Site-specific Seismic Hazard Analysis - evolving developments in practice

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ABSTRACT

Site-specific Seismic Hazard Analyses (SSHAs) are undertaken to inform seismic actions for the design of important projects in New Zealand. These have typically adopted the 2010 National Seismic Hazard Model (NSHM) as the reference NZ Source Model.

Advances in SSHA practice have included the adoption of modern NZ-region specific and international ground motion models, with epistemic uncertainty considered using logic trees. Where appropriate, modifications to the 2010 NSHM have also been made, informed by recently published paleo-seismological studies on major fault sources. Other considerations have included making the SSHA truly 'site specific' by assessing local effects due to fault proximity, basin edge, topographic, and soft soil response.

This paper presents aspects of selected SSHAs undertaken for sites in NZ and the South Pacific, where efforts have been made to incorporate 'site-specific' aspects into the assessment and considers both seismic hazard and engineering design aspects in the development of recommendations for seismic design actions for engineering projects. The discussion includes thoughts on application of 2022 NSHM hazard results in developing recommendations for future projects.

1 INTRODUCTION

Since the publication of AS/NZS 1170.0 in 2002 (Standards Australia/ Standards New Zealand 2002), practicing engineers have been carrying out Site-specific Seismic Hazard Analyses (SSHAs) in a rapidly evolving field. Clause 3.3 of AS/NZS 1170.0 requires SSHA be performed for 'special structures' with an Importance Level (IL) of 5 as well as for structures with special post-disaster functions (IL4) that have a design working life of 100 years. In addition to these requirements, NZS 1170.5 permits 'special studies' to be performed for any structure to replace the loading requirements of that Standard. This allowance for SSHA is also included in the MBIE/NZGS (2021) Earthquake Geotechnical Engineering practice modules (specifically “Method 2” to derive design ground motions in Module 1). Several major infrastructure clients require SSHA to be completed for projects considered to be lifeline or major assets of significant value.

In the intervening years since the publication of NZS 1170.5:2004, thanks to the work of geologists and seismologists our collective knowledge of New Zealand seismotectonics has steadily improved. As this knowledge has departed from what was known at the time the standard was written, the frequency of analyses performed for structures of lower importance levels (but also high commercial value) has increased, particularly in areas of high seismicity such as Wellington.

While there is no specific requirement in NZS 1170.5 to use a particular hazard model or revision, the National Seismic Hazard Model (NSHM) developed periodically by GNS Science in 2002, 2010, and 2022 (Stirling et al. 2002; Stirling et al. 2010; Gerstenberger et al. 2022 resp.) has been the ‘reference’ source model for SSHA in NZ. This paper focuses on the implementation of SSHAs in NZ up to the publication of 2022 NSHM, drawing on the 2010 NSHM as the operating reference model. During this period, the authors have performed a number of analyses for their clients throughout NZ (and the South Pacific with different source models) and have sought to incrementally refine the inputs to best reflect the most up-to-date changes in the field for each subsequent analysis. The updates to the SSHA inputs can be grouped as:

- Consideration of how epistemic uncertainty is treated during the analysis process,
- Incorporation of updated ground motion models,
- The addition of new faults and refinement of pre-defined fault parameters in seismic source models, and
- The more specific treatment of aspects that affect specific sites including but not limited to basin edge effects; close proximity to large faults; site topography; and soft soil conditions.

The changes in each of these categories that were found to be relevant to SSHAs discussed herein. In many cases, the results obtained by revising the SSHA source model, or considering these specific site effects, led to careful thought about how they should inform design recommendations for specific structures, accounting for both structural design considerations and individual client requirements and priorities.

2 GROUND MOTION MODELS

Ground motion models (GMMs) (formerly ‘attenuation relationships’, sometimes ‘Ground Motion Prediction Equations’ or GMPEs) have been continuously developed over recent decades, driven by the two following factors; firstly, successive GMMs have benefited from a larger database of available ground motion records upon which to develop statistical relationships, as well as improved methods of data processing and incorporating more rigorous statistical procedures; and secondly, the treatment of epistemic uncertainty associated with development and selection of GMM has changed over time.

