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BENEFITS OF SITE-SPECIFIC HAZARD ANALYSES FOR SEISMIC DESIGN IN NEW ZEALAND: REVISITED

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ABSTRACT

This paper revisits the sentiments expressed in a 2015 paper published by the author regarding site-specific seismic hazard analysis in New Zealand (NZ) [1]. While many of the general principles expressed remain the same, the completion of the 2022 NZ National Seismic Hazard Model (NSHM), and accompanying Draft Technical Specification TS1170.5:2024 have significantly altered how such analyses are performed in NZ, and the incremental value that they can provide beyond a code-based approach. This paper identifies instances where site-specific analyses remain valuable (and where they do not), where they will likely depart from the 'baseline' 2022 NZ NSHM (and TS1170.5:2024) results to a practically significant degree, and past practices for seismic source and ground-motion modelling choices which are now considered unviable. Lastly, challenges for practitioners and researchers are briefly addressed in order to further advance the practice of site-specific seismic hazard analysis over the next decade.

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INTRODUCTION

Probabilistic seismic hazard analysis (PSHA) [2] underpins the loading component of design codes in the seismic assessment of engineered structures in New Zealand (NZ) and the majority of nation states globally. For high-importance structures, it is common to make use of a so-called site-specific (probabilistic) seismic hazard analysis, which, in principle, seeks to perform PSHA in a manner that gives specific consideration to the most relevant source and ground-motion attributes at the site of interest. Such an analysis is naturally performed by suitably qualified personnel, typically subject to external (and ideally participatory) peer-review, and is generally considered to be an improvement upon, and thus used in lieu of, code-based seismic hazard quantification.

The broad context for the preceding 2015 paper from the author [1] was the 11-year-old seismic loading standard, NZS1170.5:2004 [3], and the gradual increase in the commissioning of site-specific seismic hazard analyses. It was intended as a relatively plain-language summary of the topic that could be used by design engineers, who were likely users of the results of such an analysis, in order to inform their clients accordingly. The completion of the 2022 update of the NZ National Seismic Hazard Model (NSHM; [4]), and the associated draft Technical Specification for NZS1170.5 (TS1170.5:2024 [5]), have drastically altered the perspectives of many regarding seismic hazard consideration in NZ, and it is therefore timely to revisit prior sentiments within this context, as well as preface new challenges and opportunities that have arisen.

The 2022 NSHM revision was a major update in the quantification of earthquake-induced ground-motion hazard in NZ in several regards, as elaborated herein, and has significantly raised the baseline rigour needed in any site-specific study to offer value beyond the results freely available from the NSHM web portal. This paper provides a plain-language overview of the nature and situations where site-specific analyses will be able to provide value relative to the NSHM web portal and TS1170.5:2024, including a re-assessment of the points addressed in the preceding 2015 paper. It also identifies challenges for the research and practitioner communities to ensure that: (1) requisite site-specific data is obtained with high-quality in order to derive the most value from such analyses; and (2) site-specific analyses in NZ can (relatively easily) refine the seismic source and ground-motion characterisation components of the 2022 NSHM as new data is collected for site-specific purposes. The views expressed are from the author's perspective as an active researcher in the field and contributor to the 2022 NSHM, as well as a site-specific seismic hazard analysis practitioner and peer-reviewer.

NSHM 2022 AND THE SITE-SPECIFIC HAZARD ANALYSIS VALUE PROPOSITION

NSHM2022 Advances

Seismic hazard analysis is an active field of scientific advancement, principally as a result of the complexity of earthquake and consequent ground-motion phenomena, and the low annual probabilities of exceedance considered relative to the historic period of earthquake observation [2]. That subsequent NSHM revisions lead to quantitative changes in hazard estimates is therefore not surprising. However, NZ is presently facing the 'fallout' of such a significant change in quantitative estimates principally because of the 20-year time period between the 2022 model (and associated TS1170.5:2024) and the preceding 2002-era model [6] that underpinned NZS1170.5:2004 [7]. This ad-hoc 20 year time period is in contrast to a more frequent and periodic update cycle, *e.g.*, the six-year cycle in the USA undertaken by the United States Geologic Survey [8].

Gerstenberger *et al.* [4] enumerate the many advances in the 2022 NSHM over the prior 2002 NSHM. The most significant of these in the context of a prospective site-specific seismic hazard analysis are:

1. Comprehensive seismic source and ground-motion char-

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acterisation models [4] - in the author's experience, more comprehensive than the overwhelming majority of prior site-specific studies in NZ pre-2022.

2. Non-characteristic and multi-segment ruptures obtained through inverting fault system constraints [9].

3. Multiple ground-motion models based on international and NZ-specific studies for crustal and subduction zone earthquakes [10].

4. Nearly 1,000,000 logic tree branches, that represent the different discrete hazard predictions resulting from modelling uncertainty [4,11].

5. Open-source documentation and computational tools, including web-based access to hazard results and derivative products such as uniform hazard spectra and disaggregation (https://nshm.gns.cri.nz/).

Revisiting the Benefits and Insights of Site-Specific Hazard Analysis Post-2022 NSHM

Bradley [1] discussed 10 different benefits and insights of site-specific hazard analysis in a circa-2015 NZ context (*i.e.*, 11 years post the NZS1170.5:2004 standard, and preceding the 2022 NSHM update). Table 1 summarises these topics, noting that six have been entirely or partially addressed by the 2022 NSHM revision, and what deviations occur as a result of using TS1170.5:2024 in place of the web-based 2022 NSHM results. These six items are addressed in the paragraphs of this section, while remaining items are discussed in subsequent sections.

