Duration of earthquake ground motion anticipated at sites in New Zealand

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ABSTRACT

Source-specific conditional distributions of the duration of ground motion anticipated at a set of representative sites in New Zealand are computed using a procedure based on the generalised conditional intensity measure (GCIM) framework. Sites in the eastern part of the North Island and the northern part of the South Island are shown to be susceptible to long duration ground motions produced by large magnitude interface earthquakes in the Hikurangi subduction zone. Nevertheless, relatively short duration ground motions produced by lower magnitude earthquakes on adjacent crustal faults are still the primary contributors to their seismic hazard. Hence, an appropriate mix of short and long duration ground motions should be selected when assessing the performance of structures located at these sites. Failure to consider hazard-consistent duration targets in addition to conditional spectra during record selection is likely to result in biased structural response estimates.

1 INTRODUCTION

The potential of earthquake-induced ground motion to inflict structural damage is often characterised by just its response spectrum. A ground motion's response spectrum has been shown to be correlated to important structural demands like peak deformations and collapse capacity (Shome et al. 1998; Baker and Cornell 2006; FEMA 2009), and thus, its prominent use in design and assessment practice is well justified. The duration of an earthquake ground motion on the other hand, which is a measure of its cumulative damage potential, is typically relegated to implicit, qualitative consideration (NZS 2004; NIST 2011; ASCE 2017) as a consequence of the inconclusive findings of early research into its effects (Hancock and Bommer 2006). A number of recent studies employing realistic, deteriorating structural models (e.g., Raghunandan and Liel 2013; Barbosa et al. 2016; Chandramohan et al. 2016b; Marafi et al. 2016; Fairhurst et al. 2017; Hammad and Moustafa 2017) have, however, demonstrated the influence of ground motion duration on structural collapse capacity and highlighted the need to explicitly consider duration, in addition to response spectra, in structural design and performance assessment.

Evaluating the importance of explicitly considering duration in structural design and assessment practice in New Zealand, first requires an assessment of the *extended* seismic hazard at its important population centres, in terms of the durations of the anticipated ground motions, in addition to their response spectra. In this study, the durations of ground motions anticipated at a set of representative sites around New Zealand, located in relatively distinct tectonic settings, are first characterised using the generalised conditional intensity measure (GCIM) framework (Bradley 2010). This study extends previous work by Tarbali and Bradley (2014) by accounting for the contribution of subduction earthquakes, computing *source-specific* probability distributions of duration, and considering a larger number of sites around the country. The implications of the computed probability distributions of duration for the design and assessment of structures at these sites are finally discussed.

2 COMPUTATION OF SOURCE-SPECIFIC CONDITIONAL DISTRIBUTIONS OF DURATION

The procedure to compute probability distributions of the durations of ground motions anticipated at a site, conditional on the exceedance of a primary amplitude-based intensity measure (IM) that is characterised by probabilistic seismic hazard analysis (PSHA) (McGuire 2004), has been described in Chandramohan et al. (2016a). This procedure is based on the GCIM framework, which extends the concept of a conditional spectrum (Abrahamson and Al Atik 2010; Baker 2011; Lin et al. 2013b) to account for IMs other than response spectra. It is intuitive to treat duration as a secondary IM and characterise it in conjunction with a primary amplitude-based IM since, for example, a long duration ground motion is not likely to cause any significant structural damage unless it also has a sufficiently high amplitude. This is also motivated by the fact that it is not possible to conduct PSHA using duration as the primary IM, since duration increases with distance from the source, thereby resulting in the divergence of the PSHA integral over all contributing seismic sources.

The duration of strong ground motion contained in an accelerogram is quantified by the metric significant duration (Trifunac and Brady 1975), Ds, in this study. Ds was shown to possess a number of desirable properties, in addition to being a good predictor of structural collapse capacity, in a comparative study of duration metrics by Chandramohan et al. (2016b). It is also readily estimated using previously published prediction equations such as Abrahamson and Silva (1996), Kempton and Stewart (2006), Bommer et al. (2009), and Afshari and Stewart (2016). Significant duration defined by the percentage range 5–75 %, denoted by Ds_{5-75}, is used in this study, since it was found to be marginally more robust and efficient compared to Ds_{5-95} by Chandramohan et al. (2016b) and Chandramohan (2016) (Chapter 5).