2.1 Progressive Ground Motion Model Development and Use

Historically, many different GMMs have been used in NZ SSHA. For example, the SSHA for the Otira Viaduct (Beca Carter Hollings & Ferner Ltd 1994) used two models; Katayama (1982) modified for NZ by Matuschka et al. (1985) for area sources, and Joyner & Boore (1982) for linear fault sources. The GMMs from that time were limited by a lack of NZ-specific ground motion data for calibration or verification.

The McVerry et al. (2006) (McVerry) GMM benefited from a significant change in the quantity of data from NZ and abroad and is based on 435 ground motions from 49 earthquakes recorded between 1966 & 1995, supplemented by overseas records where the NZ dataset was perceived deficient. An advance on preceding models was the consideration of attenuation in different tectonic region types (shallow crustal, subduction interface and slab, and volcanic crust - with higher attenuation applicable for the Taupo Volcanic Zone), faulting mechanisms, and improved recognition of soil conditions (Classes A/B, C, and D developed). The

McVerry model was used with the 2002 NSHM to inform NZS 1170.5 (Standards New Zealand 2004a), and remained a mainstay of SSHAs in New Zealand for the next 15 years.

A decade later, Bradley (2010), (2013) developed GMMs for NZ based on newer international models such as Chiou & Youngs (2008), one of the five 'Next Generation Attenuation' (NGA) shallow crustal earthquake models developed by the Pacific Earthquake Engineering Research (PEER) Center based in California; and Zhao et al. (2006), a model for shallow crustal and subduction earthquakes developed based on a large Japanese dataset. Both Bradley (2010) and Van Houtte (2017) found that the McVerry model did not perform as well as the newer models developed from larger datasets, and tended to be more conservative when estimating low period motions including Peak Ground Acceleration (PGA). The five NGA models were updated in 2014 as part of the PEER NGA-West2 Project (Bozorgnia et al. (2014)), featuring a range of further improvements. A similar PEER project 'NGA Sub' for developing a suite of international subduction earthquake GMMs has been recently completed, some of which include NZ-region specific modifiers (Bozorgnia et al. 2021). The applicability of these international models for modelling ground motion attenuation for sites in NZ have been backed by studies showing they, along with the Bradley (2013) model, compared well to NZ ground motion data (Van Houtte 2017) (Lee, et al. 2022).

2.2 Epistemic Uncertainty

Within NZ practice during the 2000s, an accepted approach to manage epistemic uncertainty associated with GMMs was to select a single 'best' model as the most applicable or relevant to the region and site conditions. A model calibrated to NZ-specific data was considered more applicable than international models, and we are unaware of published studies that rigorously compared the efficacy of various GMMs for NZ until post 2010. However, there is more to epistemic uncertainty than the source data for a particular model. Baker et al. (2021) provides an example showing four different models developed by different researchers using the same NGA-West2 data but producing significantly different ground motion predictions. The solution to this issue for some time has been to adopt a logic tree containing a suite of selected GMMs that are considered to produce credible estimates for the region, and weighting each according to a perceived level of trust, ideally informed by comparison with regional ground motion data (Scherbaum, et al. 2005). Due to the perceived quality of the McVerry model for modelling the attenuation of NZ earthquakes it was often used as the sole GMM in Probabilistic Seismic Hazard Analysis (PSHA) calculations.

Bradley et al. (2011) undertook a study of epistemic uncertainty in ground motion prediction in NZ and showed that one of the most significant sources of uncertainty in predictions was the selection of GMMs. Van Houtte (2017) showed that while several of the NGA and NGA West2 models performed better than McVerry, they also varied significantly from each other, and consequently a GMM logic tree for estimating NZ ground motions was recommended, to include a variety of international as well as NZ-specific models (e.g., McVerry et al. (2006) and Bradley (2013)), to appropriately account for epistemic uncertainty. While some international consultants undertaking SSHA in NZ were to some extent using GMM logic trees from the mid-2010s, by 2019 it is our understanding that a GMM logic tree featuring a suite of modern international and NZ-specific models had become the norm in the industry.

