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CONSIDERATION OF NEAR-FAULT EFFECTS IN NEW ZEALAND SEISMIC HAZARD ANALYSIS AND DESIGN SPECTRA

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ABSTRACT

This paper examines the manner in which near-fault ground-motion phenomena are considered in the probabilistic seismic hazard analysis underpinning the 2022 New Zealand National Seismic Hazard Model (NZ NSHM), and its subsequent codification in the draft Technical Specification TS1170.5:2004. Directivity is already implicitly considered in the 2022 NSHM, and thus the 'baseline' draft TS1170.5 spectra, before any additional near-fault factor is applied. Specific studies in NZ and California suggest that explicit modelling of directivity could result in increases of up to 15-20% for 2475-year return period $SA(T = 3.0s)$ values for 'directivity-prone locations', but are more likely to be on the order of 10% when a weighted average of multiple directivity models is considered. In contrast, the NZS1170.5:2004 near-fault factor, $N(T,D)$, results in a 36% increase for small source-to-site distances. Hence, either: (1) the NZS1170.5:2004 near-fault factor should be removed so that directivity is implicitly considered in the hazard, which is consistent with other international codes, and also consistent with the implicit treatment of deep sedimentary basin effects in the 2022 NSHM, or (2) a parametric revision of the near-fault factor is needed that results in approximately a four-fold reduction in its size. Obtaining a more precise quantification of directivity effects is complicated by multi-segment ruptures in contemporary seismic source models, and the large uncertainty in predicted directivity modification factors from the alternative existing models.

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INTRODUCTION

Ground motions in the immediate vicinity of major earthquake ruptures have been consistently observed to vary appreciably from ground motions that are distant from causative ruptures [*e.g.* 1]. Such features occur principally as a result of the evolution of slip propagation over the rupture surface and its interaction with seismic wave propagation toward the site (*i.e.*, the Doppler effect). Of particular interest, from an engineering perspective, are the conditions of so-called 'forward directivity' where the rupture propagation direction and direction of the slip vector are aligned with the direction toward the site under consideration [2]. In addition to large acceleration amplitudes, such near-fault forward-directivity ground motions can exhibit a large proportion of the seismic energy arriving in a compressed duration, resulting in significant velocity amplitudes, and a high degree of polarity in their characteristics as a function azimuth [3,4], which have been observed to be demanding to engineered systems [*e.g.* 5,6].

Recognition of the importance of forward-directivity phenomena prompted its inclusion, as a post-hoc modification factor, in the 2004 seismic loadings standard [7]. This modification was based on the first model for (forward) directivity effects of Somerville *et al.* [2], as documented in McVerry [8], and provides a factor that varies with vibration period, and source-to-site distance, relative to 11 major faults in New Zealand (NZ).

More recently, a major revision of the NZ National Seismic Hazard Model (NSHM) was completed in 2022 [9], and a draft Technical Specification for NZS1170.5 (TS1170.5:2024; [10]) proposes how the 2022 NSHM results are codified for use in seismic design in NZ. The draft TS1170.5 proposes the treatment of near-fault effects through the same near-fault factor that was adopted in NZS1170.5:2004, principally because the time constraints in developing TS1170.5:2024 following the completion of the 2022 NSHM meant that consideration to change the near-fault factor was not within scope (Ken Elwood, pers. comm.). Because the near-fault factor was developed for NZS1170.5:2004 in a post-hoc manner, it is important to scrutinise: (1) how near-fault directivity is explicitly considered within modern probabilistic seismic hazard analysis (PSHA) [11], and what such studies imply regarding the need for near-fault adjustments (if any); (2) differences between how ground-motion models in the 2022 NSHM consider (if at all) near-fault directivity as compared to how it was considered in the 2002 NSHM that underpinned NZS1170.5:2004 [12]; and (3) how design spectra are parametrically adjusted for near-fault effects in other international codes as precedent.

This paper aims to explicitly answer the questions: (1) Is the NZS1170.5:2004 near-fault factor appropriate for use in combination with the 2022 NSHM results embodied in the 'baseline' spectra in the draft TS1170.5:2024? (2) If not, how may it be considered in a modified form, or should it be considered at all? In order to address these questions the paper begins by reviewing how directivity effects are considered in PSHA, both in the specific context of the 2022 NSHM, but also more broadly in proof-of-concept studies that have attempted to model this phenomena in greater detail than is conventional. Discussion is then given to how directivity is considered in seismic design spectra, both internationally, and specifically the details of its treatment in NZ. Through a critique of how the NZS1170.5:2004 near-fault factor was developed compared with these pioneering proof-of-concept studies, recommendations are made for how near-fault factors could be considered, if at all, in seismic design

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- both via response spectral analysis and also ground-motion time series selection for nonlinear response history analysis.

MODELLING DIRECTIVITY IN SEISMIC HAZARD ANALYSIS

Explicit Treatment in PSHA

A robust treatment of near-fault directivity phenomena in the determination of seismic loads should occur explicitly within PSHA in order to properly account for: (1) all ruptures that contribute to the hazard at the site with differing degrees of directivity effects; (2) the appropriate adjustment to the mean and standard deviation of the ground-motion models as a function of the predictor variables that are considered in directivity models; and (3) appropriate randomisation over hypocentre locations, which has a primary effect on directivity for a given rupture and site geometry.

As outlined in Weatherill and Lilienkamp [13], despite the physical mechanisms and observations of directivity being clear, the explicit consideration of directivity in PSHA has been limited. This is principally because of the difficulty in the determination of the key modelling components of the problem, specifically: (1) probability of a ground-motion containing a directivity 'pulse'; (2) adjustments to the ground-motion prediction if there is a pulse; and (3) the computational challenges of considering additional predictor variables in PSHA codes and calculations and the additional summation over random hypocentre locations [13,14].

In addition to the above technical complexities in directivity modelling, there are also recent challenges posed by marrying such models with seismic source models for PSHA. Specifically, seismic source models are becoming increasingly complex, in particular, the consideration of multi-segment ruptures [15,16]. The complex geometry of multi-segment ruptures, and variations of strike, dip, and average rake angle, already pose a challenge for ground-motion prediction even without the consideration of directivity. For example, conventional active shallow crustal ground-motion models have been developed with databases where multi-segment ruptures were summarised through a single-segment 'best-fit' rupture plane [17]), and the same is true for the majority of existing directivity modification models [14]. Similarly, hypercentre probability distribution models have been developed in a single segment context [18,19], and it is not presently clear how they should be applied to multi-segment ruptures (*e.g.*, should 'splay' faults have the same probability density of hosting the hypocentre) [20].

Despite the aforementioned challenges, recently efforts have been made to explicitly consider directivity in PSHA through two proof-of-concept studies in California [20] and NZ [13]. In considering directivity effects in California, Al Atik *et al.* [20] developed new approaches to apply splines to multi-segment ruptures in order to develop notionally similar rupture geometries that were amenable to the use of existing directivity modification models. They then considered three different directivity models, with associated logic tree weights, to develop PSHA results with and without explicit treatment of directivity, and hence determine a multiplicative ratio resulting from its explicit inclusion. When performing PSHA with explicit directivity modelling in NZ, Weatherill and Lilienkamp [13] considered only the Bayless *et al.* [21] directivity modification model (also one of the models considered by Al Atik *et al.* [20]), but developed a machine-learning-based strategy to handle the geometric complexities from multi-segment ruptures and also address computational challenges that hinder directivity computation.

