRECTIVITY CONSIDERATION

The seismic hazard for the 2022 NZ NSHM is computed for the RotD50 directionality definition (Boore, 2010) using GMMs that generally do not explicitly consider near-fault directivity (CY14 being the one exception). However, all the models do implicitly consider directivity in that they are regressed using near-fault ground motions that exhibit the effects of directivity phenomena.

In some seismic hazard analysis applications, it is common to use post hoc modifications to GMMs to explicitly account for directivity. Donahue *et al.* (2019) provide a summary of commonly used models and the practical challenges for their application. Early in the 2022 NZ NSHM project, it was identified that the explicit consideration of directivity in GMMs would

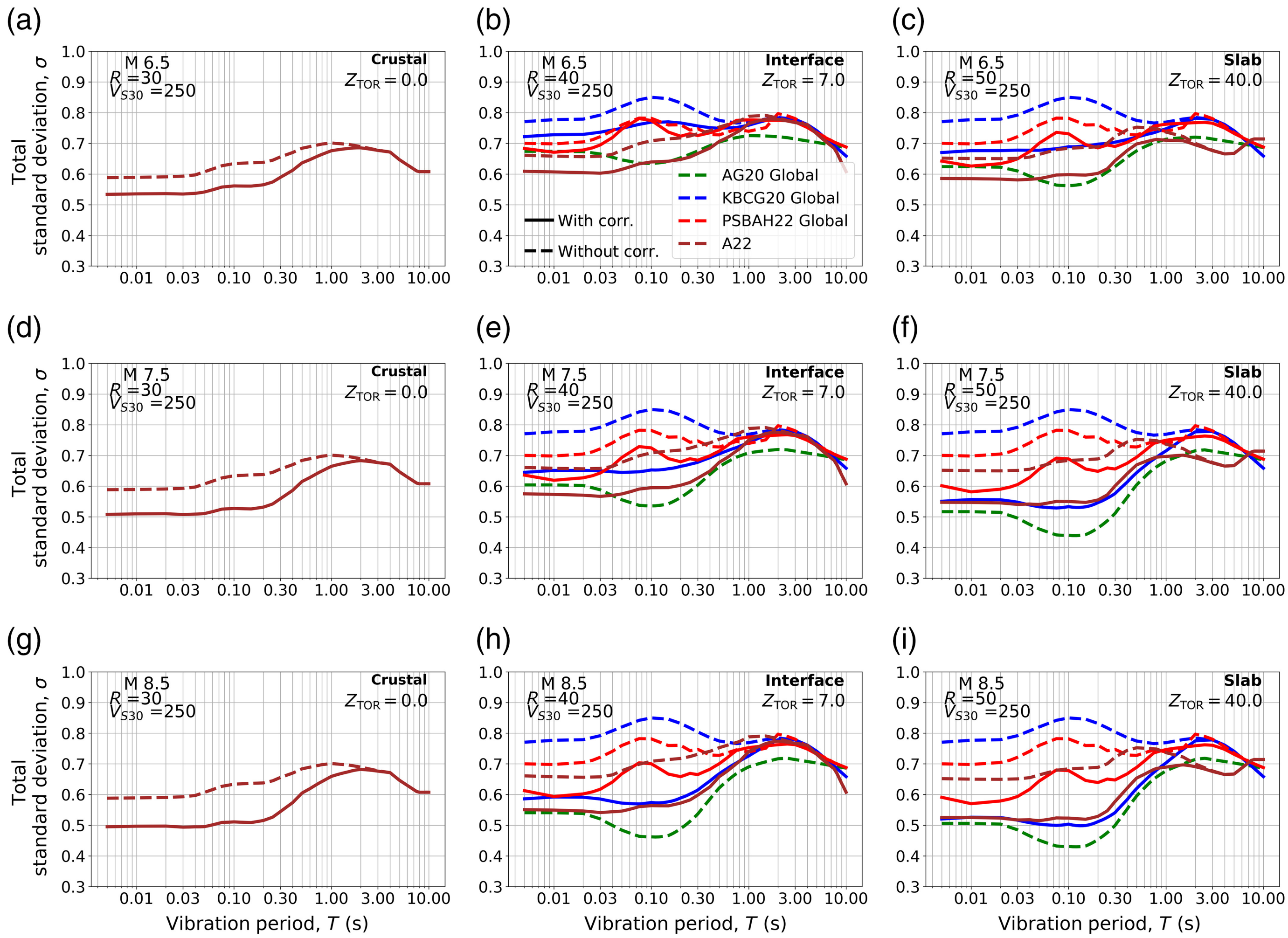

Figure 9. Reduction in total standard deviation, σ, predictions due to the inclusion of nonlinear site response dependence for (a,d,g) active shallow crustal, (b,e,h) subduction interface, and (c,f,i) subduction slab for three different earthquake scenarios (the three rows of figures). All active shallow crustal models, other than A22 and BSSA14, already exhibit a significant reduction in standard deviation with nonlinear site response and are not explicitly shown (see Fig. 6). Of the subduction interface and slab models, AG20 is the only model that natively includes this nonlinear site response dependence on σ. The color version of this figure is available only in the electronic edition.

be challenging. This is primarily because the seismicity rate model (SRM) component of 2022 NZ NSHM (Gerstenberger and Van Dissen, 2022) provides complex multisegment ruptures; few existing directivity adjustment models can handle multisegment rupture geometries, and none have been specifically calibrated for them. As a result, an exploratory study was undertaken using the prior 2010 SRM "characteristic" single-plane geometries (Stirling *et al.