Code-based parametrisation and conservatism (Points 1,2,4): Because the results from the 2022 NSHM are direct PSHA results then it does not have the issues with conservatism and parametrised code-based spectra [12]. However, TS1170.5:2024 elected not to adopt the 'multi-point spectra' approach of ASCE 7-22 [13], which would have used the 2022 NSHM results directly, and therefore the parametric spectral shape formulation in TS1170.5 does suffer from these same problems as NZS1170.5:2004, albeit to a lesser degree because of a more flexible formulation.

Near-fault factor (Point 3): Near-fault effects (namely rupture directivity) are implicitly considered in the 2022 NSHM in that all adopted ground-motion models were regressed using near-fault ground motions that exhibit the effects of directivity phenomena [10,14]. While some site-specific projects do adopt post-hoc directivity modification factors [*e.g.* 15], their application is complicated by alternative directivity modification models giving widely varying results, as well as the 2022 NSHM seismic source model containing non-characteristic and complex multi-segment ruptures that the directivity modifications were generally not applicable for. As discussed in Bradley *et al.* [10], specific analysis by Weatherill and Lilienkamp [14], using the Bayless *et al.* [16] directivity model, indicates that explicit consideration of directivity results in hazard changes of less than 10% for $SA(T=3.0s)$ values in most locations in NZ (with smaller changes at other vibration periods) as compared to differences up to 25% with the characteristic source model used in the 2010 NZ NSHM [17]. As discussed in Bradley [1], NZS1170.5:2004 adopts a parametric near-fault factor which is a function of vibration period and source-to-site distance. Issues with this near-fault factor include consideration of only 11 major faults, and also neglecting the relative contribution of such faults to the site-specific hazard. For vibration periods, $T>5$ s, and source-to-site distances, $D<2$ km the near-fault factor results in a 72% increase in ground motion amplitudes - values that are clearly appreciably higher than the results obtained from Weatherill and Lilienkamp [14]. The current draft of TS1170.5:2024 retains this near-fault factor without modification, which certainly suggests an over-prediction for locations such as Wellington, where active shallow crustal sources with potential directivity, like the Wellington and Wairarapa fault, represent approximately only 50% of the hazard, with ruptures on the Hikurangi subduction interface comprising the remainder.

Discrete site classes and amplitude-independent spectra (Point 6): All ground-motion models in the 2022 NSHM adopt the 30-m time-averaged shear-wave velocity, $V_{S,30}$, as the primary site characterisation parameter, and TS1170.5:2024 subsequently adopted a discrete site classification system predominantly based on $V_{S,30}$ values. Furthermore, the effects of nonlinear site response on response spectral shapes are directly considered for TS1170.5:2024. These changes represent a significant advancement from the representation of site effects in NZS1170.5:2004, and align with international practice.

Source disaggregation (Point 9): The NSHM website (https://nshm.gns.cri.nz/) provides common disaggregation information for all major urban and rural cities and towns in NZ; for several site conditions, spectral vibration periods, and probabilities of exceedance. This website is directly cited in TS1170.5:2024, thus enabling engineering practitioners access to magnitudes for geotechnical calculations, and more general disaggregation information for conventional code-based ground-motion time series selection [*e.g.* 18] - information that was entirely absent in NZS1170.5:2004.

NSHM2022 LIMITATIONS IN A SITE-SPECIFIC CONTEXT

Despite the methodological advances in the 2022 NSHM, it was still developed with the principal goal of a nationwide model in mind, and therefore has numerous technical limitations relative to a site-specific study, namely:

1. Computed for a discrete grid of locations (*i.e.*, lat/lon values).

2. Computed for a discrete array of $V_{S,30}$ values,

3. No explicit consideration of depths to shear-wave velocities of 1.0 and 2.5 km/s ($Z_{1.0}$ and $Z_{2.5}$, respectively).

4. Only rotation-independent 50th percentile (RotD50 [19]) horizontal response spectral intensity measures are considered.

5. Site response for the specific stratigraphy of the site, and any appreciable surface topography, is not explicitly considered.

6. Near-fault directivity is not explicitly considered.

7. Many seismic source and ground-motion modelling components are not site- or even region-specific.

8. Post-2022 data on seismicity and faults in the region of the site, and site-specific observed ground motions at, or near, the site are not incorporated.