Seismic engineers providing SSHAs rely on their judgement, informed by published guidance as noted above, to create an appropriate GMM logic tree. A recent example developed the authors for sites in NZ is shown in Figure 1. A review of SSHA reports by others often show similar choices in models, with some differences in weighting, and the decision whether to continue to include the McVerry GMM in the mix or not. The impact of a modern GMM logic tree compared to solely adopting a single model (McVerry in this case) is shown in Figure 2 for two return periods of shaking at a site in Wellington (Site Class C, V_{S30} 450m/s), where the source model used for both analyses is the NSHM 2010 model (as implemented in PSHA software OpenQuake by GNS Science, with updates to June 2019). The influence of the both the adoption of GMMs developed based on newer, larger datasets, and the incorporation of epistemic uncertainty via the logic tree, has increased the ground motion estimates for both return periods, and changed the spectral shape significantly, particularly at moderate to long vibration periods for the selected soil site class conditions.

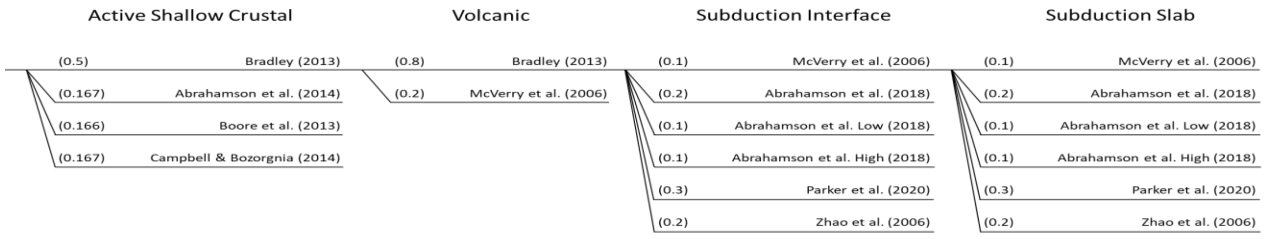

Figure 1: Ground motion model logic tree adopted for SSHAs around New Zealand.

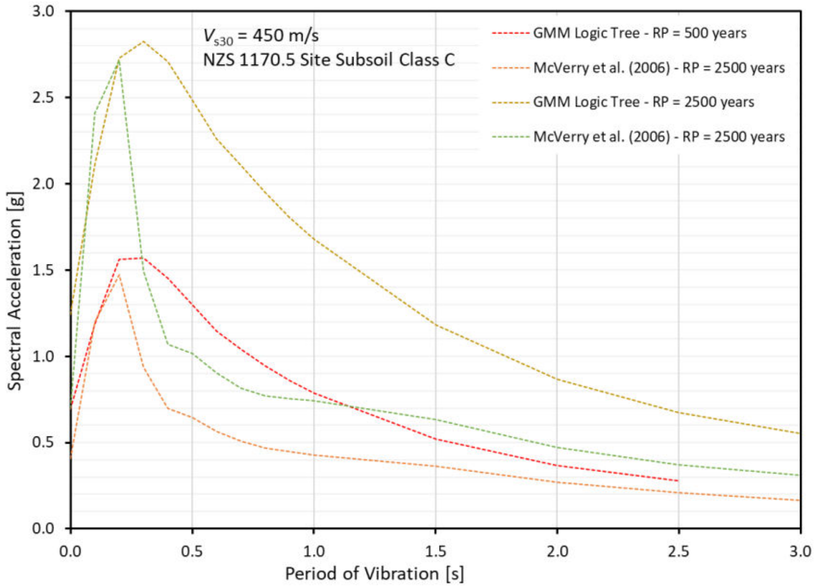

Figure 2: Comparison of Uniform Hazard Spectra at a Wellington site (Site Class C, V_{s30} of 450m/s) for 500-year and 2500-year return period (RP), constructed using the legacy McVerry model, and a modern GMM suite within a logic tree. The 2010 NSHM source model is used for all cases.

The NSHM 2022 has included changes to both the source model and seen the development of two new NZ-specific GMMs to be included alongside a suite of modern international shallow crustal ‘NGA2West’ and subduction ‘NGASub’ models within a GMM logic tree (Gerstenberger, et al. 2022). Previous generation models including McVerry, and Zhao et al. (2006) were not included. The differences as a result of the new GMMs are shown in Table 1, where the source model adopted remains constant (2010 NSHM).