*, 2012) to gauge the size of directivity adjustments, as documented in Weatherill (2022). This exploratory analysis has also been subsequently extended, since the completion of the 2022 NZ NSHM project, by Weatherill and Lilienkamp (2023). As a summary of their findings, Figure 11 illustrates the results from Weatherill and Lilienkamp (2023) in terms of the percentage change in SA(3.0 s), for the 2% in 50-year exceedance probability, when the post hoc directivity factor of Bayless *et al.* (2020) is applied to the Stafford (2022) GMM for crustal sources using the 2010 and 2022 versions of the NZ SRM. The primary difference between the 2010 and 2022 SRMs is that the former uses characteristic ruptures, compared with the noncharacteristic and potential multifault ruptures in the 2022 SRM. Figure 11a illustrates that the more limited set of possible ruptures in the 2010 SRM results in more spatially localized variations in the hazard differences due to directivity in comparison to that with the 2022 SRM (Fig. 11b). The hazard differences range up to ±25% with the 2010 SRM, but with the 2022 SRM most locations in NZ have a variation of less than 10% for SA(3.0 s). The size of these effects is less pronounced for other vibration periods and also decreases as the exceedance probability increases.

The size of the changes in SA(T = 3.0 s) for large population centers of NZ (such as Christchurch, Wellington, and Auckland) are modest because (1) Christchurch's and Auckland's hazard is dominated by near-source seismicity on distributed sources or fault-based sources that are distant; and (2) Wellington's seismic hazard has a large component from

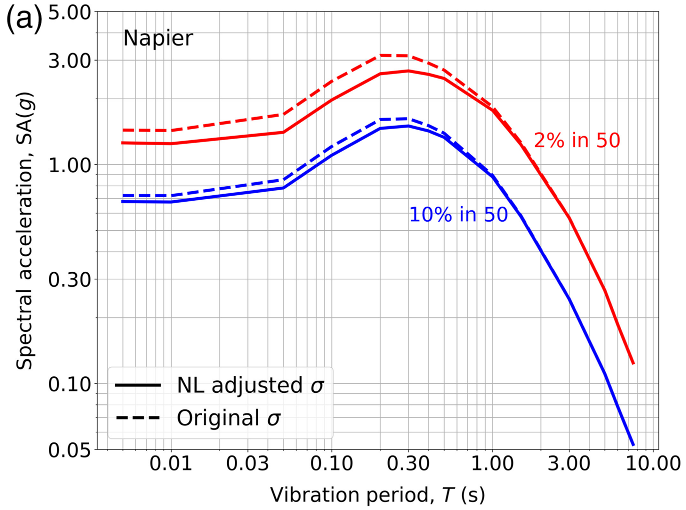

Figure 10. Effect of including nonlinear site response dependence in GMM standard deviations on uniform hazard spectra for: (a) Napier and (b) Wellington. The color version of this figure is available only in the electronic edition.