Minimum Viable Product for Site-Specific Hazard in NZ

Points 1-3 in the above list relate solely to pre-computed results which are available on the web, rather than fundamental limitations of the underlying 2022 NSHM itself. Therefore, they can be collectively considered to represent the 'minimum viable product' of a purported site-specific seismic hazard analysis -

Table 1: Benefits and insights from site-specific hazard analysis identified by Bradley [1] and the degree to which they are addressed (or not) with the 2022 NSHM and TS1170.5:2024

Item	**Description**	**Addressed in 2022 NSHM?**	**Addressed in TS1170.5:2024?**
1. Site-specific spectral shape	Spectral shape varies with site location, site conditions, and return period vs. constant spectral shape, C(T), in NZS1170.5:2004	Yes	Partailly - parametric shapes adopted, but do vary with site conditions and ground-motion intensity
2. Site-specific 'return period' factors	Slope of the hazard curve varies with site location, site conditions and SA period vs. constant return period factor, R, in NZS1170.5:2004	Yes	As above
3. Near source factor	Parametric near-fault factor, N(T,D), used for a limited number of mapped faults	Partially - ground motion amplitudes due to near-fault effects are accounted for, but only implicitly through the standard deviation in the observations about the model mean prediction, rather than explicit parametric dependence	No - The NZS1170.5:2004 N(T,D) factor is retained, arguably double-counting the consideration of near-fault effects
4. Sources of conservatism	During the processing of fitting PSHA results into a codified parametric form the modelling adopts a conservative approach	Yes	Partially - parametric spectral shape development follows similar notion of conservatism, but the increased number of spectral shape parameters means degree of conservatism is likely less
5. Current vs. dated knowledge	Knowledge of earthquake source and ground-motion phenomena continue to evolve, as do models used to forecast the seismic hazard	Provides a comprehensive consideration of earthquake science into a hazard forecast, as at the date of completion (2022)	As to the left
6. Discrete site classes and an amplitude-independent spectral shape	NZS1170.5:2004 used discrete alphabet-based site classes vs. The continuous $V_{S,30}$ parameter; constant spectral shape does not reflect effect of nonlinear site response for softer soil sites	Yes	Partially - discrete site classes are used, albiet based principally on $V_{S,30}$; parametric spectral shape does change with ground-motion intensity due to nonlinear site effects
7. Direct site response analysis modelling	Specific sites can exhibit site response that can differ markedly from the ergodic average modelling through conventional ground-motion models	No	
8. Intensity measures other than PGA or SA	Ground-motion is tri-directional with intensity that is a function of amplitude, frequency content, and duration \cite{kramerGeotechnicalEarthquakeEngineering1996}, but NZS1170.5:2004 provides only horizontal SA values (with non-hazard-based simplified methods to infer vertical SA values)	No	No
9. Dominant scenarios from disaggregation	PSHA involves considering all seismic sources and disaggregation enables insight into the dominant scenarios; NZS1170.5:2004 does not provide any such information	Yes	Yes
10. Scenario-based hazard analysis	In addition to hazard curves, uniform hazard spectra, and disaggregation from PSHA it can be insightful to consider 'what will be the ground-motion intensity if a particular earthquake rupture occurs?"	No	No

i.e., to simply execute the underpinning science embodied in the 2022 NSHM for the site-specific location, and near-surface site conditions ($V_{S,30}, Z_{1.0}, Z_{2.5}$).

From the author's experience, the effect of points 1 and 2 on hazard results, i.e., using a site-specific location and $V_{S,30}$ vs. the nearest 0.1° gridded location and discrete $V_{S,30}$ value available at https://nshm.gns.cri.nz/, are in the low single digit percentages. Such differences are therefore often 'in the noise' relative to the uncertainty in the estimate of the true $V_{S,30}$ value at the site, and hence, the inaccuracy resulting from the gridded location and $V_{S,30}$ values are themselves not practically significant for standard (*e.g.*, Importance Level 2) engineered structures. A larger difference in hazard results does come from the implicit $Z_{1.0}$ and $Z_{2.5}$ values used in the 2022 NSHM vs. the values that are actually reflective of the site in question, which is discussed in the next section.

Before leaving this section it is also worth reflecting on how new scientific methods in the 2022 NSHM have, at least in the author's opinion, made some historical modelling decisions no longer tenable, such that they would be unlikely to satisfy a site-specific seismic hazard analysis peer reviewer. Most notably: (1) seismic source models that adopt the so-called *maximum magnitude model* [2, Section 3.5.7] for fault sources and do not allow for non-characteristic or multi-segment earthquakes on fault networks; (2) ground-motion models that are not developed on global datasets with possible fine-tuning against local (NZ) data and do not contain parametric forms that are significantly informed by ground-motion simulations to extrapolate beyond observational data constraints; and (3) superficial treatment of modelling uncertainty through 'shallow' logic trees. The first and third point, in particular, reflect 'step changes' with respect to how NZ-based site-specific hazard studies were being considered prior to the completion of the 2022 NSHM, and thus require practitioners to upskill. The open-source documentation and access to computational codes available on the 2022 NSHM website (https://nshm.gns.cri.nz/) helps to increase transparency of the model development process and programmatic implementation.

Site-Specific $Z_1.0$ and $Z_2.5$ Values

While ground-motion models used in the 2022 NSHM all incorporate $V_{S,30}$ as a predictor variable to describe surficial site response, the majority of models[1] also use the depth to an S-wave velocity of 1.0 or 2.5 km/s, $Z_{1.0}$ or $Z_{2.5}$, respectively (here Z_X is used to refer to either of these parameters). While $V_{S,30}$ and Z_X values do exhibit a correlation [*e.g.* 22], these sediment depth parameters have been recognised as important to reflect long-period ground-motion amplitudes since the NGA-West1 project in 2008 [23].