2.3 Magnitude Weighting

It is well understood that the duration of shaking is a significant contributor to fatigue-related structural damage. In the development of uniform hazard spectra (UHS) for design, NZS 1170.5 adopted a ‘magnitude-weighting’ procedure proposed by Idriss (1985) (also called ‘duration-weighting’) implemented by modifying the McVerry et al. (2006) GMM. This was done to normalise the spectra for the influence of small magnitude earthquakes that produce few significant cycles of shaking, whereas large magnitude events may have many cycles. The Idriss (1985) magnitude weighting relationship is based on the calculation of number of equivalent cycles, n_{eq} in an earthquake using the Seed et al. (1975) variant of the Palmgren-Miner (P-M) fatigue theory, developed for soil liquefaction triggering assessments, but has its origins in observations of metal fatigue response (Green & Terri, 2005). The code committee only applied the Idriss relationship to reduce the intensity of spectra from smaller magnitude events, which is particularly significant in areas and/or for return periods where low magnitude earthquakes dominate the hazard at the site.

Table 1: Comparison of uniform hazard values for a site in Wellington (Site Class C, V_{s30} of 450m/s) with GMMs adopted by Stirling et al. (2012), Beca custom logic tree (2020-2022), and the new suite adopted by Gerstenberger et al. (2022) using the same seismic source model (2010 NSHM).

Period of Vibration [s]	Spectral Acceleration at a Return Period of 500 Years [g]		
	NSHM 2010 with McVerry GMM	NSHM 2010 with custom GMM logic tree	NSHM 2010 with Gerstenberger et al. (2022) GMM logic tree
0 (PGA)	0.41	0.70	0.71
0.5	0.85	1.30	1.09
1.5	0.26	0.52	0.48
3.0	0.12	0.22	0.19

Figure 3 shows the results of an SSHA performed by some of the authors for a site in Auckland, where UHS produced using the Bradley (2010, 2013) GMM are compared with UHS calculated using the McVerry et al. (2006) GMM – the latter with and without the magnitude weighting correction applied. Further thoughts on the use of duration weighting going forward are presented later in Section 4 of this paper.

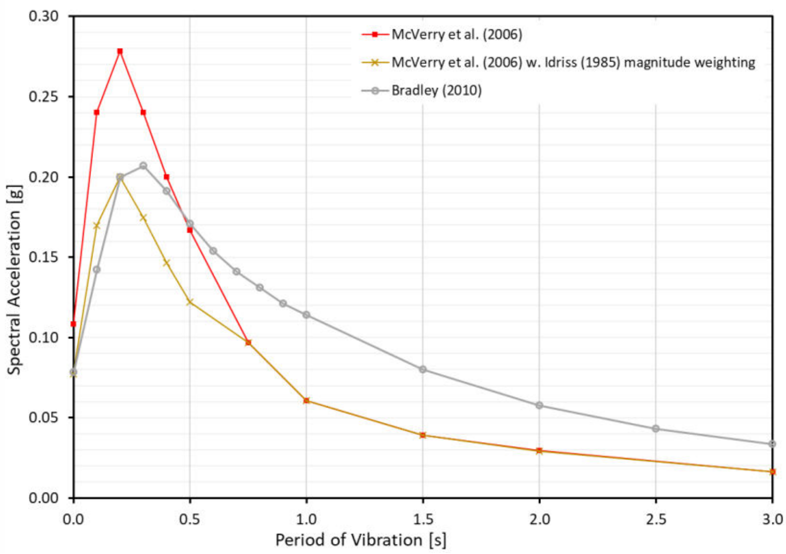

Figure 3: Comparison of uniform hazard spectra for Auckland generated from varying ground motion models for a return period of 500 years.

3 SEISMIC SOURCE MODEL REVISIONS

The seismicity of New Zealand's known major faults have been the subject of continuous study. Each NSHM version reflects the state of knowledge of the time (i.e., 2002, 2012, 2022). For SSHAs completed in the late 2010s/ early 2020s, prior to the revision of the NSHM in 2022, region-specific changes to the 2010 NSHM were sometimes required to capture the latest understanding of the seismicity at specific sites. As part of SSHAs performed by the authors during this period, a review of the relevant published fault studies was undertaken, with emphasis on major fault sources in relatively close proximity, and with moderate to high slip rates, and therefore have an ability to influence the calculated hazard at the site, particularly at ULS. With one exception in the examples presented, background seismicity rates were not revised. For this task, expert seismological advice was provided by Dr. Kelvin Berryman of Berryman Research & Consulting Limited (BRC). SSHAs during this period were carried out for engineering projects in Tauranga, Napier, Porirua, Wellington, Nelson, and Queenstown.