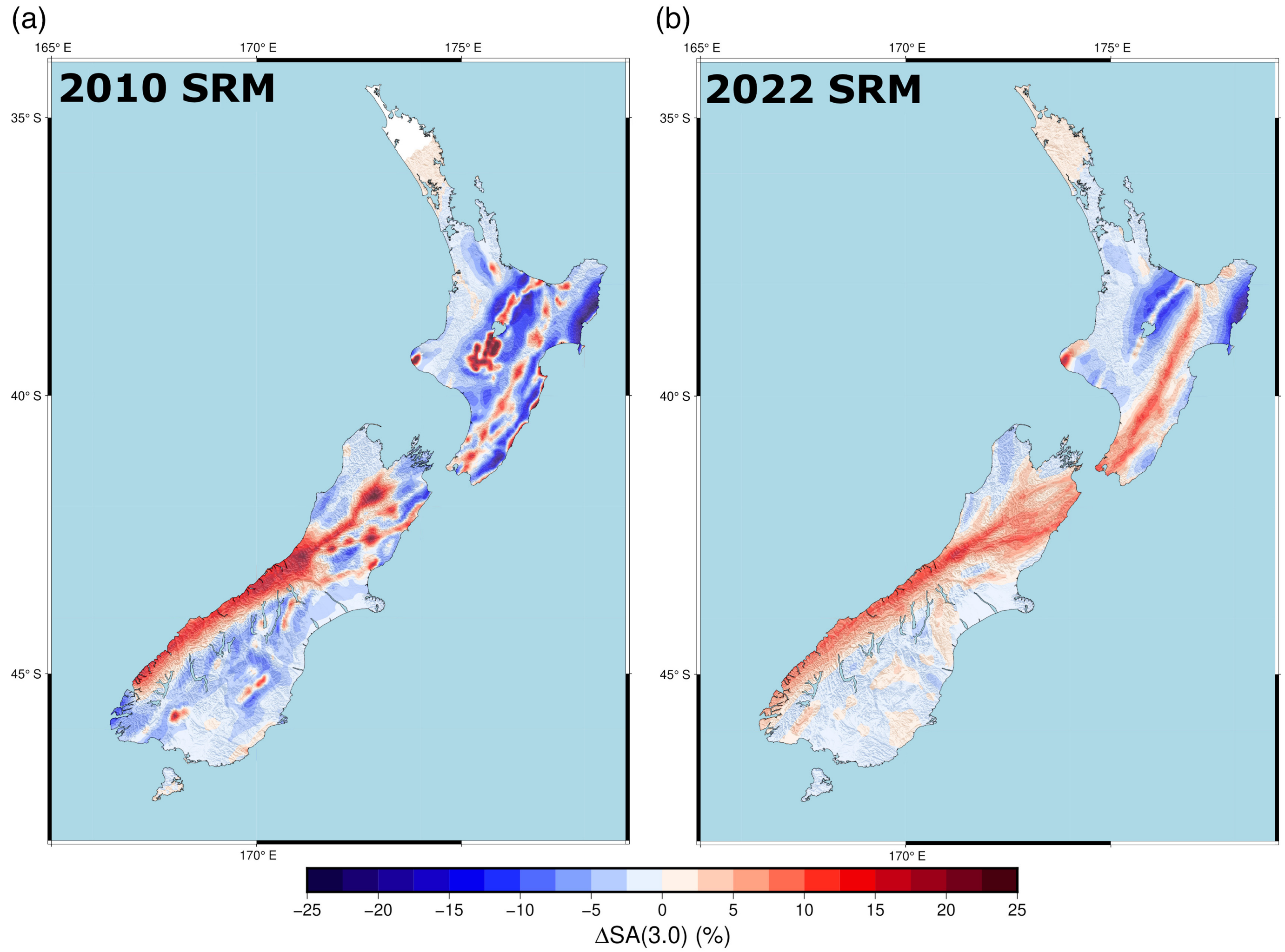

Figure 11. Percentage changes in the SA($T = 3.0$ s) hazard values for the 2% in 50-year exceedance probability, based on: (a) the 2010 seismicity rate model; and (b) mean rupture rates from the 2022 seismicity rate model (i.e., averaged over all source logic tree branches). Both analysis cases used the Stafford (2022) GMM. The color version of this figure is available only in the electronic edition.

subduction interface events for which the active shallow crustal-based directivity considerations are not applicable. As a result of the preliminary work of Weatherill (2022), directivity was not explicitly considered in the 2022 NZ NSHM owing to the small effects in large population centers and the difficulty in considering it with multifault rupture models. However, site-specific hazard studies that use the 2022 NZ NSHM as a starting point may wish to consider directivity in a post hoc sense using either existing models (despite their incompatibility with multifault ruptures) or models that may be available in the near future.