Figure 1 provides an illustrative example of the results of Al Atik *et al.* [20] for a site in San Bernadino, which is a high hazard site dominated by the proximal rupture of the Southern San Andreas fault. The disaggregation of three-second pseudo-acceleration response spectra, $SA(T = 3.0s)$, for the 2475-year return period illustrates that the hazard is dominated by $M > 7.5$ events at $R_{rup} < 10$ km. The directivity amplification factors are indicated by the y-axis value ('PSA ratio') in the bottom plot as a function of vibration period, for three different models that were considered. The Bayless and Somerville [22] model (BS13) represents an update of the original Somerville *et al.* [2] model. The Chiou and Spudich [23] model (CS13) is based on the directivity point parameter, and is included in the Chiou and Youngs [24] NGA-West2 model. The Bayless *et al.* [21] model (BSS20) represents a next-generation refinement of the BS13 model, with a focus on the inclusion of ground-motion simulation data to 'fill' the dataset gaps that exist using only historical ground-motion records, and also to accomodate complex and multi-segment ruptures. From Figure 1 it is evident that there is a significant difference in the directivity adjustment from the three alternative models considered for $T > 1$ s. The most notable features are: (1) a nearly constant 25% increase using the BS13 model; (2) a steep increase in the BSS20 prediction with increasing T, with a value of ≈20% for $T = 3$ s, and ≈40% for $T = 5$ s; and (3) only a 1-3% increase using the CS13 model. Based on a weighting of 0.25, 0.25, and 0.5 for the BS13, BSS20, and CS13 models (discussed subsequently), the weighted average suggests an approximately 13% increase for $T = 3$ s, but the three model predictions range from 2-24%, clearly illustrating significant epistemic uncertainty.

Weatherill and Lilienkamp [13] examined the effect of explicitly modelling directivity phenomena in seismic hazard for NZ using both the 2010 NSHM [25] and 2022 NSHM. In fact, the interim work documented in Weatherill [26] (a precursor to Weatherill and Lilienkamp [13]) was a strong factor in the decision to not explicitly consider directivity in the 2022 NSHM [27]. Their study was also a proof-of-concept in that they only considered a single ground-motion model (*i.e.*, Stafford [28]) and only the BSS20 directivity modification model. Figure 2 illustrates the percentage change in hazard resulting from the explicit modelling of directivity for $SA(T = 3.0s)$ for the 2475-year return period. As elaborated on in their paper, and also summarised in Bradley *et al.* [27], the explicit consideration of directivity results in hazard changes of less than 10% for $SA(T = 3.0s)$ values in most locations in NZ. For other vibration periods, the differences were generally smaller. Conversely, these differences were appreciably less than the differences of up to 25% obtained using the 2010 NZ NSHM source model because of its treatment of faults as 'characteristic' [13].

When considering the results from Weatherill and Lilienkamp [13] depicted in Figure 2 it is important to reflect on the use of the BSS20 model, and that Al Atik *et al.* illustrated this model as predicting appreciably larger results than the CS13 model. In the case of Figure 1, the weighted average adjustment was approximately half of that from the BSS20 model. As discussed in the Supplementary Material of Weatherill and Lilienkamp [13], the Bayless model is not constrained to be 'centred' for forward prediction applications, and they found that this resulted in a $0-0.2$ natural log bias in the mean adjustment which is scenario specific. This over-prediction bias should also be bore in mind in the above quantitative results. Thus, one could consider that had Weatherill and Lilienkamp also considered multiple models in the same manner as Al Atik *et al.*then their results would be something

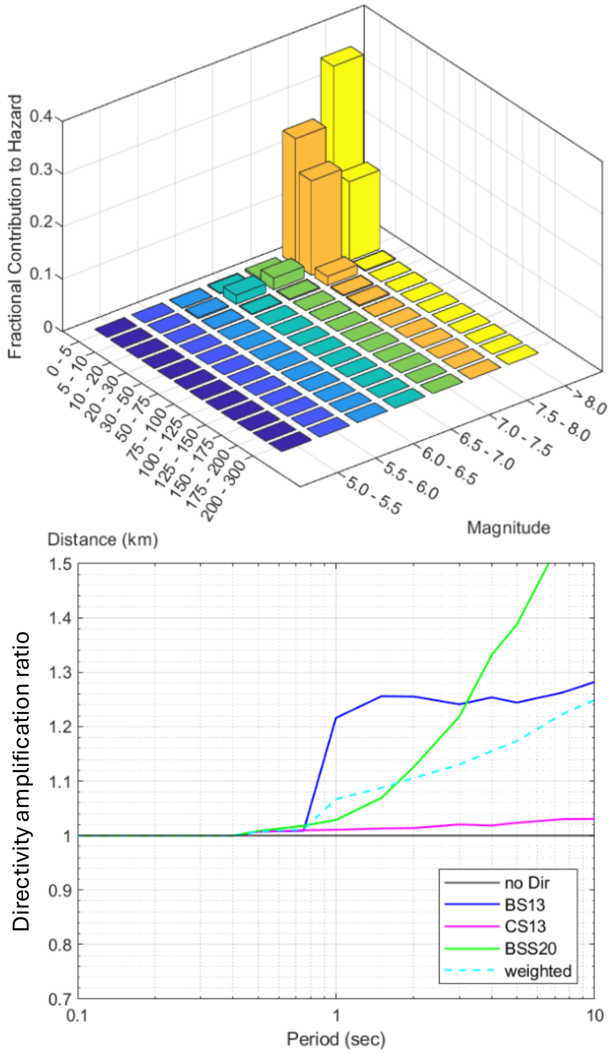

Figure 1: Example directivity modification result from Al Atik **et al.** *[20] for a* $V_{S,30} = 760$ *m/s rock site in San Bernadino that is dominated by a large near-source strike-slip rupture on the San Andreas Fault: (Top) Disaggregation of* $SA(T = 3.0s)$ *for the 2475-year return period illustrating* $M > 7.5$ *at* $R_{rup} < 10$ *km events dominating the hazard; (Bottom) Directivity modification factor with vibration period for the 2475-year return period for three different models as well as the weighted average.*

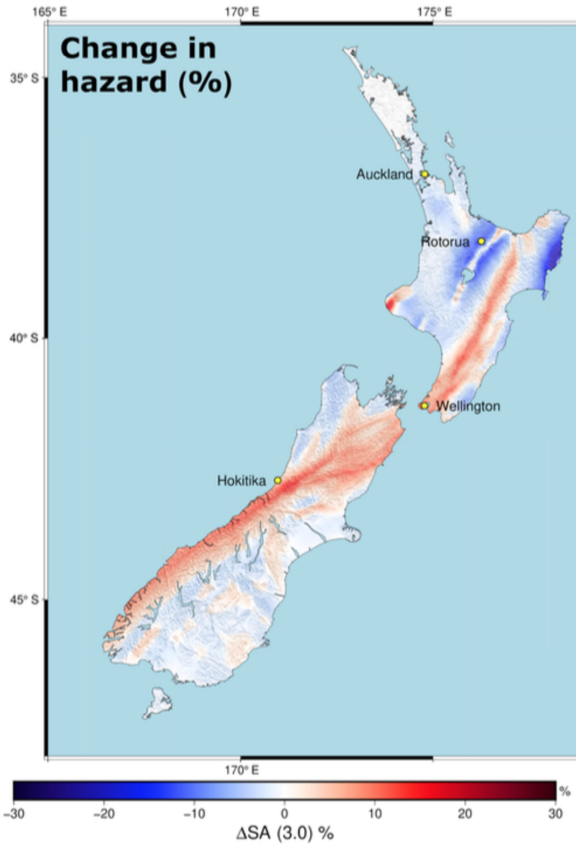

Figure 2: Directivity amplification determined by Weatherill and Lilienkamp [13] for the 2022 NSHM using the Stafford (2022) ground-motion model and the Bayless **et al.***(2020) model (BSS20) for* $SA(T = 3.0s)$.

on the order of 50% smaller for the high-directivity regions[1].