Comparison of the response spectra derived from using the default 2010 NSHM and our revised source models for these studies are presented in Figure 4. The resulting changes in hazard estimates were relatively modest in most cases, but typically resulted in some increase in amplitude of design spectra over the unmodified 2010 NSHM. The largest changes occurred in Nelson and are on account of the changes made to both the major regional faults but also the background seismicity, which notably impacted moderate to long period response. A detailed summary of these changes have not be included in the interests of brevity.

4 SITE-SPECIFIC MODIFIERS

4.1 Earthquake Duration

As presented in Section 2.4, NZS1170.5:2004 adopted magnitude weighting within PSHA hazard calculations to normalise for the number of equivalent stress cycles, and hence fatigue demand in structural design. The modification was of particular benefit as it corrected for a bias in the McVerry GMM which tends to over-estimate low period shaking amplitudes, as typically contributed strongly from low magnitude, close distance seismic sources in a PSHA calculation. Going forwards, the adoption of modern GMMs may suggest there are less benefits to applying magnitude weighting, but it remains desirable to normalise the fatigue demand for both structural and geotechnical design. Geotechnical engineers apply assessment method-specific magnitude weighting factors in liquefaction triggering and seismic slope displacement calculations, thus precluding including magnitude weighting as a modifier to GMMs within PSHA calculations. As there is also a high desirability in unifying the seismic design parameters across engineering disciplines, we consider that any duration modification in future code updates should be undertaken in post PSHA processing, using the seismic hazard disaggregation data as input to region-specific duration weighting factors. It should also be undertaken prior to any structural performance modification factors (or ‘risk-based’ considerations as discussed by Niño et al. (2004) or Horspool et al. (2021)). This approach could take advantage of advances in duration weighting that better consider multi-directional shaking and soil non-linear response (Green et al. 2018), or alternatively a correlation to cumulative damage measures such as CAV_{STD} as developed for the nuclear industry may be considered (Campbell & Bozorgnia 2023).

4.2 Basin Edge Effects

For SSHA undertaken in the Thorndon basin of the Wellington CBD, consideration of basin edge effects (BEE) is required following strong motion recordings made in the 2016 Kaikoura earthquakes, and the preceding 2013 Lake Grassmere and Seddon events. These showed that significant site amplification at long periods of vibration were attributed to the super-position of incoming seismic waves from below the site and refracted from the basin edge that were a function of the 3D geometry of the underlying soil-rock interface and were not simply due to 1D soil amplification effects as conventionally accounted for using Site Class factors in the loading standard. It is not yet confirmed what approach will be adopted by the new loadings standard that is currently in development, however a recent EQC research report by Bradley et al. (2021) considered two empirical approaches to assess the observed amplification factor specifically for the Thorndon basin:

- **Method 1:** Response spectra recorded in the basin were normalised by rock motions recorded at a nearby station from the same events. The observed spectral ratios showed amplifications exceeded the expected amplifications due to Site Class D conditions over the period range 1 – 3s. An empirical GMM was used to normalise for Class D conditions to obtain the amplification considered solely due to BEE.