Adoption of $V_{S,30}$ and Z_X values in site-specific PSHA naturally requires that they can be estimated at a specific location. There are long-established methods for determining shallow S-wave velocity profiles using invasive and non-invasive methods needed to compute $V_{S,30}$, and such methods are becoming routinely used in NZ with the adoption of $V_{S,30}$ as the primary site characterisation parameter in TS1170.5:2024 [24]. Estimation of Z_X values are more challenging because of the typical depths at which they occur - making direct measurement on a site-specific basis prohibitively costly for most project budgets (except where it is known to be less than approximately 100 m depth). As a result, it is instead common to obtain Z_X values from velocity models that synthesise seismic tomography, reflection, refraction, and surface wave analysis; petrologic and hydrologic borelogs; gravity; and surficial geology datasets. The NZ velocity model (NZVM) of Thomson *et al.* [25] is an example for NZ.

On a site-specific basis it is possible to carefully consider multiple means by which to estimate these Z_X values and, with experience, ultimately determine values that can be used in PSHA. However, it was decided for the 2022 NSHM that it was not suitable to consider Z_X values on a nationwide basis because either: (1) a single mean estimate at each location using a model such as Thomson *et al.* [25] would have appreciable error at a non-trivial fraction of locations in NZ; or (2) considering an array of Z_X values (*e.g.*, that could be selected from on the web tool, just as one selects from an array of $V_{S,30}$ values) would result in a prohibitive number of analyses to undertake.

As a result of the decision to not explicitly consider Z_X values for the 2022 NSHM, Z_X values were implicitly determined based on empirical correlations with an associated $V_{S,30}$ value. That is, Z_X values are still used in the 2022 NSHM, as required inputs by the adopted ground-motion models, but they become entirely dependent on the adopted $V_{S,30}$ value, rather than another independent variable. Figure 1 illustrates the $Z_{1.0} - V_{S,30}$ values from the 2022 NSHM site database [26], as compared to one such $Z_{1.0} - V_{S,30}$ empirical correlation [22]. Although many of the quantitative data from the 2022 NSHM site database have low precision [26], it is evident that there is significant uncertainty in the correlation, which has been consistently observed for other regions globally. Figure 1 also indicates the effect of $Z_{1.0}$ on median response spectra for a site with $V_{S,30} = 500$ m/s and three values of $Z_{1.0} = 50, 500, 800$ m [2]. The largest differences in response spectra occur at long spectral vibration periods. For example, relative to the $SA(T = 3.0s)$ value for $Z_{1.0} = 500$ m, the 60% increase in depth to $Z_{1.0} = 800$ m results in a 18% increase in $SA(T = 3.0s)$, while the 10-fold reduction in depth to $Z_{1.0} =$ 50 m results in a decrease of 26% in $SA(T = 3.0s)$. The top panel of Figure 1 illustrates the $Z_{1.0} - V_{S,30}$ pairs representative of the bottom panel of the plot. The dashed lines in this figure, which are a factor of five above and below the correlation model given by the solid line, also qualitatively seperate sites into three general domains: (1) within the dashed lines are nominally ordinary sites with respect to their $Z_{1.0} - V_{S,30}$ values; (2) sites in the bottom left are shallow soft soil sites; and (3) sites in the top right are deep stiff soil sites. Shallow soft soil sites will have long-period ground-motion amplitudes, on average, that are appreciably lower than predicted by ignoring the site-specific Z_X values. Deep stiff soil sites will have long-period ground-motion amplitudes, on average, that are appreciably higher than predicted by ignoring the site-specific Z_X values.

A key conclusion from Figure 1, and the associated discussion above, is that the degree to which a sites $Z_{1.0} - V_{S,30}$ data pair deviates from the implicit correlation adopted in the 2022 NSHM can be used to infer the degree to which a 'minimum viable product' site-specific study would yield different results from the 2022 NSHM, when long-period spectral ordinates are of interest. This is particularly relevant for shallow soft soil and deep stiff soil sites. While such sites can exist over much of NZ's diverse tectonic environment, the implications of these non-ordinary site conditions have been clearly observed in major historical earthquakes in NZ. Shallow soft soil site response in Wellington during the 2013 Cook Strait and 2016 Kaikōura earthquakes [28, 29], and deep stiff soil site response in the Canterbury Plains during the 2010-2011 Canterbury earthquake sequence [30,31],

[1] Atkinson [20] was the only model to not use either $Z_{1.0}$ or $Z_{2.5}$. It is inferred that Atkinson observed little to no dependence on $Z_{1.0}$ given $V_{S,30}$ because of the estimation uncertainties in the NZ-specific dataset considered, as opposed to the lack of a physical dependence [*e.g.* 21]; all other models in the 2022 NSHM have $Z_{1.0}$/$Z_{2.5}$ dependence based on global datasets.