Directivity Consideration in the 2022 NSHM

The 2022 NSHM did not explicitly model near-fault directivity phenomena[2] However, that does not mean that directivity is entirely neglected in the 2022 NSHM. As noted by Weatherill and Lilienkamp [13, see Supplemental Notes], directivity was implicitly considered in that the mean and standard deviation of all adopted ground-motion models were developed from regression analysis with observational data that included near-fault ground motions with directivity phenomena contained in them.

[1]Noting that the divergence among the alternative models is less pronounced for sites that have lower directivity modification factors [20].

[2]The Chiou and Youngs [24] model was included in the 2022 NSHM, and explicitly considers directivity through the directivity point parameter, but the directivity functionality of this model was not used in the 2022 NSHM implementation.

Thus, observed near-fault ground motions that are considered in ground-motion model development will exhibit variability in their long period SA values partly as a result of varying degrees of directivity, and thus will largely be reflected in the standard deviation of the ground-motion model at small source-to-site distances.

Implicit consideration of directivity does, however, have some obvious disadvantages. Weatherill and Lilienkamp [13] refer to sentiments originally expressed by Abrahamson [29] that the standard deviation model of a ground-motion model is constrained by a large number of observations at different source-to-site distances and azimuths, and therefore may not be representative of that which should be used for directivity settings. While such sentiment is still true, it should be kept in context with the era in which it was made. At that time, conventional models [*e.g.* 30] considered standard deviation solely as a function of magnitude (hence the comment of Abrahamson [29] about averaging over a range of distances). Nowadays several models [*e.g.*, 31] consider standard deviation as a function of magnitude, source-to-site distance, 30-m time-averaged S-wave velocity ($V_{S,30}$) and nonlinear site response, although many models still adopt simple dependence solely on magnitude [32]. Thus the large amount of ground-motion data for larger source-to-site distances, and smaller magnitudes need not affect the resulting model standard deviation prediction for larger magnitudes and small source-to-site distances for which directivity is an issue. Thus, the present day downsides of the implicit consideration of directivity should be weighed up against the current status of explicitly modelling, and its downside, which is the large relative model-to-model variation we see in the implied directivity adjustment (*i.e.*, Figure 1).

The implicit treatment of directivity in the 2022 NSHM is consistent with the 'baseline' cases that Al Atik *et al.* [20] and Weatherill and Lilienkamp [13] considered. Thus, the quantitative values of directivity modification that they computed, as discussed previously, are directly relevant in the subsequent consideration of how directivity is considered in codified design spectra, which is discussed in the next section.

TREATMENT OF DIRECTIVITY IN DESIGN SPECTRA

International Codes and Standards Perspective

Before examining the treatment of directivity in NZ seismic design spectra, it is useful to briefly survey how near-fault directivity is treated in international codes and standards, which is summarised for a non-exhaustive list below:

1. ASCE 7-22 (USA, [33]): Near-fault sites are designated as locations that are within 15km of a potential $M \geq 7$ rupture, or within 10km of a $6 \leq M \geq 7$ rupture. Eq. 12.8-7 of ASCE 7-22 provides a minimum base shear requirement for high seismic hazard sites, which is anchored to the spectral acceleration on rock-like site conditions for $SA(T = 1.0s)$ (in contrast to a source-to-site distance to specific named faults). This requirement has existed in its current form as early as ASCE 7-05 [34] and the 2003 NEHRP provisions [35] (albeit with a different coefficient value). The motivation for this minimum base shear requirement (John Hooper, pers. comm.) was to recognise that the simple "$1/T$" scaling of response spectra does not reflect the shape of ground motions that exhibit significant near-fault or pulse-like effects. Because the base shear minimum is anchored to rock-like conditions, then the vibration period at which this minimum governs varies appreciably with site conditions (on the order of $T = 2s$ for stiff soil/rock, and up to $T > 5s$ for soft soil conditions). Notably, this minimum also exists in ASCE 7-22, which now contains a multi-period response spectrum, so the original motivation of the limitation of the "$1/T$" scaling of the response spectral shape is no longer relevant. Related to more advanced analysis - ASCE 7-22 also requires site-specific seismic hazard studies should account for near-fault directivity. Near-fault directivity should be explicitly considered when ground-motion time series are selected for nonlinear response history analyses. Specifically, the proportion of near-fault records should be consistent with the seismic hazard disaggregation, ground motions should be oriented into fault normal (FN) and fault parallel (FP) directions when applied to the structural model, and spectral matching modifications are not permitted for near-fault motions.

2. UBC97 (USA, [36]): Although no longer a contemporary standard, UBC97 introduced near-fault considerations through the parameters N_a and N_v which scale different portions of the design response spectra. The factors varied with source-to-site distance, soil type, and seismic source characteristics. UBC97 is notable in that it led to other codes that were updated soon after 1997 either directly following this approach (e.g., in Taiwan), or adopting a similar approach (e.g., in NZ).

3. Eurocode 8 (EU countries, [37]): There are no specific definitions of near-fault sites, and no near-fault factor modifications to the design spectra. Implicitly, near-fault sites are considered as sites within 15 km of a $M >= 6.5$ fault, and high-importance (class IV) structures require a site-specific spectra that includes near source effects (Clause 10.6(3)).

4. NCh433 Of.96 Mod.2009 (Chile, [38]): This design standard for regular buildings and industrial facilities does not have any explicit factors for near-fault directivity. An alternative standard, NCh2745 Of.2013 [39], specifically for the design of base-isolated buildings, requires that structures located within 10 km of an active fault have a site-specific hazard study.

5. IS 1893 (Part 1) 2016 (India, [40]): There are no specific near-fault factors for design spectra. For structures in high seismic zones (Zone V), and near active faults, site-specific studies are recommended (though not required).

6. CPA 2011 (Taiwan, [41]): Near-fault factors are included through coefficients N_a and N_v, as per the UBC97 approach.

A synthesis of the above codes and standards is that near-fault directivity phenomena are generally not explicitly considered in the codification of the design spectra. The only exceptions are the current Taiwan design code, which mirrors the UBC97 approach (which did not determine design spectra from the uniform hazard spectra from PSHA; and is not followed in contemporary US practice through the ASCE 7-series of standards). Although it is not stated anywhere, this 1997 UBC precedent may have been the catalyst for the original 1170.5:2004 near-fault factor discussed in the next section. Secondly, the approaches in different codes are somewhat consistent in pointing to the use (required or recommended) of site-specific hazard studies for near-fault sites, but they are generally not prescriptive in how such site-specific studies should treat near-fault effects (and hence the problems alluded to in the state-of-the-art studies discussed in the previous section).

In contrast to the lack of explicit consideration for near-fault directivity in design spectra, those codes and standards that directly discuss ground-motion time series selection do typically have explicit guidance on the consideration of near-fault phenomena in the selection of ground motions for use in response history analysis. This includes the proportion of ground motions that reflect near-fault conditions, polarity of ground-motion intensity in the horizontal plane (directionality), and how the ground motions are oriented along the orthogonal axes of the building relative to the strike direction of nearby faults.