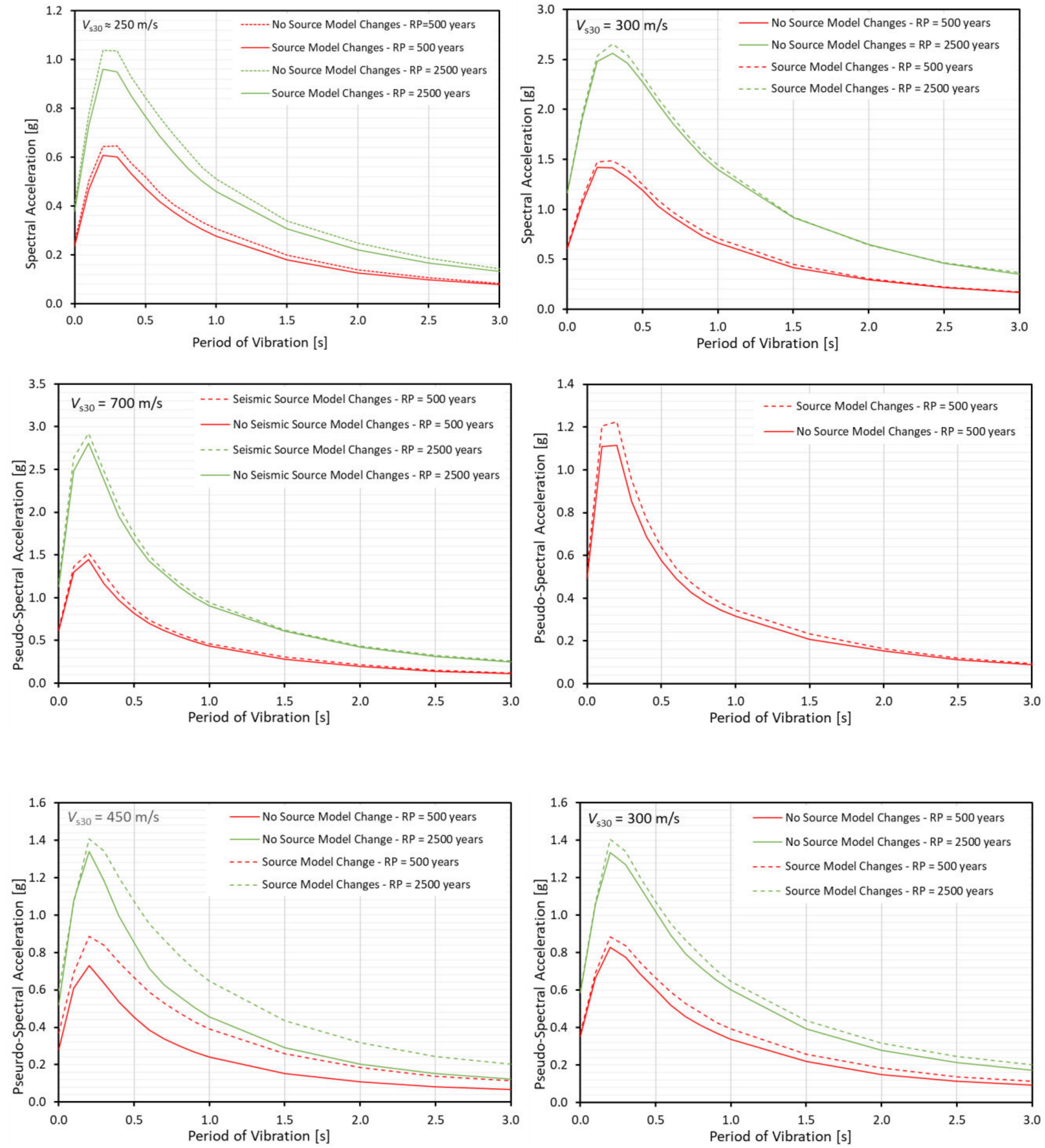

Figure 4: Uniform hazard spectra as a result of changes made by Beca / BRC to seismic source properties in Tauranga (top left), Napier (top right), Porirua (mid left), Wellington (mid right), Nelson (bottom left), and Queenstown (bottom right). The same GMM logic tree was used for all calculations.

- **Method 2:** A statistical procedure was used to consider the difference between ground motion estimates using empirical GMMs and the measured earthquake recordings, separately considering the overall model bias, the between-event, and between-site residuals. This approach is similar to how empirical GMMs are developed, albeit with a very small / limited dataset. The two methods result in broadly similar BEE amplification factors over the period range of interest (0.5 – 3s). Bradley et al (2021) proposed a function enveloping the Method 2 analysis results.

In implementing this model for a specific site located between the fault scarp and the basin centre, we interpreted Bradley's function to represent the BEE at the centre of the basin where the stations used to develop the relationship are located, and it would be expected to taper towards no amplification at the basin edge as marked by the Wellington fault scarp. A linear tapering between the fault scarp and the centre of the basin was adopted to scale the amplification factor to an appropriate level for the site.