The following is a brief description of the procedure to compute source-specific conditional distributions of ground motion duration. Traditional PSHA calculations are first carried out using a primary amplitude-based IM, typically pseudo spectral acceleration at the fundamental elastic modal period of the building under consideration, $S_a(T_1)$. Deaggregation calculations (McGuire 1995) are then carried out to determine the list of earthquake scenarios that are most likely to lead to the exceedance of a certain value of $S_a(T_1)$ at the site. The i^{th} earthquake scenario is defined by (*i*) rupture parameters such as magnitude, faulting mechanism, and source type, ST_i, collectively referred to as $\boldsymbol{Rup}_i$; (*ii*) site parameters such as source-to-site distance, Vs_{30}: average shear wave velocity of the top 30 m of the soil profile, and basin depth, collectively denoted as $\boldsymbol{Site}_i$; (*iii*) total residual or ε-value for $S_a(T_1)$, ε_i; and (*iv*) deaggregation weight, p_i. A prediction equation for Ds is then used to compute the mean, μ, and standard deviation, σ, of the natural logarithm of Ds anticipated at the site for each earthquake scenario, as functions of its $\boldsymbol{Rup}$ and $\boldsymbol{Site}$:

$$\mu_{\ln Ds(i)} = f(\boldsymbol{Rup}_i, \boldsymbol{Site}_i) \tag{1a}$$

$$\sigma_{\ln Ds(i)} = g(\boldsymbol{Rup}_i, \boldsymbol{Site}_i) \tag{1b}$$

The conditional distribution of $\ln Ds$ for each contributing earthquake scenario is then computed using

$$\mu_{\ln Ds(i)\,|\,\ln S_a(T_1)} = \mu_{\ln Ds(i)} + \rho(T_1)\varepsilon_i\sigma_{\ln Ds(i)} \tag{2a}$$

$$\sigma_{\ln Ds(i)\,|\,\ln S_a(T_1)} = \sigma_{\ln Ds(i)}\sqrt{1-\rho(T_1)^2} \tag{2b}$$

where $\rho(T_1)$ represents the correlation between the ε-values from the predictions of $\ln S_a(T_1)$ and $\ln Ds$, estimated using a prediction model such as Bradley (2011). The relative contribution of each type of seismic source (e.g., interface, in-slab, crustal, or volcanic) to the total site seismic hazard, $\bar{p}$, is computed by summing the deaggregation weights corresponding to all contributing earthquake scenarios from that type of source using

$$\bar{p}_{(st)} = \sum_{ST_i=st} p_i \tag{3}$$

where ST is a random variable and st represents a specific source type. Source-specific conditional distributions of $\ln Ds$ are then computed for each seismic source type, st, as a weighted average of the conditional distributions of $\ln Ds$ for all contributing earthquake scenarios from that type of source, using

$$\mu_{\ln Ds(st)\,|\,\ln S_a(T_1)} = \sum_{ST_i=st} \frac{p_i}{\bar{p}_{(st)}} \left[\mu_{\ln Ds(i)\,|\,\ln S_a(T_1)}\right] \tag{4a}$$

$$\sigma_{\ln Ds(st)\,|\,\ln S_a(T_1)} = \sqrt{\sum_{ST_i=st} \frac{p_i}{\bar{p}_{(st)}} \left[\sigma^2_{\ln Ds(i)\,|\,\ln S_a(T_1)} + \left(\mu_{\ln Ds(i)\,|\,\ln S_a(T_1)} - \mu_{\ln Ds(st)\,|\,\ln S_a(T_1)}\right)^2\right]} \tag{4b}$$

The motivation for computing distinct distributions for contributions from each type of seismic source is to account for the inherent differences in the characteristics of ground motions (e.g., response spectra and durations) produced by them. This strategy represents a practical middle-ground between Lin et al. (2013a), which recommends computing a weighted average distribution over all source types, and Bradley (2012), which recommends treating each earthquake scenario individually.

3 CONDITIONAL DISTRIBUTIONS OF DURATION AT SITES IN NEW ZEALAND

The sites considered in this study and the earthquake sources contributing to their seismic hazard are plotted in Figure 1. These sites are located in relatively distinct tectonic settings (Litchfield et al. 2014) and contain some of the biggest population centres in the country. Some smaller cities such as Queenstown have also been included to broaden the area covered by the study.