NZS1170.5:2004 Near-Fault Factor, $N(T,D)$

The near-fault factor, $N(T,D)$, in NZS1170.5:2004 is a parametric adjustment to the 'baseline' spectra, which is based on the 'Larger' component definition [42]. The near-fault factor has the following key features: (1) varies with vibration period, with non-unity adjustments for $T > 1.5$ s; (2) varies linearly with source-to-site distance, D, to a 'major' fault, with the maximum adjustment for $D < 2$ km, and no adjustment for $D > 20$ km; and (3) 11 major faults are identified within NZ for which this nearest source-to-site distance, D, is determined. Figure 3 provides an illustration of the 11 faults for which are considered, the tapering of the effect with distance from these faults, and also the variation as a function of vibration period.

McVerry [8] discusses the basic approach that was used to determine the near-fault factor, $N(T,D)$, which includes:

1. Consideration of forward-directivity on the average horizontal ground motion, as well as azimuthal polarisation of long-period motions

2. Because $N(T,D)$ is applied as a posterior modification to the baseline spectra, it is unknown the degree to which directivity-inducing faults dominate the hazard. Given this, 'major' faults, with expected magnitude $M > 7$ and slip rate > 5 mm/yr, are assumed to be the dominant contributor to the hazard.

3. Events on these major faults were considered to have $M \approx 7.5$; that maximum forward directivity occurs in one-third of cases (with neutral directivity in the other two-thirds); the fraction of the fault that ruptures toward the site is $X = 0.75$, and the angle between the fault strike and the site is close to $\theta = 0$ - hence, $X cos\theta = 0.75$.

4. The Somerville *et al.* model [2] was used with these assumptions to guide the development of the $N(T,D)$ parametrisation.

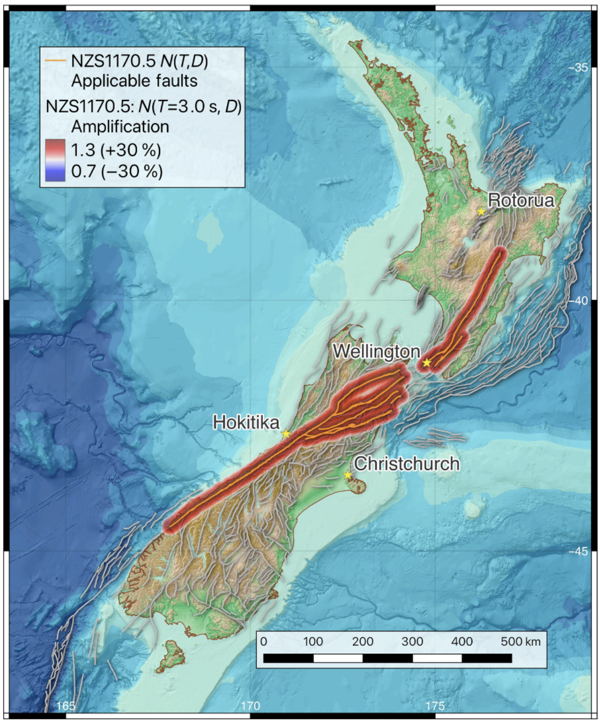

Figure 3: The NZS1170.5:2004 $N(T,D)$ factor for $SA(T=3s)$, illustrating the 11 'major' faults that it applies to, and the source-to-site distance dependence from these faults (after [13]).

The documentation in McVerry [8] is relatively brief, but it is clearly indicated that the Somerville *et al.* relationships are used to consider both: (1) the increase in average horizontal spectra resulting from directivity (*i.e.*, Table 4 and Figure 9a from [2]); and (2) the effect of polarisation between the fault-normal and average (*i.e.*, FN/Average) horizontal components (*i.e.*, Tables 6-7 and Figures 13-15 from [2]). The respective predictions of these models are shown in Figure 4. The maximum directivity adjustment using $X cos\theta = 0.75$ from Somerville *et al.*, and the adjustment assuming one-in-three forward directivity (and two-in-three neutral directivity) are shown in red lines - both of which are independent of any other parameters, such as source-to-site distance. The horizontal directionality/polarisation, quantified in the FN-to-average horizontal ratio, from Somerville *et al.* is then depicted in dashed blue for source-to-site distances of 2, 5, 10, and 20 km. The product of the directivity and polarization factors is depicted in the solid black lines for the same four source-to-site distances. This product is intended to re-create

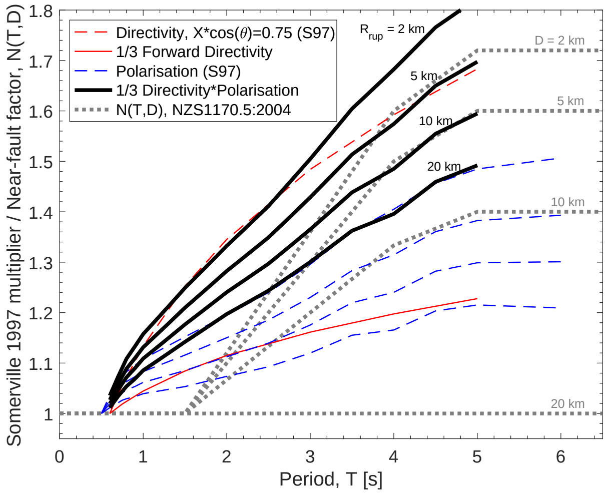

Figure 4: Comparison of the period- and distance-dependence of the $N(T,D)$ factor relative to predictive models from Somerville* et al. *[2].

that shown in Figure 3 of McVerry [8] based on the description in that text, and although it does not produce the exact same result, it is similar. Comparing the product of the directivity and polarization factors from Somerville *et al.* illustrates that they do exhibit a broadly consistent trend with the NZS1170.5:2004 $N(T,D)$ factors, which are shown in dashed grey lines for the equivalent distances (denoted as D in NZS1170.5:2004). That is, the increase with increasing vibration period, and also with reducing source-to-site distance. However, beyond these generalities, there are clearly appreciable differences in the actual quantitative values that they suggest.

Issues with $N(T,D)$

The prior discussions highlight an appreciable difference in the size of directivity adjustments to 'baseline' response spectra between state-of-the-art explicit directivity modelling studies [13,20] and the parametrisation of NZS1170.5:2004, and hence further scrutiny of the latter (given it was proposed over 20 years ago).

There are several important issues that arise from the logic adopted in the development of the $N(T,D)$ factor, namely: (1) that the directivity-inducing faults contribute the 'majority' (*i.e.*, assumed to be 100%) of the seismic hazard at the site; (2) how a model of polarisation was used in addition to the increase in the average horizontal ground motion; and (3) the assumption of one-in-three forward-directivity and two-in-three neutral directivity ground-motions.