4.3 Near-Fault Effects

Sites in close proximity to faults may be subject to 'near-fault' forward directivity effects including strong velocity pulses and permanent ground deformations. Most existing empirical GMMs including the recent NGA2West suite do not explicitly model velocity pulses in near fault events, and although the effects are likely incorporated within the range of scatter in the curve fit and therefore the standard deviation of the models, any directivity effects are expected to be largely diluted in calculated response spectra, even at the low probabilities of shaking hazard adopted for ULS. Unless specific modifications are incorporated into PSHA calculations, the results will not incorporate either the probability of pulse being observed in an event (which is not definite for a particular fault rupture) but also its characteristics: the pulse period and amplitude. However, a design spectrum for a structure within close proximity to 'major' active faults (particularly strike-slip and reverse-oblique faults) should account for the potential effects, which can be significant particularly for taller structures and base-isolated structures that respond to by long period ground oscillations. For selected 'major' active fault sources with high slip rates NZS1170.5 accounts for these through factoring up the long period response spectra. The adjustment is based on a broad band effect at long period proposed by Somerville et al. (1997). There are some recognised deficiencies in this approach (Donohue et al. 2019), notably magnitude dependence of the directivity pulse, and newer models offer improvements - for example Shahi & Baker (2011) and Bayless & Somerville (2013). These models were developed for implementation within PSHA calculations but could inform a post-PSHA adjustment factor for a future loadings standard update.

The authors have considered near-fault effects for SSHAs at sites in Porirua and Wellington using a range of models. Adjustments post-PSHA to the uniform hazard spectra for ULS and higher limit states have also been considered for faults that are considered 'major' using both the Bayless & Somerville model and the existing recommendations in NZS1170.5:2004.

4.4 Topographic Amplification

Physical models and historical records show that the topography can affect the shaking at a site, notably amplification at crests of steep slopes due to constructive interference of incoming shear waves, and de-amplification at the base of slopes. An NZTA research report by Brabhaharan et al. (2017) provides a literature review and develops summary recommendations for estimating topographic amplification factors for seismic design of high cut slopes, with an emphasis on Peak Ground Acceleration (PGA).

For a recent infrastructure project in Porirua located near the crest of a hill, consideration of the impact on the response spectrum was required. The method of Bouckovalas & Papadimitriou (2004), based on parametric numerical modelling, was adopted to estimate topographic amplification for horizontal and parasitic vertical accelerations at the site location. The method considers the influences of geometry (slope angle, height of slope, distance from the slope crest) and stiffness of the slope materials (shear wave velocity of soil or rock) on the topographic amplification factor. The factor varies as a function of the frequency of incoming waves. In our implementation of the equations, a cut-off frequency of 25 Hz was adopted for assessing the amplification factor at PGA, refer Figure 5. Application of the model to the site yielded an increase in the expected horizontal structural shaking between 1.0 and 1.3, with short periods experiencing the largest amplification, which were of significance to both the structural and geotechnical design.

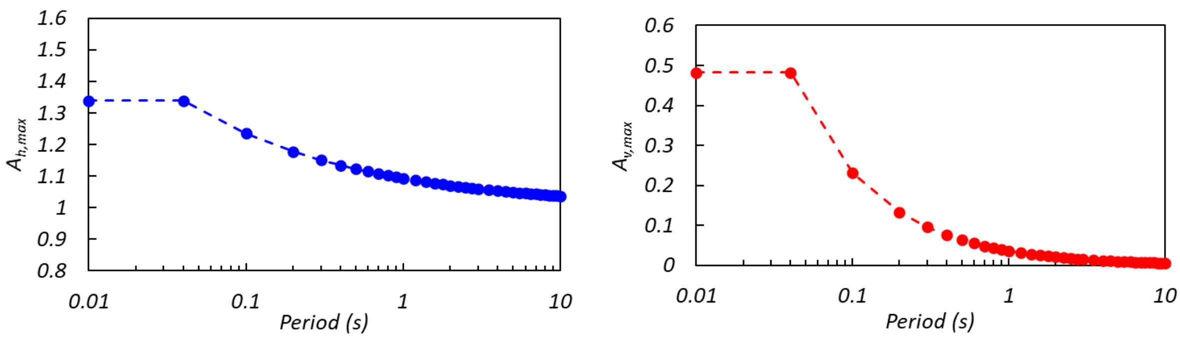

Figure 5: Topographic Amplification factors for horizontal ($A_{h,max}$) and parasitic vertical ($A_{v,max}$) acceleration using the method of Boukovalas & Papadimitriou (2004).