DISCUSSION AND LIMITATIONS

Although the GMC model component of the 2022 NZ NSHM represents a major advancement relative to prior NZ NSHMs and we believe is consistent with the state-of-the-art for other National Seismic Hazard Model projects, there remain multiple elements that were not addressed due to limitations in available data and/or time for this update. In the paragraphs below we provide sentiments about several limitations that were considered, but ultimately not addressed, many of which represent obvious topics for attention in the immediate future.

Degree of NZ-specific regionalization: The NZ-specific ground-motion dataset lacks large-magnitude, small source-to-site distance events, such that reliance on foreign data and models (both empirical and theoretical) will remain of first-order importance. However, there are important improvements in the NZ data that are achievable and would make meaningful enhancements for NZ-specific modeling. First, the proportion of instrument locations with directly measured site conditions is low relative to international databases, such as the NGA-West2 and NGA-Sub databases (Wotherspoon *et al.*, 2023). Low-quality site data make it difficult to draw inferences as to whether systematic deviations in residuals are due to source, path, or site effects, and thus the ability to consider NZ-specific site response adjustments (e.g., to correct for the NZ-specific crustal profile), as well as NZ-specific anelastic attenuation and near-surface site attenuation effects. The quality of the amplitude data from broadband instruments in the GeoNet instrument network was also evident in the development of the New Zealand database (Hutchinson *et al.*, 2022), resulting in a lack of very low-amplitude ground motions that would be useful for further study of regionalization of anelastic attenuation and, particularly, back-arc attenuation (where the amplitudes are frequently too low from moderate magnitude events to be reliably recorded on strong-motion instruments). Thus, improvements in NZ-specific observations will naturally be an essential component toward further NZ-specific regionalization, including spatially nonergodic GMMs (Lavrentiadis *et al.*, 2022).

Subduction zone ground-motion modeling: The scientific understanding and modeling of subduction-induced ground motions is arguably a decade or more behind that of active shallow crustal earthquakes. At the outset of the 2022 NZ NSHM, we considered subduction GMMs that were developed as far back as 2006 (Lee, Bradley, Manea, *et al.*, 2022). In the second half of the project timeline, the majority of the NGA-Sub GMMs were released and ultimately formed the basis for the adopted GMC logic tree for subduction sources (Fig. 7). The NGA-Sub models reflect a significant advancement in the state of subduction zone GMMs, similar to the impact of the NGA-West1 models had for active shallow crustal earthquakes. Nonetheless, there remain significant model-to-model variations in the NGA-Sub models. Furthermore, during the course of the model examination we identified several aspects of the models that we considered had a negative impact on the resulting seismic hazard results, and that we ultimately applied corrections for—namely, adjustments for back-arc anelastic attenuation and nonlinear site response effects on the apparent aleatory standard deviation were added to models that did not have them. Given the significant degree to which the seismic hazard in NZ is contributed to by subduction sources (i.e., subduction sources comprise on the order of 60%–75% of the hazard in NZ's capital city, Wellington, for the 10% in 50-year exceedance probability over a range of SA vibration periods), further advances in subduction GMMs are likely to have a large bearing on future seismic hazard forecasts for NZ.

Use of constraints from ground-motion simulations: The GMC model of the 2022 NZ NSHM ultimately relied entirely on empirical GMMs without direct input from NZ-specific ground-motion simulations due to a lack of time for their integration into the project, and also due to uncertainties in their constraint and validation against observations. Although contemporary empirical GMMs are increasingly based on constraints from simulations, such simulations have not been NZ-specific and usually are intended to represent global features. In contrast, NZ-specific simulations for major fault sources and specific regions, such as major urban centers on sedimentary basins (e.g., Wellington, Canterbury), have the potential to enable meaningful adjustments to GMMs to reflect region-specific phenomena. During the 2022 NZ NSHM, we did have a workstream focused on using simulations to examine the ability to model region-specific sedimentary basin effects (de la Torre *et al.*, 2022; Lee, Bradley, Hill, *et al.*, 2022) and anticipate results from that ongoing workstream to lead into such region-specific modifications of the future NZ NSHMs.