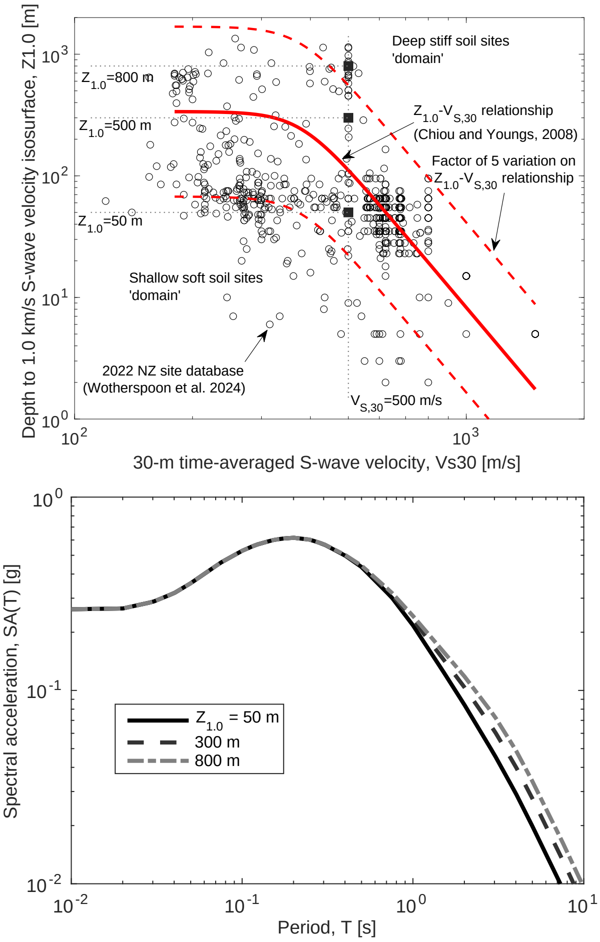

Figure 1: Top: $Z_{1.0} - V_{S,30}$ ***values of the 2022 NSHM site database compared with a*** $Z_{1.0} - V_{S,30}$ ***correlation. Bottom: Illustration of the effect of*** $Z_{1.0}$ ***on median ground-motion model predictions using the Chiou* et al.** *[27] model (after Baker* **et al.** *[2, Figure 4.25]). The degree to which a sites'*** $Z_{1.0} - V_{S,30}$ ***data pair deviates from the implicit correlation indicates whether a site-specific study would yield different results from the 2022 NSHM.***

are notable examples as discussed in the cited references.

CONTINUED BENEFITS OF SITE-SPECIFIC ANALYSIS BEYOND THE 2022 NSHM

This section addresses points 5,7, and 8 in Table 1 with a focus on the benefits and insights post-2022 NSHM to differentiate discussion from that in Bradley [1]. An additional subsection on region- and site-specific modelling, which was not discussed in Bradley [1], is also discussed because of the emphasis it has received in recent years. The sentiments associated with point 10 (scenario-based seismic hazard analysis) in Table 1 remain unchanged from those discussed in Bradley [1], and are therefore not repeated in this paper.

Current vs. Pre-2022 Knowledge

As discussed in Bradley [1], site-specific hazard studies can include best-available knowledge at the time of their study. In contrast, the 2022 NSHM naturally includes pre-2022 data and methods. While the NZ NSHM was officially released in late 2022, many of underpinning datasets and methods were finalised before this time (typically late 2021 from the author's experience). Thus, already at the time of writing this article, approximately 3.5 years of new data and methods have continued to be developed through the on-going NZ NSHM programme, other NZ funded research, and other international efforts - the perpetual wheels of scientific advancement and knowledge assimilation do not rest!

While it is true that macro-level data collection and methodological advancements typically take appreciable time, that is not necessarily the case for location- or region-specific datasets. New data of fault deformation and timing of paleo-events on regional fault structures, and region- and site-specific observations of ground-motion, or site characterisation measures to better understand the velocity profile (and hence Z_X values) will enable updates to the 'base' source and ground-motion models adopted in the 2022 NSHM and result in notable spatially-localised changes in seismic hazard.

The 2022 NSHM was also completed at a time when no significant aftershock sequences were causing order-of-magnitude increases in earthquake activity as compared to their longer term average. For example, the 2010-2011 Canterbury and 2016 Kaikōura earthquakes led to appreciable aftershock sequences that resulted in the development of region-specific modifications to prior NSHMs [*e.g.* 32,33]. This is because prior NSHMs, as well as the 2022 NSHM, are not 'living' models that automatically ingest current earthquake activity in order to provide time-varying forecasts (an example being that of Field *et al.* [34]). Thus, another reason to undertake a site-specific study would be to adjust the 'static' forecast from the 2022 NSHM in the aftermath of another appreciable aftershock sequence that leads to medium-term (*i.e.*, years to decades) changes to the seismic hazard at a site of interest.

The collection of additional scientific knowledge, as well as the static nature of NSHM forecasts, illustrates the interplay between the value of a site-specific seismic hazard analysis and the revision cycle for NSHM updates. As outlined in the introductory remarks, it has been 20 years since the prior NSHM update that influenced a major code/standard document. In comparison to the formalised six-year cycle for NSHM updates in the USA, at the time of writing, there is no formal update cycle in NZ. When the duration between NSHM updates increases, site-specific seismic hazard analyses become an increasingly valuable tool for common engineered structures to provide a client with up-to-date information (in terms of seismic hazard) that can avoid near-term problems, such as structures being under-designed[2]. Conversely, as the duration between NSHM updates decreases (which is most likely to materialise when there is a fixed update cycle), site-specific hazard analyses are more likely to be restricted to high-importance structures and performed by analysts and companies who are themselves able to start at the leading edge of such scientific advancements.