Contributions from Non-directivity Ruptures to the Hazard

The most important (*i.e.*, limiting) assumption is that the development of $N(T,D)$ assumed that 100% of the hazard was caused by the 'major' near-source fault. Results from modern PSHA illustrates many instances where this is not the case. In NZ, this is a particularly common situation because of the significant hazard posed by subduction zone ruptures. For example, in Wellington, for $SA(T=3.0s)$ at the 2475-year return period, active shallow crustal sources, such as the Wellington fault and Wairarapa fault, comprise only 50% of the total hazard, with the majority of the remainder coming from major earthquakes on the subduction interface. This occurs because of the large fraction of total compressional deformation at these latitudes occurring on the subduction interface and thus much higher slip rates than the upper plate crustal faults. In contrast, in the central South Island, sites located in the immediate proximity to the Alpine Fault and the southern extent of the Marlborough fault zone (which is still relatively distant to the Hikurangi subduction interface), the hazard is almost 100% caused by near-source crustal faults. Weatherill and Lilienkamp discuss this point is great detail, and it is a principal reason for the over-estimation of $N(T,D)$ relative to the direct results from explicitly considering directivity in PSHA, as shown in Figures 1 and 2.

Polarization

NZS1170.5:2004 defines ground-motion SA amplitudes based on the 'Larger' component [42]. This is a historical definition, representing the larger of the two SA values from the as-recorded components of the ground motion. It is limited by the fact that it is sensitive to the orientation of the two axes of the instrument in the horizontal plane, which is undesirable, given that this orientation is typically arbitary. As a result, this Larger component definition is statistically larger (the difference is approximately 15-20% at the long periods, $T > 1s$, of concern in discussions of forward directivity [43,44]) than the median horizontal shaking over all possible azimuths (the so-called RotD50 value [45]), but smaller (by about 8%) than the maximum value in any orientation (the so-called RotD100 value). For reference, the ratio between the RotD100 and RotD50 values ranges, on average, from 20-30% as a function of vibration period.

To develop $N(T,D)$, McVerry [8] utilized the FN/Average polarity factor of Somerville. However, the use of this factor is inconsistent with the NZS1170.5:2004 spectra already being the Larger component, as opposed to the average horizonal component. This results in the polarity factor component adopted being approximately 25% too large for the long vibration periods of interest.

Fraction of Forward-, Neutral-, and Backward-Directivity Ruptures

It is not clear what the technical basis was for the assumption noted in McVerry [8] that one-in-three events caused forward directivity, and the other two-in-three were neutral. Irrespective, consideration of the fraction of forward-, neutral- and backward-directivity ground-motions has advanced significantly over the past 20 years. A key consideration that has emerged is that as earthquake magnitude increases, a higher proportion of the observed ground motions will contain waveform features that are reflective of forward-directivity phenomena. This is because evidence has shown that the length of rupture toward the site needed to cause such effects can be a relative small fraction of the total fault length (since it is the absolute rupture length toward the site that matters, not the ratio of rupture length toward the site vs. the total rupture length [46]). As a result, the median prediction of a ground-motion model (that does not explicitly consider directivity) for a near-fault site will *not* correspond to a neutral-directivity condition, but something partway on the continuum toward forward directivity. This median model tendency is referred to as 'centring' [14] in the development of directivity adjustment models, and ensuring that models are centred is a critical feature to ensure an unbiased adjustment.

Current Considerations of Directivity in the Draft TS1170.5:2024

The draft TS1170.5 is based on the results from the 2022 NSHM that, as previously discussed, implicitly considered directivity in the utilised ground-motion models. The draft TS1170.5 proposes the treatment of near-fault effects through the same near-fault factor that was adopted in NZS1170.5:2004.

In addition to the issues identified in the prior subsections, it is important to note that the draft TS1170.5:2024 and NZS1170.5:2004 differ in that the former is based on the RotD50 definition of horizontal shaking, while the latter is based on the Larger component definition. Given that the RotD50 definition is approximately equal to the average horizontal (*i.e.*, geometric mean) component definition [45], then only the average horizontal directivity modification should be considered (*i.e.*, the red lines in Figure 4), and not the additional effect of the polarity adjustment (*i.e.*, the black lines in Figure 4). Further sentiments on why the polarity adjustment should not be considered are given in a subsequent section on practical recommendations.

Consider now when the polarity component of a directivity adjustment is not considered, and with the simplistic notion of one-in-three forward-directivity ground motions that was used to obtain the solid red line in Figure 4. Despite the Somerville *et al.* model being 27 years old, this simple model is actually in the numerical range suggested by the proof-of-concept studies performed by Al Atik *et al.* [20] and Weatherill and Lilienkamp [13] for sites whose seismic hazard is entirely dominated by a near-fault crustal source.

PRACTICAL RECOMMENDATIONS FOR CONSIDERING NEAR-FAULT EFFECTS IN SEISMIC DESIGN FOR NZ

Given the previous discussion, the following recommendations are made for the consideration of directivity in seismic design spectra and ground-motion time series selection:

RotD50 Response Spectra

The TS1170.5 committee should decide whether the relative small mean effect of directivity, and the appreciable uncertainty in the estimation of this mean effect (*e.g.*, Figure 1b), warrant it being explicitly considered; or whether it is sufficient to simply take the view that the 2022 NSHM already implicitly considers directivity (with the recognition that explicit modelling via parametrisation is better than implicit modelling in the residual standard deviation). The treatment of directivity implicitly is also consistent with contemporary international codes that do not adopt an equivalent near-fault factor.

The consideration of directivity in the 2022 NZ NSHM is loosely similar to the consideration of deep sedimentary basin response - empirical ground-motion models do provide $Z_{1.0}$ and $Z_{2.5}$ parameters (depths to 1.0 and 2.5 km/s S-wave velocities) to model these effects beyond those which are implicitly considered via $V_{S,30}$ alone, but the development of the 2022 NSHM ultimately decided that nationwide models for estimating $Z_{1.0}$ and $Z_{2.5}$ parameters were insufficiently robust for direct use by inexperienced users, and therefore adopted for this deep sedimentary basin effect to be implicitly considered based on $V_{S,30}$ only.

If, despite the above, directivity is desired for explicit inclusion, then adjustments need to be made to the current NZS1170.5:2004-based $N(T,D)$ factor to be compatible with the 'baseline' spectra in the draft TS1170.5:2024. Weatherill and Lilienkamp note that the general spatial distribution across NZ of the PSHA-based near-fault directivity adjustment is similar to that from NZS1170.5:2004 (*i.e.*, compare Figure 2 and Figure 3), only that the size of the 1170.5:2004-based factor is too large - hence, the use of the existing 11 major faults could be retained. Specifically, they note that their PSHA-based result for $SA(T = 3.0s)$ suggests a maximum increase of 15-20% as compared to the 36% increase from the 1170.5:2004-based factor.

Taking further account of the prior sentiments discussed with respect to the study of Al Atik *et al.* (*i.e.*, Figure 1 and associated text) that the Bayless *et al.* model is uncentred (0-0.2 log unit bias) and that it gives higher results than the CS13 model, such that the weighted average adjustment is often on the order of 50% of the Bayless *et al.* values, then the 15-20% statement in Weatherill and Lilienkamp would become 7.5-10%. This is approximately a factor of 4 reduction in the 1170.5:2004-based factor - and this would be the recommendation for a first-order ‘correction’ if the notion of an explicit near-fault factor adjustment was desired to be retained.