4.5 Soft Soil Response

For sites where low stiffness soil profiles are subjected to very high amplitude motions, for example as derived from a PSHA calculation for a low-probability shaking hazard in a high seismicity region, there can be an apparent incompatibility between the PSHA results and physical limits on the ability of the soft soils to transfer high amplitude motions in shear. For such cases, it is best to undertake a ground response analysis that considers the non-linear stress-strain response of the soils within the soil profile and their influence on the passage of the ground motion from rock at depth to the ground surface. Higher amplitude input motions will tend to result in more shearing in soft soils, and increased soil damping, particularly at high frequencies but across the spectrum, and period shift of the soil profile to longer period site amplification. This trend is not considered in a PSHA calculation that solely utilises ground motion models. A recent study for a deep, low stiffness soil profile in Port Vila, Vanuatu showed a considerable benefit in reducing the design ground surface response spectra following a ground response analysis.

5 DESIGN RECOMMENDATIONS

5.1 Basis for Design

As a result of the significant changes in seismic hazard observed in some regions of New Zealand in recent SSHA and in the publication of the 2022 NSHM results, determining the appropriate design spectra to inform the basis of design of engineering projects is highly topical at present. In current design standards and in ongoing practice, the results of PSHA are used to ‘inform’ design spectra. This means that PSHA is one important factor which is considered when choosing appropriate levels of design for structures, but that other factors must also be considered.

For high seismicity sites where the hazard is dominated by a few significant nearby active faults, the design level of shaking may not be well categorised by PSHA alone, particularly for high importance or high value structures typically designed to very low probabilities of shaking hazard. In such cases PSHA has been shown to produce values of shaking far exceeding that which any of the major contributing faults could be reasonably said to produce for these sites (i.e., extremely unlikely levels). In such cases we have found a review of the single-event intensity from a deterministic seismic hazard analysis (DSHA) that considers scenario events from the dominant contributing faults to be informative, and may drive discussions with the client, design leads and peer reviewers on major projects as to the appropriate basis of design in order to meet both the clients objectives in terms of seismic performance but also pragmatic considerations of cost and our ability to engineer solutions for extreme design ground motions.

5.2 Generation of Design Spectra

Design spectra allow a number of aspects to be incorporated or considered when there might not be an agreed method for doing so, recognising always that precision in the field of seismology is not warranted. This includes well-accepted procedures including stylisation of spectral branches, truncation of the spectrum at short periods, and adjustments to hazard spectra to account for large-displacements of long-period structures, the impact of duration, and the frequency content of ground motions.

'Truncation' of response spectra to provide a constant acceleration below the peak of the PSHA-derived hazard spectra at low periods of vibration (i.e., the plateau of NZS 1170.5 spectra) is justifiable for structural design because structures are expected to have some level of ductility, which in turn will lead to an elongation of the structural period beyond the truncated range at ULS.

6 CONCLUSIONS

Site-specific Seismic Hazard Analyses are conducted in New Zealand engineering practice to better inform the characterisation of seismic hazard at the site of interest to inform engineering design of a significant or high value building or infrastructure project, and replace the simplified seismic hazard provisions in the New Zealand loadings standard NZS1170.5:2004. The intention is that they present the current state of knowledge of the hazard at time of the study, and incorporate 'site-specific' considerations that include the unique site-response considerations (e.g., soil profile and basin amplification, topographic effects), and near fault effects where appropriate.

This paper reviews some of the considerations made by the authors through the course of undertaking SSHAs over the last decade but in particular the last few years, for the formulation of spectra for the design of structures. Many of these issues will need to be considered by the code committee, informed by the results provided by the NSHM 2022.

The authors have found that an open dialogue between the seismic engineers undertaking the SSHA and the structural & geotechnical design team is particularly important during the course of completing an SSHA, the interrogation of the results, and the development of design recommendations that inform the basis of design for the structure. This has allowed for a more co-ordinated design philosophy to be developed – both in terms of meeting code requirements and a clients performance needs for the asset, but also pragmatic considerations to manage cost, programme, and constructability. Design spectra informed in this manner permit a reasonable level of design for the structures, and provides the design team and client with a high level of confidence in the design process.

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