Intensity Measures other than RotD50 Horizontal Response Spectra

Bradley [1] discussed the importance of intensity measures other than pseudo-spectral acceleration, SA, and peak ground acceleration, $PGA = SA(T = 0)$, for a general description of ground motion severity. The 2022 NSHM provides seismic hazard analysis results only for SA based on the RotD50-definition in the horizontal plane. Hence, it does not provide other specific information about ground motion directivity and directionality [*e.g.* 35] in the horizontal plane, nor does it give attention to the

[2] Even if not officially, according to regulatory wording citing old design loads, at least as far as the competitive property rental market is concerned.

increasing consideration for vertical ground-motion intensity.

While for most (particularly structural) engineering applications, horizontal PGA and SA intensity measures will continue to be prevalent in simplified design methods, the need to explicitly consider other intensity measures is particularly understood in the domain of ground-motion selection [*e.g.* 2, Chapter 10]. Just as the 2022 NSHM (and TS1170.5:2024) has raised the profession regarding the consideration of seismic loading in simplified design approaches, the forthcoming SESOC guidelines on nonlinear response history analysis [18] are likely to have the same effect on ground-motion selection for nonlinear response history analysis. A site-specific hazard analysis seamlessly enables additional information that is increasingly desired for ground-motion selection, such as conditional spectra [*e.g.* 2, Section 7.5], as well as the consideration of vertical spectra and non-SA intensity measures. Lastly, the SESOC guidelines on nonlinear response history analysis [18] also preface the challenges that exist when using parametrised spectral shapes, such as in TS1170.5:2024, for ground-motion selection at short vibration periods within the 'spectral plateau', and hence site-specific hazard analysis information is valuable to avoid these issues.

In geotechnical earthquake engineering, contemporary methods of analysis are also frequently using intensity measures other than *PGA* and *SA*. Examples include seismic earth pressures [36] and slope displacements [37] based on peak ground velocity, *PGV*, and liquefaction-induced building settlements using a measure of cumulative absolute velocity, *CAV* [38]. With the 2022 NSHM providing only *PGA* and *SA* hazard information, these contemporary methods are not able to be considered in a hazard-consistent manner (*i.e.*the author is aware of heuristics to estimate these non-*SA* IMs via correlations with *SA* values, but obviously this is undesirable given the uncertainties that are present). Hence, site-specific hazard analyses can be used to explicitly obtain hazard curves for non-*SA* IMs, so that they can be used appropriately in a manner compatible with NZS1170.5:2002 [39] or equivalent.

Site-Specific Response Analysis

Bradley [1] addressed the additional insights that explicit modelling of the dynamic response of near-surface stratigraphy (so-called site response analysis) can have for determining seismic hazard. These include the: (1) specific stratigraphy of a site, which may reflect a velocity profile that differs from the implicit average profile, for a given $V_{S,30}$ value, within an empirical ground-motion model; and (2) the specific nonlinear constitutive behaviour of the sediments as compared to the general nonlinear parametric scaling in an empirical ground-motion model. While TS1170.5:2004 specifically refers to Site Class VII soils as requiring a site-specific study, the above benefits of a site response analysis are not limited to soils with very low shear-wave velocities.

Baker *et al.* [2, Section 8.6] provide a summary of different approaches to account for site-specific site effects, as well as how they can be incorporated into site-specific seismic hazard analysis. Over the past decade significant further research and development has also occurred in the field of one-dimensional site response analysis, as well as advances in the practical application of different methods [40,41], and treatment of modelling uncertainties [42]. Importantly, numerous studies have shown that one-dimensional site response analyses using conventional approaches and assumptions can potentially produce appreciable bias and uncertainty as compared with observations [43–45]. Thus, such wave propagation-based analyses should only be undertaken with, and under the participatory peer review of, suitably qualified experts. Otherwise, one runs the real risk of obtaining results that are less consistent with reality than those using the simple $V_{S,30}$-based parametrisation in empirical ground-motion models.

Toward Region- and Site-Specific Source and Ground-Motion Modelling

Many source and ground-motion model components in the 2022 NSHM are neither region- nor site-specific. To illustrate, consider the following two situations: (1) the prediction of a moment magnitude $M = 7$ event at a source-to-site distance of $R_{Rup} = 30$ km for a site with $V_{S,30} = 300$ m/s; and (2) the predicted magnitude of an earthquake rupture on an active shallow crustal fault for a rupture geometry with an area of $A = 1000$ km^2. In the first situation, with the exception of the additional attenuation with distance in the back-arc region of the north-west North Island [10], the predicted ground motion distribution will be the same for all other locations in NZ, *e.g.*, for a rupture in the eastern North Island vs. the south-east of the South Island. That is, the systematic variation in the source, path and site phenomena that will occur between these locations is not accounted for in the models. Similarly, in the second example, the predicted mean magnitude will be $M \approx 7.1$ for this event whether it is located on the southern extent of the Alpine Fault, or the lower North Island region of the Axial Tectonic Belt.

The lack of regional variation in the prediction examples above are a result of the fact that underpinning prediction models have grouped similar data from global observations as a proxy for a large number of observations for the actual prediction scenario that is of concern. In the field of stochastic methods this equivalence between multiple observations at different spatial locations, and repeat observations at a single point in space over time, is referred to as the *ergodic assumption* [46]. Thus, predictions that relax this assumption are commonly referred to as *non-ergodic* predictions. In the preceding 2015 paper [1], no mention was made of non-ergodic predictions, because such considerations were generally limited to research studies, or for the highest-importance structures. However, there is now greater awareness of the benefits of explicitly addressing (or at least considering) this issue, as well as practical methods to actually implement it. The allure of adopting non-ergodic methods is a reduction in the apparent aleatory variability in predictive models for which, all other things equal, leads to a reduction in hazard estimates - particularly for large return periods [47].