Neglect of near-fault directivity: As discussed in the prior section, near-fault directivity effects were not explicitly considered, with the notion for such effects to be considered in some fashion by the engineering community when making use of the direct results that come from the 2022 NZ NSHM. Clearly, it would be more beneficial to be able to directly incorporate directivity effects within the seismic hazard calculation itself to consistently account for the contribution of multiple seismic sources to the hazard calculation (i.e., that common code-based "adjustment factors" are typically based on the proximity of the site to a nearby crustal fault and therefore neglect how much that fault actually contributes to the seismic hazard). An example of this complication is that seismic hazard results in the lower North Island have a major contribution from the subduction interface source, such that the effects of directivity from shallow crustal events on hazard may not be strong; yet, many locations in the lower North Island are located in close proximity to high-slip-rate crustal faults, for which directivity in a specific rupture scenario could be significant. Weatherill and Lilienkamp (2023) provide further considerations on the complexity of explicitly including directivity in seismic hazard calculations, particularly for NSHM-type applications (i.e., not site-specific), and possible pathways for further progress.

CONCLUSIONS

This article summarized the GMC model component as part of the 2022 NZ NSHM update. A NZ-specific database was developed, and prospective NZ-specific and global GMMs were examined with respect to this database, as well as their predictor variable scaling for other seismic scenarios that dominate seismic hazard but cannot be adequately constrained by strong-motion observations. The GMC logic tree was developed considering both the backbone models, which have their own native epistemic uncertainty, as well as conventional GMMs for which additional epistemic uncertainty in the mean prediction was applied. Weights on the alternative GMMs were determined through a structured expert elicitation process. Several of the GMMs were also modified to explicitly account for back-arc anelastic attenuation, nonlinear site response effects on the apparent aleatory standard deviation, and partial correlation of epistemic uncertainty—factors that we determined had a first-order effect on hazard results.

Despite the significant advancement of the GMC component of the 2022 NZ NSHM relative to the prior instance in 2010, which used a single GMM, there remain several short-term opportunities for further improvements associated with improvements in NZ-specific data collection, subduction GMMs, use of simulations, and consideration of near-fault directivity.

DATA AND RESOURCES

All data and resources used are cited in relevant locations throughout the article.

DECLARATION OF COMPETING INTERESTS

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REFERENCES

Abrahamson, N., and Z. Gülerce (2020). Regionalized ground-motion models for subduction earthquakes based on the NGA-SUB database, *PEER Report No. 2020/25*, 237 pp.

Abrahamson, N., and W. Silva (2008). Summary of the Abrahamson & Silva NGA ground motion relations, *Earthq. Spectra* **24,** no. 1, 67–97.

Abrahamson, N., N. Gregor, and K. Addo (2016). BC hydro ground motion prediction equations for subduction earthquakes, *Earthq. Spectra* **32,** no. 1, 23–44.

Abrahamson, N. A., W. J. Silva, and R. Kamai (2014). Summary of the ASK14 ground motion relation for active crustal regions, *Earthq. Spectra* **30,** no. 3, 1025–1055, doi: 10.1193/070913EQS198M.

Abrahamson, N., N. Kuehn, Z. Gülerce, N. Gregor, Y. Bozorgnia, G. Parker, J. Stewart, B. Chiou, I. Idriss, K. Campbell, *et al.* (2018). Update of the BC hydro subduction ground-motion model using the NGA-subduction dataset, *Technical Rept. 2018/02*, PEER, doi: 10.55461/OYCD7434.

Al Atik, L., and N. Abrahamson (2010). Nonlinear site response effects on the standard deviations of predicted ground motions, *Bull. Seismol. Soc. Am.* **100,** no. 3, 1288–1292.

Al Atik, L., and R. R. Youngs (2014). Epistemic uncertainty for NGA-West2 models, *Earthq. Spectra* **30,** no. 3, 1301–1318.

Anderson, J., and J. Brune (1999). Probabilistic seismic hazard analysis without the ergodic assumption, *Seismol. Res. Lett.* **70,** no. 1, 19–28.

Atkinson, G. (2022). Backbone ground motion models for crustal, interface, and slab earthquakes in New Zealand, *Technical Rept. 2022/48*, GNS Science, doi: 10.21420/QMJ6-P189.