Potential Polarisation Adjustment

Near-fault ground-motions are more polarised than ‘far-field’ ground motions [47]. Shahi and Baker [47] found that this ‘directionality’ was only statistically apparent for source-to-site distances less than 5 km, and vibration periods longer than approximately $T = 0.5s$, consistent with the basic parametrisation of Somerville *et al.* [2]. Thus, even if the RotD50 spectra in TS1170.5 is not adjusted, it is possible on a site- and fault-specific basis to consider non-RotD50 response spectra for the different orientations of the structure. Shahi and Baker [47] provide more general expressions for polarisation as a function of the azimuth between the fault strike direction and the orientation of interest. For simplicity, in a conventional design context, the following step-by-step procedure could be used:

1. Using the existing 11 ‘major’ faults in NZS1170.5:2004, determine if the site is within 5 km of the nearest source.
2. Use a directionality adjustment to obtain the RotD100 values, and determine the spectra in the fault normal (FN) direction, SA_{FN}, based on the RotD100/RotD50 ratio, and the fraction of the hazard that is caused by active shallow crustal ruptures, P_{ACR} (Equation 1).

$$SA_{FN} \approx \left[1 + P_{ACR}\left(\frac{SA_{RotD100}}{SA_{RotD50}} - 1\right)\right] SA_{RotD50} \qquad (1)$$

3. Continue to use the RotD50 spectra in the fault parallel direction. This will be slightly conservative, but avoids a design spectra in one direction that is lower than the RotD50 value
4. If it is desired to decompose the spectra into other azimuth angles that are consistent with the principal directions of a structural system then linear interpolation between the fault normal and parallel spectra can be used with the azimuthal angle.

The basis for P_{ACR} in Equation 1 is that the fault-normal adjustment should only be increased due to the contribution of the faults that actually lead to clear polarity at the site (forward-directivity ruptures, in this case). Thus, strictly speaking, this should be the disaggregation probability of these such ruptures. However, the determination of this associated probability is not straightforward due to the non-characteristic and multi-segment nature of the seismic source model in the 2022 NSHM. Given that distributed seismicity contributes little to the total hazard for regions of high seismic hazard (which is the case for all sites in close proximity to the 11 ‘major’ faults identified in NZS1170.5:2004, *e.g.*, Figure 2), then P_{ACR} will be suitable as a proxy for the probability that the hazard is dominated by the actual modelled faults that pose the forward-directivity potential for the site. Furthermore, this disaggregation probability is directly available from the 2022 NSHM website (https://nshm.gns.cri.nz/). For example, for $SA(T = 3.0s)$ for the 2475-year return period, $P_{ACR} \approx 0.5$ for Wellington (almost entirely due to ruptures including the Wellington fault), and $P_{ACR} \approx 1.0$ for Franz Josef (ruptures of the Alpine fault).

Ground-Motion Time-Series Selection

One of the principal features of near-fault ground motions with forward directivity is that the inelastic seismic demands that they impose on structures can be appreciably greater than what one might infer based on their 5%-viscously damped response spectra. Nonlinear response history analysis is the principal means by which to account for such features. While contemporary international codes and standards generally do not modify the design spectra to account for near-fault directivity, they are consistent in explicit consideration of near-fault directivity for ground-motion selection. There are well-established processes for the consideration of ground-motion time series in the near-fault region [11,48–50], including NZ-specific guidance from SESOC[51] that is compatible with the sentiments expressed in this paper, and recommended for adoption.

Care in Mixing Probabilism and Determinism

A final comment in practical considerations is a cautionary sentiment about mixing probabilism and determinism. The author has frequently participated in discussions where PSHA-based response spectra are obtained, and then adjustments to such spectra are proposed to account for features that are not explicitly considered in the PSHA calculation. The consideration of directivity adjustments is one such example, and the notion of adjustments is clearly worthy of consideration as the earlier sentiments in this paper have expressed. However, it is paramount that adjustments are done so in a probabilistically consistent manner, and not based on a deterministic / scenario / worst-case manner. The two examples of this which have been addressed in earlier discussions are: (1) the frequency at which ‘maximum’ forward directivity conditions occur, and (2) the azimuthal variation in ground-motion amplitudes due to polarity resulting from directivity effects. In such instances it is common to hear proposals that such directivity adjustments should reflect the maximum forward directivity condition and also be in the fault-normal direction. Neither of these worst-case assumptions are probabilistically consistent with the use of a ‘baseline’ ground motion spectra for a specific return period (say, 2475 years). In fact, in essence, they result in a ground motion that actually has a larger equivalent return period, as discussed in detail by Stewart *et al.* [52].

FUTURE OPPORTUNITIES FOR DIRECTIVITY MODELLING IN NZ DESIGN SPECTRA

The practical recommendations of the prior section provide immediate options for design practice in NZ. The section attempts to summarise the author’s view of the approaches for considering directivity in the medium-to-long term in seismic design standards and codes of practice.

The occurrence of ‘directivity effects’ in the near-field is not a binary phenomena, and is best thought of as having a continuous range of severity - where the notions of ’backward’ and ’forward’ directivity reflect the two ends of this continuum. Because the hypocentral location of future earthquake ruptures is unknown, then a probabilistic consideration of potential directivity phenomena, as taken in state-of-the-art approaches [13,20], is the only suitable way to consider this phenomena for seismic design spectra that are based on the results of PSHA. Thus, this implies that directivity phenomena should be considered in the PSHA calculation itself, and should not be a post-hoc modification factor in future seismic design guidelines (because it is generally not possible to be probabilistically consistent in a post-hoc application). A desire to consider 'more severe ground-motions' should simply be obtained by considering a different ground-motion annual exceedance probability/rate, since this accounts for the possibility that the more severe motion is caused by greater directivity, and/or any other number of ground-motion phenomena. In the end, the structure cares not the underlying causal phenomena that produced the ground motion that it is subjected to, it simply cares about the absolute severity of the motion itself.

By treating directivity phenomena within the hazard calculation itself it also ensures that any explicit directivity modelling is internally consistent with the ground-motion models that it is applied to. The examples in this paper illustrate this situation in two ways: (1) that the NZS1170.5:2004 near-fault factor was initially conceptualised in the context of a ground-motion hazard defined in terms of the 'Larger' horizontal component, whereas the draft TS1170.5:2024 is based on the 'RotD50' horizontal component; and (2) while there remains appreciable uncertainty among contemporary directivity models, directivity models will continue to be improved in lock-step with efforts to improve baseline ground-motion models used in PSHA, principally through the use of physics-based simulations to explore complex directivity scenarios that are poorly represented in observational datasets.

Thus, a core focus of future NZ NSHM efforts should be an attempt to include explicit directivity calculations in the nationwide PSHA calculations. In doing so, there will naturally be tailwinds associated with similar efforts internationally, and also in the development of improved models and/or their practical implementation. The recent work of Withers *et al.* [53] represents a pilot example of this for the United States NSHM (albeit using only the Watson-Lamprey *et al.* [19] model), and very recently some of the aforementioned issues in the BSS20 model have been purported to have been overcome [54].

CONCLUSIONS

This paper addressed the question of whether the NZS1170.5:2004 near-fault factor is appropriate for use in combination with the 2022 NSHM results embodied in the 'baseline' spectra in the draft TS1170.5:2024. It was shown that state-of-the-art approaches for explicitly modelling near-fault directivity produce directivity multiplication factors that are approximately four times smaller than the direct application of the NZS1170.5:2004 near-fault factor, $N(T,D)$, with the draft TS1170.5:2024 'baseline' spectra. Comparison with international codes and standards illustrates that, with one exception (Taiwan) near-fault factors are not considered in other countries. The scientific limitations of the development of the $N(T,D)$ factor were examined, as well as the compatibility problem with the draft TS1170.5:2024 spectra changing to a RotD50 horizontal definition, from the previous NZS1170.5:2004 Larger component definition.