Baker *et al.* [2, Chapter 8] provides a comprehensive introduction to the topic of non-ergodic hazard analysis, considering both seismic source and ground-motion modelling; while Lavrentiadis *et al.* [48] provide a more comprehensive overview specific to empirical ground-motion modelling. The basic idea is that increasing region- or site-specific data allows one to reduce the implicit dependence of the model on global observations, and place increasing emphasis on region- and site-specific specific data. Although it is common to see people make the binary distinction between an ergodic and non-ergodic model, in fact all models exist on an *ergodic continuum* as discussed by Baker *et al.* [2, Figure 8.2].

In considering the portions of the seismic hazard problem that are most amenable to relaxing the ergodic assumption, Baker *et al.* [2, Chapter 8] discuss how it is easiest to constrain the site portion of the ground-motion model, followed by the ground-motion path component. Constraining region-specific features of the source component of the ground-motion model, and the seismic source model itself, are complicated by the lack (and often complete absence) of larger magnitude rupture observations on the region-specific faults that dominate the hazard at the site of interest. To summarise, non-ergodic (*i.e.*, region- and site-specific) treatment of ground motion represents the largest area of differentiation between a site-specific study and the 2022 NSHM.

Site-Specific Weights on the 2022 NSHM Logic Tree

The 2022 NSHM considered extensive logic trees for the seismic source and ground-motion characterisation models [4]. The weighting for the logic tree was developed through a structured process of expert elicitation [49]. The prescribed model weights are all constant values, that is, they do not vary as a function of earthquake magnitude, source-to-site distance, site conditions, spectral vibration period. This implies that all models are considered to have a constant relative degree-of-belief. Obviously, this is not the case, and was a practical concession in the 2022 NSHM development because of its application on a nationwide basis.

In a site-specific hazard analysis setting it is possible to more specifically understand the rupture scenarios that affect the hazard (via disaggregation), and place a greater scrutiny on the alternative models for predicting these scenarios. In doing so a greater degree of model preference can be ascribed via the weights given to alternative models. For example, a particular ground-motion model may have been given a uniform logic tree weight for use in the 2022 NSHM, but for a particular site-specific application this model may be deemed to poorly model severe nonlinear site response (or conversely very hard rock sites) as compared to other models, and would therefore be down-weighted.

CHALLENGES TO ADVANCE SITE-SPECIFIC HAZARD ANALYSIS PRACTICE

From the author's perspective and first-hand experience there are several short-term challenges to continue advancing the state of practice in this field, both of which are readily achievable.

Computational Access to the 2022 NSHM

The significant advances of the 2022 NSHM come with an associated consequence that the model is appreciably more complex (which has associated training implications as subsequently discussed). The open-source documentation on the NSHM website provides comprehensive information for users to better understand the nature and features of the model. However, the complexity of the model is such that the documentation alone does not enable the model to be reproducible. To aid in reproducibility, the programmatic implementation of the model input files are available (https://nshm.gns.cri.nz/Resources/ModelComponents, last accessed Dec 2024) for use in the open-source OpenQuake engine [50]. While the complete logic tree has nearly 1,000,000 branches, which can be computationally challenging for routine applications; anecdotal evidence (Christopher DiCaprio, pers. comm., Oct 2024) indicates that 100,000 random-selected branches can yield sufficiently accurate fractiles of the hazard for most practical applications.

Site-Specific Site Characterisation Data Collection

Realising the benefits of a site-specific hazard analysis (*i.e.*, obtaining a different result than simply via the publicly available 2022 NSHM website) requires valuable data collection at the specific site of interest. As a present indication, only 11% of the nationwide seismic instrument network has measured estimates of $V_{S,30}$ [26], and it remains common for the author to see instances of site-specific studies where the approach(es) to estimate $V_{S,30}$ are less than desired for a basic site-specific seismic hazard analysis. The requirement to obtain a 30-m velocity profile, and consequent $V_{S,30}$ value, for site classification in TS1170.5:2024 should significantly raise the national capacity and capability in geophysical testing, and there is already empirical evidence suggesting that this is the case. Furthermore, as discussed in the section *Site-specific* $Z_{1.0}$ *and* $Z_{2.5}$ *values*, increasingly high-quality estimates of these S-wave velocity depth parameters should also be obtained.

With a view toward increasingly site-specific treatment of site response, additional advances in practice are needed in site characterisation, namely: (1) placement of temporary seismometers to record vibrations that can be used to determine the seismic site behaviour relative to that predicted by an (ergodic) ground-motion model, and hence determine site-specific adjustments; and (2) for softer soil sites, collection of site characterisation field and laboratory data that can be used in the calibration of constitutive modelling parameters for nonlinear dynamic site response analyses.

New Region-Specific Seismicity and Fault Characterisation Information

As alluded to in prior sections, regional fault-specific deformation and/or paleoseismic data will continue to be collected and collated, as well as project-specific field work for high-importance site-specific studies. Seismicity and geodesy data will also continue to be collected through the national networks (*i.e.*, GeoNet), though the effects of this are less significant, as a few additional years of such data is unlikely to drastically change the current seismic source models that are principally constrained using such data.