Atkinson, G. M., and J. Adams (2013). Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps, *Can. J. Civ. Eng.* **40,** no. 10, 988–998.

Atkinson, G. M., J. J. Bommer, and N. A. Abrahamson (2014). Alternative approaches to modeling epistemic uncertainty in ground motions in probabilistic seismic-hazard analysis, *Seismol. Res. Lett.* **85,** no. 6, 1141–1144.

Baker, J., B. Bradley, and P. Stafford (2021). *Seismic Hazard and Risk Analysis*, Cambridge University Press, Cambridge, United Kingdom.

Bayless, J. R., P. Somerville, and A. A. Skarlatoudis (2020). A rupture directivity adjustment model applicable to the NGA-West2 ground motion models and complex fault geometries, available at https://earthquake.usgs.gov/cfusion/external_grants/reports/G18AP00092.pdf (last accessed September 2022).

Bommer, J., and N. Abrahamson (2006). Why do modern probabilistic seismic-hazard analyses often lead to increased hazard estimates? *Bull. Seismol. Soc. Am.* **96,** no. 6, 1967–1977.

Bommer, J. J., and P. J. Stafford (2020). Selecting ground-motion models for site-specific PSHA: Adaptability versus applicability, *Bull. Seismol. Soc. Am.* **110,** no. 6, 2801–2815, doi: 10.1785/0120200171.

Boore, D. M. (2010). Orientation-independent, nongeometric-mean measures of seismic intensity from two horizontal components of motion, *Bull. Seismol. Soc. Am.* **100,** no. 4, 1830–1835.

Boore, D. M., J. P. Stewart, E. Seyhan, and G. M. Atkinson (2014). NGA-west2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes, *Earthq. Spectra* **30,** no. 3, 1057–1085.

Boore, D. M., R. R. Youngs, A. R. Kottke, J. J. Bommer, R. Darragh, W. J. Silva, P. J. Stafford, L. Al Atik, A. Rodriguez-Marek, and J. Kaklamanos (2022). Construction of a ground-motion logic tree through host-to-target region adjustments applied to an adaptable ground-motion prediction model, *Bull. Seismol. Soc. Am.* **112,** no. 6, 3063–3080.

Bora, S. S., B. Bradley, E. Manea, M. Gerstenberger, R. Lee, P. Stafford, G. Atkinson, A. Kaiser, C. Dicaprio, and R. Van Dissen (2023). Ground-motion characterization models for the 2022 revision of the New Zealand national seismic hazard model and associated hazard sensitivities, *Bull. Seismol. Soc. Am.* (this issue).

Bozorgnia, Y., N. A. Abrahamson, S. K. Ahdi, T. D. Ancheta, L. A. Atik, R. J. Archuleta, G. M. Atkinson, D. M. Boore, K. W. Campbell, B. S-J. Chiou, *et al.* (2022). NGA-Subduction research program, *Earthq. Spectra* **38,** no. 2, 783–798.

Bozorgnia, Y., N. A. Abrahamson, L. A. Atik, T. D. Ancheta, G. M. Atkinson, J. W. Baker, A. Baltay, D. M. Boore, K. W. Campbell, B. S. J. Chiou, *et al.* (2014). NGA-West2 research project, *Earthq. Spectra* **30,** no. 3, 973–987.

Bradley, B. A. (2013). A New Zealand-specific pseudospectral acceleration ground-motion prediction equation for active shallow crustal earthquakes based on foreign models, *Bull. Seismol. Soc. Am.* **103,** no. 3, 1801–1822.

Bradley, B., S. Bora, and R. Lee (2022). Summary of the ground-motion characterisation model for the 2022 New Zealand National Seismic Hazard Model, doi: 10.21420/9BMK-ZK64.

Bradley, B. A., M. W. Stirling, G. H. McVerry, and M. Gerstenberger (2012). Consideration and propagation of epistemic uncertainties in New Zealand probabilistic seismic hazard analysis, *Bull. Seismol. Soc. Am.* **102,** no. 4, 1554–1568.

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, *Earthq. Spectra* **30,** no. 3, 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, *Earthq. Spectra* **30,** no. 3, 1117–1153.

Chiou, B., R. Youngs, N. Abrahamson, and K. Addo (2010). Ground-motion attenuation model for small-to-moderate shallow crustal earthquakes in California and its implications on regionalization of ground-motion prediction models, *Earthq. Spectra* **26,** no. 4, 907–926.