On the basis of the provided evidence it was recommended that either the $N(T,D)$ factor should be completely removed from any revision to the draft TS1170.5:2024, or significantly revised to achieve an approximately factor-of-four reduction. Several other recommendations for immediate practical consideration were noted, including possible polarisation adjustments to address the larger directionality in near-fault motions, as well as NZ-specific guidance for ground-motion time series selection. Lastly, it was recommended that future seismic design spectra in NZ should continue to avoid a post-hoc near-fault directivity factor, and focus on its explicit inclusion within the next revision of the NZ NSHM.

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REFERENCES

1 Pitarka A, Irikura K, Iwata T and Sekiguchi H (1998). "Three-dimensional simulation of the near-fault ground motion for the 1995 Hyogo-Ken Nanbu (Kobe), Japan, earthquake". *Bulletin of the Seismological Society of America*, **88**(2): 428–440. https://doi.org/10.1785/BSSA0880020428

2 Somerville PG, Smith NF, Graves RW and Abrahamson NA (1997). "Modification of Empirical Strong Ground Motion Attenuation Relations to Include the Amplitude and Duration Effects of Rupture Directivity". *Seismological Research Letters*, **68**(1): 199–222. https://doi.org/10.1785/gssrl.68.1.199

3 Bray J and Rodriguez-Marek A (2004). "Characterization of forward-directivity ground motions in the near-fault region". *Soil Dynamics and Earthquake Engineering*, **24**: 815–828. https://doi.org/10.1016/j.soildyn.2004.05.001

4 Baker JW (2007). "Quantitative Classification of Near-Fault Ground Motions Using Wavelet Analysis". *Bulletin of the Seismological Society of America*, **97**(5): 1486–1501. https://doi.org/10.1785/0120060255

5 Alavi B and Krawinkler H (2004). "Behavior of moment-resisting frame structures subjected to near-fault ground motions". *Earthquake Engineering & Structural Dynamics*, **33**(6): 687–706. https://doi.org/10.1002/eqe.369

6 Champion C and Liel A (2012). "The effect of near-fault directivity on building seismic collapse risk". *Earthquake Engineering & Structural Dynamics*, **41**(10): 1391–1409. https://doi.org/10.1002/eqe.1188

7 Standards New Zealand (2004). "*NZS 1170.5:2004 Structural Design Actions, Part 5: Earthquake Actions - New Zealand*": Wellington, New Zealand, 82pp.

8 McVerry G (2003). "From hazard maps to code spectra for New Zealand". *2003 Pacific Conference on Earthquake Engineering*: 13–15 February, Christchurch, New Zealand, 9pp.

9 Gerstenberger MC, Bora S, Bradley BA, DiCaprio C, Kaiser A, Manea EF, Nicol A, Rollins C, Stirling MW, Thingbaijam KKS, Van Dissen RJ, Abbott ER, Atkinson GM, Chamberlain C, Christophersen A, Clark K, Coffey GL, de la Torre CA, Ellis SM, Fraser J, Graham K, Griffin J, Hamling IJ, Hill MP, Howell A, Hulsey A, Hutchinson J, Iturrieta P, Johnson KM, Jurgens VO, Kirkman R, Langridge RM, Lee RL, Litchfield NJ, Maurer J, Milner KR, Rastin S, Rattenbury MS, Rhoades DA, Ristau J, Schorlemmer D, Seebeck H, Shaw BE, Stafford PJ, Stolte AC, Townend J, Villamor P, Wallace LM, Weatherill G, Williams CA and Wotherspoon LM (2024). "The 2022 Aotearoa New Zealand National Seismic Hazard Model: Process, Overview, and Results". *Bulletin of the Seismological Society of America*, **114**(1): 7–36. https://doi.org/10.1785/0120230182

10 Standards New Zealand (2024). "Draft Technical Specifi-

cation for 'Structural design actions - Part 5: Earthquake actions - New Zealand' (TS1170.5)".

11 Baker JW, Bradley BA and Stafford PJ (2021). *Seismic Hazard and Risk Analysis*. Cambridge University Press, Cambridge, ISBN 978-1-108-42505-6. https://www.cambridge.org/core/books/seismic-hazard-and-risk-analysis/177B4BA01FC2600AA53A22B27598A06C

12 Stirling M, McVerry G and Berryman K (2002). "A new seismic hazard model for New Zealand". *Bulletin of the Seismological Society of America*, **92**(5): 1878–1903. https://doi.org/10.1785/0120010156

13 Weatherill G and Lilienkamp H (2024). "Capturing Directivity in Probabilistic Seismic Hazard Analysis for New Zealand: Challenges, Implications, and a Machine Learning Approach for Implementation". *Bulletin of the Seismological Society of America*, **114**(1): 373–398. https://doi.org/10.1785/0120230161

14 Donahue J, Stewart J, Gregor N and Bozorgnia Y (2019). *"Ground-Motion Directivity Modeling for Seismic Hazard Applications"*. Technical Report PEER Report 2019/03.

15 Field EH and Page MT (2011). "Estimating Earthquake-Rupture Rates on a Fault or Fault System". *Bulletin of the Seismological Society of America*, **101**(1): 79–92. https://doi.org/10.1785/0120100004

16 Gerstenberger MC, Van Dissen R, Rollins C, DiCaprio C, Thingbaijim KKS, Bora S, Chamberlain C, Christophersen A, Coffey GL, Ellis SM, Iturrieta P, Johnson KM, Litchfield NJ, Nicol A, Milner KR, Rastin SJ, Rhoades D, Seebeck H, Shaw BE, Stirling MW, Wallace L, Allen TI, Bradley BA, Charlton D, Clark KJ, Fraser J, Griffin J, Hamling IJ, Howell A, Hudson-Doyle E, Hulsey A, Jurgens VO, Kaiser AE, Kirkman R, Langridge RM, Maurer J, Rattenbury MS, Ristau J, Schorlemmer D, Townend J, Villamor P and Williams C (2024). "The Seismicity Rate Model for the 2022 Aotearoa New Zealand National Seismic Hazard Model". *Bulletin of the Seismological Society of America*, **114**(1): 182–216. https://doi.org/10.1785/0120230165

17 Ancheta TD, Darragh RB, Stewart JP, Seyhan E, Silva WJ, Chiou BSJ, Wooddell KE, Graves RW, Kottke AR, Boore DM, Kishida T and Donahue JL (2014). "NGA-West2 Database". *Earthquake Spectra*, **30**(3): 989–1005. https://doi.org/10.1193/070913EQS197M

18 Mai PM, Spudich P and Boatwright J (2005). "Hypocenter Locations in Finite-Source Rupture Models". *Bulletin of the Seismological Society of America*, **95**(3): 965–980. https://doi.org/10.1785/0120040111

19 Watson-Lamprey J (2018). *"Capturing directivity effects in the mean and aleatory variability of the NGA- West2 ground motion prediction equations"*. Technical Report PEER Report No. 2018/04.

20 Al Atik L, Gregor N, Mazzoni S and Bozorgnia Y (2023). *"Directivity-based probabilistic seismic hazard analysis for the state of California: Report 2, directivity implementation"*. Technical Report Report GIRS-2023-05, Natural Hazards Risk & Resiliency Research Center, B. John Institute for the Risk Sciences, University of California, Los Angeles.

21 Bayless JR, Somerville P and Skarlatoudis AA (2020). *"A Rupture Directivity Adjustment Model Applicable to the NGA-West2 Ground Motion Models and Complex Fault Geometries"*. Technical Report USGS Final Technical Report: USGS Award G18AP00092.