The principal challenge, at present, where post-2022 data is available for a site-specific study is how it should be considered in the development of the seismic source characterisation model. The historical use of the so-called *maximum magnitude model* [2, Section 3.5.7], where modelled faults are treated as pure characteristic sources, and distributed seismicity sources are used to handle all non-characteristic ('tail') seismicity, enabled a fault system to be separated into a collection of individual faults, and thus new fault-specific data has an effect that is isolated to that particular fault. In contrast, the use of inversion approaches applied to the entire fault system in the 2022 NSHM [51] means that new fault-specific data, in theory, affects the magnitude-frequency distribution on all fault segments in the network.

The complexity of the fault system inversion approach makes it significantly less accessible (in its present framing and computational implementation) for practitioners to contemplate re-running the inversion with the availability of new fault-based data. Nonetheless, the ability for site-specific seismic hazard practitioners to be able to directly adjust the inversion algorithms forming the fault source component of the 2022 NSHM will be a necessity to ensure that post-2022 information is able to be routinely updated[3]. If it is not available, it will most likely lead to a situation in which practitioners, for the valid practical reason of timeframe, will revert to a maximum magnitude (*i.e.*, characteristic) model approach to fault sources; which I

[3] It is possible to develop a comprehensive seismic source model, for a site-specific application, that does not make use of an inversion-style approach, but it requires appreciable experience to avoid pitfalls. Such an approach may be desirable where uncertainties in fault dip and seismogenic thickness are of particular concern, uncertainties that are not explicitly considered in the 2022 NSHM source model grand inversion.

earlier identified as likely to be otherwise viewed as a technically unviable option.

To balance the above sentiments, it is also important to note that the fault system inversion approach does reduce the sensitivity of the resulting seismic source model to new fault-specific information. That is, in the characteristic source paradigm, a single data point, e.g., a paleoseismic rupture date/magnitude, could significantly influence a fault estimated recurrence interval. In the fault system inversion model, the large number of data constraints that are jointly solved for the entire fault system means that the addition of a small volume of new fault-specific data is unlikely to result in significant changes to individual fault behaviour in the seismic source model. The implication of this logic is that a nationwide revision to the entire source model may not need to occur as frequently as it would have under the characteristic earthquake paradigm.

Technical Training of Seismic Hazard Practitioners and Users of Site-Specific Study Results

The greater ease of accessing seismic hazard information and underlying computational tools, naturally raises concerns that they will be increasingly utilised by inexperienced users. It is the author's opinion that education and training represents the largest barrier to broad progress in the discipline.

As illustrated from the progression of major NSHM products in NZ from 2002 – 2022 [4,6,17] in terms of: technical methods, number of scientific collaborators, and extent of documentation, among others; the science of seismic hazard analysis has advanced substantially over the past two decades. In contrast, the manner in which seismic hazard products are 'translated' into conventional seismic design loading has not appreciably changed (i.e., via a uniform hazard spectra for specific probabilities of exceedance, or equivalently, return periods). Likely related to this, the majority of practicing earthquake engineers will have had no direct training on seismic hazard analysis within typical four-year undergraduate degree qualifications. Even at the (post)graduate level, it is relatively rare to find universities that offer courses solely devoted to seismic hazard analysis, with hazard analysis content often being briefly covered as an aside in courses on geotechnical or structural earthquake engineering.

The lack of comprehensive training in seismic hazard analysis is typically the root-cause in common misunderstandings of the field and 'surprises' when large earthquakes, and their consequent strong ground motions, occur [*e.g.* 2, Chapter 12]. The recent availability of comprehensive textbooks on seismic hazard analysis [*e.g.* 2] will reduce barriers for educators to teach such content, and also allow practitioners to engage in additional self-teaching. However, progress will additionally require efforts from learned societies, technical mentoring and training within practicing organisations, and robust participatory peer review on projects that utilise site-specific studies.

CONCLUSIONS

This paper has examined the benefits and insights of site-specific seismic hazard analysis, revisiting sentiments expressed in a 2015 paper by the author [1] in light of the recent completion of the 2022 NSHM [4] and TS1170.5:2024 [5]. The significant advances in the 2022 NSHM, as reflected in TS1170.5:2024, address six of the 10 benefits outlined in 2015, yet there remain many benefits to site-specific seismic hazard analysis in NZ. The limitations of the 2022 NSHM for use in site-specific seismic hazard analysis applications were outlined, and thus the author's view of a minimum viable site-specific seismic hazard analysis study presented. The determination of site-specific depths to the 1.0 and 2.5 km/s S-wave velocity horizons ($Z_{1.0}$ and $Z_{2.5}$, respectively) are a particularly important means to obtain value beyond the 2022 NSHM. Other advantages for seismic hazard characterisation that can be incorporated in a site-specific study include the: (1) use of the latest seismic source and ground-motion characterisation knowledge; (2) consideration of realistic vertical spectra and intensity measures other than spectral accelerations, which is particularly useful for ground-motion selection; (3) site-specific site response analysis; and (4) consideration of region- and site-specific phenomena. Realising these continuing potential benefits of site-specific hazard analyses will require addressing several challenges, most notably, improved data collection for quantifying the specific attributes of the site of interest (i.e., site characterisation); the incorporation of region- and site-specific information associated with seismic source, path, and site effects; and a continued focus on education and training.

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