Christophersen, A., and M. C. Gerstenberger (2023). Expert judgment in the 2022 Aotearoa New Zealand national seismic hazard model, *Seismol. Res. Lett.*, doi: 10.1785/0220230250.

de la Torre, C., B. Bradley, R. Lee, F. Kuncar, L. Wotherspoon, A. Kaiser, and E. Manea (2022). Combining observed elastic basin amplification factors with 1d nonlinear site response analyses to predict site/basin response for strong ground motions: Application to wellington, New Zealand, *Earthq. Spectra* doi: 10.1177/87552930231209726.

Donahue, J., J. Stewart, N. Gregor, and Y. Bozorgnia (2019). *Ground-Motion Directivity Modeling for Seismic Hazard Applications*, Pacific Earthquake Engineering Research Center (PEER), University of California, Berkeley, California, U.S.A.

Eberhart-Phillips, D., M. Reyners, and S. Bannister (2015). A 3d QP attenuation model for all of New Zealand, *Seismol. Res. Lett.* **86,** no. 6, 1655–1663.

Gerstenberger, M., and R. Van Dissen (2022). *The Seismicity Rate Model for the 2022 New Zealand National Seismic Hazard Model*, GNS Science, Lower Hutt, New Zealand.

Gerstenberger, M., S. Bora, B. Bradley, C. Dicaprio, and R. Van Dissen (2022). *New Zealand National Seismic Hazard Model 2022 Revision: Model, Hazard and Process Overview*, GNS Science, Lower Hutt, New Zealand.

Gerstenberger, M., G. McVerry, D. Rhoades, and M. Stirling (2014). Seismic hazard modeling for the recovery of Christchurch, *Earthq. Spectra* **30,** no. 1, 17–29.

Gerstenberger, M. C., D. A. Rhoades, and G. H. McVerry (2016). A hybrid time-dependent probabilistic seismic-hazard model for Canterbury, New Zealand, *Seismol. Res. Lett.* **87,** no. 6, 1311–1318.

Hutchinson, J., B. Bradley, R. Lee, L. Wotherspoon, M. Dupuis, C. Schill, J. Motha, A. Kaiser, and E. Manea (2022). 2021 New Zealand ground motion database, *GNS Science Rept. 2021/56*, GNS Science, Lower Hutt (NZ), doi: 10.21420/Z20E-5507.

Hutchinson, J., C. Zhu, B. Bradley, R. Lee, L. Wotherspoon, M. Dupuis, C. Schill, J. Motha, E. Manea, and A. Kaiser (2023). 2023 New Zealand ground motion database, *Bull. Seismol. Soc. Am.* 35 (in revision).

Incorporated Research Institutions for Seismology (IRIS) (2012). *Standard for the Exchange of Earthquake Data*, SEED format version 2.4, 244 pp.

Keefer, D. L., and S. E. Bodily (1983). Three-point approximations for continuous random variables, *Manage. Sci.* **29,** no. 5, 595–609.

Kuehn, N., Y. Bozorgnia, K. Campbell, and N. Gregor (2020). Partially non-ergodic ground-motion model for subduction regions using the NGA-Subduction database, *Technical Rept. 2020/04*, PEER, doi: 10.55461/NZZW1930.

Lavrentiadis, G., N. A. Abrahamson, K. M. Nicolas, Y. Bozorgnia, C. A. Goulet, A. Babič, J. Macedo, M. Dolšek, N. Gregor, A. R. Kottke, *et al.* (2022). Overview and introduction to development of non-ergodic earthquake ground-motion models, *Bull. Earthq. Eng.* **21,** 5121–5150, doi: 10.1007/s10518-022-01485-x.

Lee, R. L., B. A. Bradley, E. F. Manea, and J. Hutchinson (2022). Evaluation of empirical ground-motion models for New Zealand application, *Technical Rept. 2022/46*, GNS Science, doi: 10.21420/W2M5-YC09.

Lee, R., B. Bradley, M. Hill, C. de la Torre, A. Kaiser, and L. Wotherspoon (2022). 3D ground motion simulation-based site amplification considering multiple basin geometries: A Wellington, New Zealand, case study, *GNS Sci. Rept. 2022/40*, GNS Science, Lower Hutt (NZ), doi: 10.21420/R21F-3C28.