The duration of ground motion experienced at a site typically increases with both earthquake magnitude and distance from the source, although the effect of magnitude is more dominant (Abrahamson and Silva 1996). Hence, relatively long duration ground motions are expected from large magnitude interface earthquakes produced by the Hikurangi subduction zone, compared to the typically smaller magnitude crustal earthquakes. Although the Puysegur subduction zone off the coast of Fiordland is also capable of producing such large magnitude interface earthquakes, it is not discussed in this study since the resulting ground motion does not affect any large population centres. Both subduction zones also produce relatively lower magnitude in-slab earthquakes, but their contribution to the seismic hazard at most of the considered sites is not significant, as demonstrated below.

PSHA calculations were carried out using the OpenQuake Engine (Pagani et al. 2014) and the implementation of the New Zealand national seismic hazard model (Stirling et al. 2012) by Horspool et al. (2017). Bradley (2013) is used as the prediction model for response spectra from crustal and volcanic earthquakes, while the McVerry et al. (2006) model is used for interface and in-slab earthquakes. $S_a(1.0\,\mathrm{s}, 5\,\%)$ values that are exceeded with a probability of 2 % in 50 years at each site are plotted in Figure 2, from which it is seen that among the considered sites, Wellington has the highest seismicity and Auckland the lowest.

Deaggregation computations were then conducted, and the likelihoods of earthquakes from each type of seismic source causing an exceedance of the respective $S_a(1.0\,\mathrm{s}, 5\,\%)$ values plotted in Figure 2, computed using Equation (3), are plotted in Figure 3. The mean magnitudes of earthquakes from each type of seismic source most likely to cause the exceedance of the $S_a(1.0\,\mathrm{s}, 5\,\%)$ values are plotted in Figure 4. Finally, the distributions of Ds_{5-75} conditional on the exceedance of the $S_a(1.0\,\mathrm{s}, 5\,\%)$ values are plotted in Figure 5. These distributions are computed using the Abrahamson and Silva (1996) prediction model for Ds and the Bradley (2011) model for the correlation between the ε-values of $S_a(1.0\,\mathrm{s}, 5\,\%)$ and Ds. These models are used for earthquakes produced by all types of seismic sources although they were developed only for crustal earthquakes, since analogous models do not currently exist for the other considered seismic source types. The Abrahamson and Silva (1996) prediction model for Ds was preferred over newer models for crustal earthquakes such as Kempton and Stewart (2006) and Afshari and Stewart (2016), since it was found to be the most conservative when extrapolated above its range of calibrated magnitudes for use in conjunction with interface earthquakes. The Bommer et al. (2009) model was not used since it produces unexpected results when extrapolated to higher magnitudes, as shown by Chandramohan et al. (2016a).

Wellington, Gisborne, Napier, Nelson, and Rotorua are observed from Figures 3 to 5, to be susceptible to long duration ground motions with median $Ds_{5-75} \sim 15$–$25\,\mathrm{s}$ from $M_W \sim 8.4$ interface earthquakes in the Hikurangi subduction zone,