22 Bayless J and Somerville P (2013). *"Final report of the NGA-West2 directivity working group. Chapter 2."* PEER Report No. 2013/09.

23 Chiou B and Spudich P (2013). *"Final report of the NGA-West2 directivity working group. Chapter 6,"*. Technical Report PEER Report No. 2013/09., Pacific Earthquake Engineering Center.

24 Chiou BSJ and Youngs RR (2014). "Update of the Chiou and Youngs NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra". *Earthquake Spectra*, **30**(3): 1117–1153. https://doi.org/10.1193/072813EQS219M

25 Stirling M, McVerry G, Gerstenberger M, Litchfield N, Van Dissen R, Berryman K, Barnes P, Wallace L, Villamor P, Langridge R, Lamarche G, Nodder S, Reyners M, Bradley B, Rhoades D, Smith W, Nicol A, Pettinga J, Clark K and Jacobs K (2012). "National Seismic Hazard Model for New Zealand: 2010 Update". *Bulletin of the Seismological Society of America*, **102**(4): 1514–1542. https://doi.org/10.1785/0120110170

26 Weatherill G (2022). *"Impact of directivity on probabilistic seismic hazard calculations in New Zealand"*. Technical Report GNS Science report; 2022/01. https://doi.org/10.21420/RETZ-D556

27 Bradley BA, Bora SS, Lee RL, Manea EF, Gerstenberger MC, Stafford PJ, Atkinson GM, Weatherill G, Hutchinson J, de la Torre CA, Hulsey AM and Kaiser AE (2024). "The Ground-Motion Characterization Model for the 2022 New Zealand National Seismic Hazard Model". *Bulletin of the Seismological Society of America*, **114**(1): 329–349. https://doi.org/10.1785/0120230170

28 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"*. Technical Report GNS Science report; 2022/15. https://doi.org/10.21420/5098-0S19

29 Abrahamson NA (2000). "Effects of rupture directivity on probabilistic seismic hazard analysis". *6th International Conference on Seismic Zonation*, p. 6.

30 Abrahamson NA and Silva WJ (1997). "Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes". *Seismological Research Letters*, **68**(1): 94–127. https://doi.org/10.1785/gssrl.68.1.94

31 Abrahamson NA, Silva WJ and Kamai R (2014). "Summary of the ASK14 Ground Motion Relation for Active Crustal Regions". *Earthquake Spectra*, **30**(3): 1025–1055. https://doi.org/10.1193/070913EQS198M

32 Douglas J (2024). "Ground motion prediction equations 1964-2023 (incomplete)". https://doi.org/https://doi.org/10.6084/m9.figshare.26827750.v1

33 ASCE (2022). "ASCE/SEI 7-22 Minimum Design Loads and Associated Criteria for Buildings and Other Structures".

34 ASCE (2005). "ASCE/SEI 7-05 Minimum Design Loads for Buildings and Other Structures".

35 Building Seismic Safety Council (2003). *"Recommended Provisions for Seismic Regulations for New Buildings and Other Structures"*. Technical report.

36 International Conference of Building Officials (1997). "Uniform Building Code (UBC-97), Structural Engineering Design Provisions".

37 CEN (2004). *"Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings"*. Technical report, Brussels.

38 Instituto Nacional de Normalización (2009). *"NCh433 Of.96*

Mod.2009: Diseño sísmico de edificios [Seismic design of buildings]. Instituto Nacional de Normalización". Technical report.

39 Instituto Nacional de Normalización (2013). *"NCh2745 Of.2013: Análisis y diseño de edificios con aislamiento sísmico [Analysis and design of buildings with seismic isolation]. Instituto Nacional de Normalización"*. Technical report.

40 Bureau of Indian Standards (2016). *"IS 1893 (Part 1):2016: Criteria for earthquake resistant design of structures. Bureau of Indian Standards."* Technical report.

41 Construction and Planning Agency, Ministry of the Interior (2011). "Seismic design code and commentary for buildings".

42 Bradley BA and Baker JW (2015). "Ground motion directionality in the 2010–2011 Canterbury earthquakes". *Earthquake Engineering & Structural Dynamics*, **44**(3): 371–384, number: 3. https://doi.org/10.1002/eqe.2474

43 Boore DM and Kishida T (2017). "Relations between Some Horizontal-Component Ground-Motion Intensity Measures Used in Practice". *Bulletin of the Seismological Society of America*, **107**(1): 334–343. https://doi.org/10.1785/0120160250

44 Bradley BA and Baker JW (2015). "Ground motion directionality in the 2010–2011 Canterbury earthquakes". *Earthquake Engineering & Structural Dynamics*, **44**(3): 371–384. https://doi.org/10.1002/eqe.2474

45 Boore D, Watson-Lamprey J and Abrahamson N (2006). "Orientation-independent measures of ground motion". *Bulletin of the Seismological Society of America*, **96**(4A): 1502–1511. https://doi.org/10.1785/0120050209

46 Spudich P, Rowshandel B, Shahi SK, Baker JW and Chiou BSJ (2014). "Comparison of NGA-West2 Directivity Models". *Earthquake Spectra*, **30**(3): 1199–1221. https://doi.org/10.1193/080313EQS222M

47 Shahi SK and Baker JW (2014). "NGA-West2 Models for Ground Motion Directionality". *Earthquake Spectra*, **30**(3): 1285–1300. https://doi.org/10.1193/040913EQS097M

48 Tarbali K, Bradley BA and Baker JW (2019). "Ground Motion Selection in the Near-Fault Region Considering Directivity-Induced Pulse Effects". *Earthquake Spectra*, **35**(2): 759–786. https://doi.org/10.1193/102517EQS223M

49 Almufti I, Motamed R, Grant DN and Willford M (2015). "Incorporation of Velocity Pulses in Design Ground Motions for Response History Analysis Using a Probabilistic Framework". *Earthquake Spectra*, **31**(3): 1647–1666. https://doi.org/10.1193/032113EQS072M

50 Hayden C, Bray J and Abrahamson N (2014). "Selection of Near-Fault Pulse Motions". *Journal of Geotechnical and Geoenvironmental Engineering*, **140**(7): 04014030. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001129

51 SESOC (2024). *"Nonlinear Response History Analysis Design Guide"*. Technical report, Structural Engineering Society New Zealand (draft for public consultation). https://www.sesoc.org.nz/design-resources/guidelines/nz-industry-nlrha-guidelines-public-comment-draft

52 Stewart JP, Abrahamson N, Atkinson GM, Baker J, Boore D, Bozorgnia Y, Campbell K, Comartin C, Idriss IM, Lew M, Mehrain M, Moehle J, Naeim F and Sabol T (2011). "Representation of bidirectional ground motion for design spectra in building codes". *Earthquake Spectra*, **27**(3): 927–937. https://doi.org/10.1193/1.3608001

53 Withers K, Moschetti M, Powers P, Petersen M, Graves R, Aagaard BT, Baltay A, Luco N, Wirth E, Rezaeian S and Thompson E (2024). "Integration of rupture directivity models for the US National Seismic Hazard Model". *Earthquake Spectra*, **40**(2): 1066–1098. https://doi.org/10.1177/87552930241232708

54 Bayless J, Abrahamson NA and Somerville PG (2025). "A rupture directivity adjustment model and its application in seismic hazard". *Earthquake Spectra*, **41**(1): 753–781. https://doi.org/10.1177/87552930241290632