Lee, R., B. Bradley, E. Manea, J. Hutchinson, and S. S. Bora (2023). Evaluation of empirical ground-motion models for the 2022 New Zealand National Seismic Hazard Model revision, *Bull. Seismol. Soc. Am.* doi: 10.1785/0120230180 (this issue).

Mazzoni, S., T. Kishida, J. P. Stewart, V. Contreras, R. B. Darragh, T. D. Ancheta, B. S. Chiou, W. J. Silva, and Y. Bozorgnia (2022). Relational database used for ground-motion model development in the NGA-Sub project, *Earthq. Spectra* **38,** no. 2, 1529–1548.

McVerry, G., J. Zhao, N. Abrahamson, and P. Somerville (2006). New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes, *Bull. New Zeal. Soc. Earthq. Eng.* **39,** no. 1, 1–58.

Miller, A., and T. Rice (1983). Discrete approximations of probability distributions, *Manage. Sci.* **29,** no. 3, 352–362.

Parker, G. A., J. P. Stewart, D. M. Boore, G. M. Atkinson, and B. Hassani (2022). NGA-subduction global ground motion models with regional adjustment factors, *Earthq. Spectra* **38,** no. 1, 456–493, doi: 10.1177/87552930211034889.

Petersen, M. D., A. M. Shumway, P. M. Powers, C. S. Mueller, M. P. Moschetti, A. D. Frankel, S. Rezaeian, D. E. McNamara, N. Luco, O. S. Boyd, *et al.* (2020). The 2018 update of the US National Seismic Hazard Model: Overview of model and implications, *Earthq. Spectra* **36,** no. 1, 5–41.

Rezaeian, S., M. D. Petersen, M. P. Moschetti, P. Powers, S. C. Harmsen, and A. D. Frankel (2014). Implementation of NGA-West2 ground motion models in the 2014 US National Seismic Hazard maps, *Earthq. Spectra* **30,** no. 3, 1319–1333.

Stafford, P. (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, doi: 10.21420/5098-0S19.

Stirling, M., G. McVerry, and K. Berryman (2002). A new seismic hazard model for New Zealand, *Bull. Seismol. Soc. Am.* **92,** no. 5, 1878–1903.

Stirling, M., G. McVerry, M. Gerstenberger, N. Litchfield, R. Van Dissen, K. Berryman, P. Barnes, L. Wallace, P. Villamor, R. Langridge, *et al.* (2012). National Seismic Hazard Model for New Zealand: 2010 update, *Bull. Seismol. Soc. Am.* **102,** no. 4, 1514–1542.

Van Houtte, C. (2017). Performance of response spectral models against New Zealand data, *Bull. New Zeal. Soc. Earthq. Eng.* **50,** no. 1, 21–38.

Van Houtte, C., S. Bannister, C. Holden, S. Bourguignon, and G. McVerry (2017). The New Zealand strong motion database, *Bull. New Zeal. Soc. Earthq. Eng.* **50,** no. 1, 1–20.

Weatherill, G. (2022). Impact of directivity on probabilistic seismic hazard calculations in New Zealand, doi: 10.21420/RETZ-D556.

Weatherill, G., and H. Lilienkamp (2023). Capturing directivity in probabilistic seismic hazard analysis for New Zealand: Challenges, implications and a machine learning approach for implementation, *Bull. Seismol. Soc. Am.*, 59 (this issue).

Wotherspoon, L. M., A. E. Kaiser, A. C. Stolte, and E. F. Manea (2023). Development of the site characterization database for the 2022 New Zealand National Seismic Hazard Model, *Seismol. Res. Lett.*, doi: 10.1785/0220230219

Zhao, J., and M. Gerstenberger (2010). Ground-motion prediction models for post-earthquake rapid reporting and reliable loss modelling using a sparsely distributed recording network in New Zealand, *GNS Science Consultancy Rept. 2010/123*, GNS Science, Lower Hutt, New Zealand, 82 pp.

Zhao, J., J. Zhang, A. Asano, Y. Ohno, T. Oouchi, T. Takahashi, H. Ogawa, K. Irikura, H. Thio, P. Somerville, *et al.* (2006). Attenuation relations of strong ground motion in Japan using site classification based on predominant period, *Bull. Seismol. Soc. Am.* **96,** no. 3, 898–913.

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