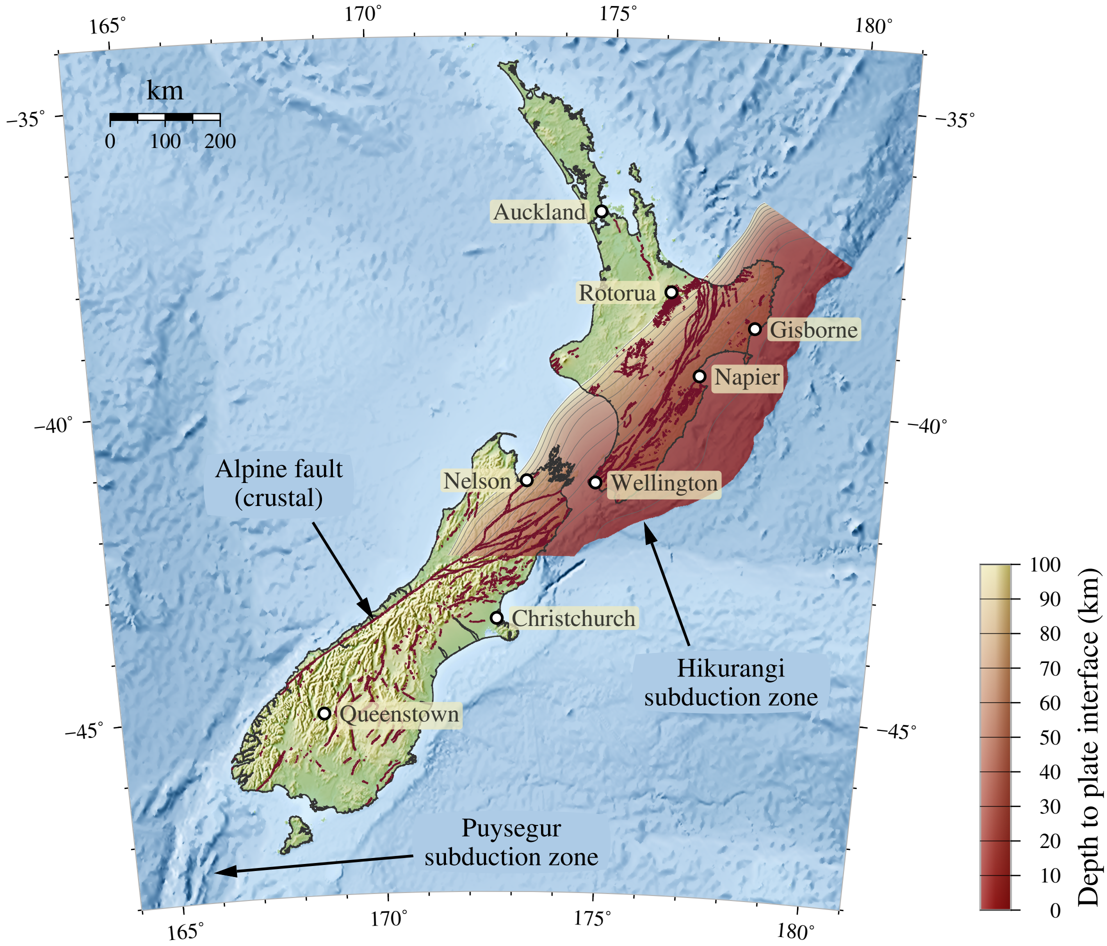

Figure 1: Map of the sites considered in this study and the earthquakes sources contributing to their seismic hazard. Crustal fault data obtained from Langridge et al. (2016) is plotted using dark red lines. Hikurangi subduction zone data obtained from Williams et al. (2013) is plotted using shaded contours.

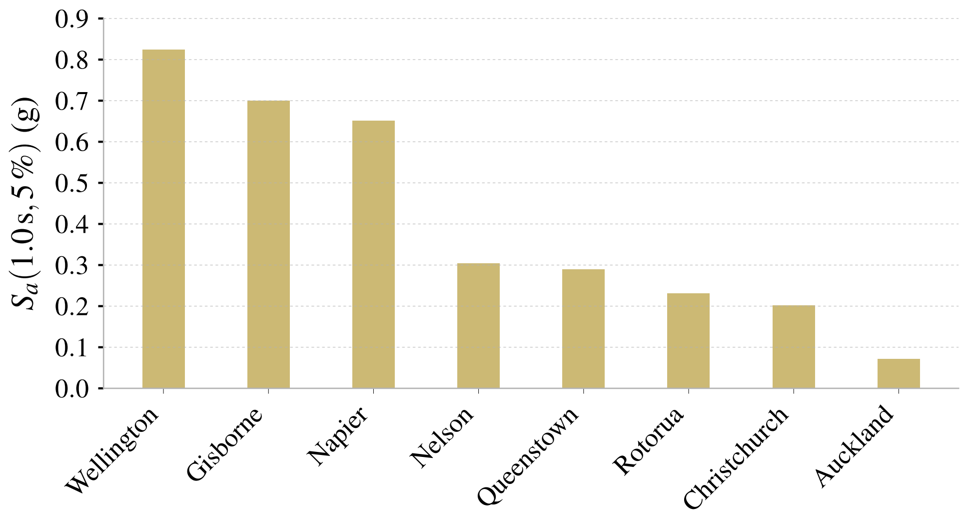

Figure 2: $S_a(1.0\,\mathrm{s}, 5\,\%)$ values that are exceeded with a probability of 2 % in 50 years.

in addition to relatively short duration ground motions with median $Ds_{5-75} \sim 5$–10 s from earthquakes on adjacent crustal faults. Interface earthquakes contribute nearly 50 % of the seismic hazard at Nelson, while their relative contribution at

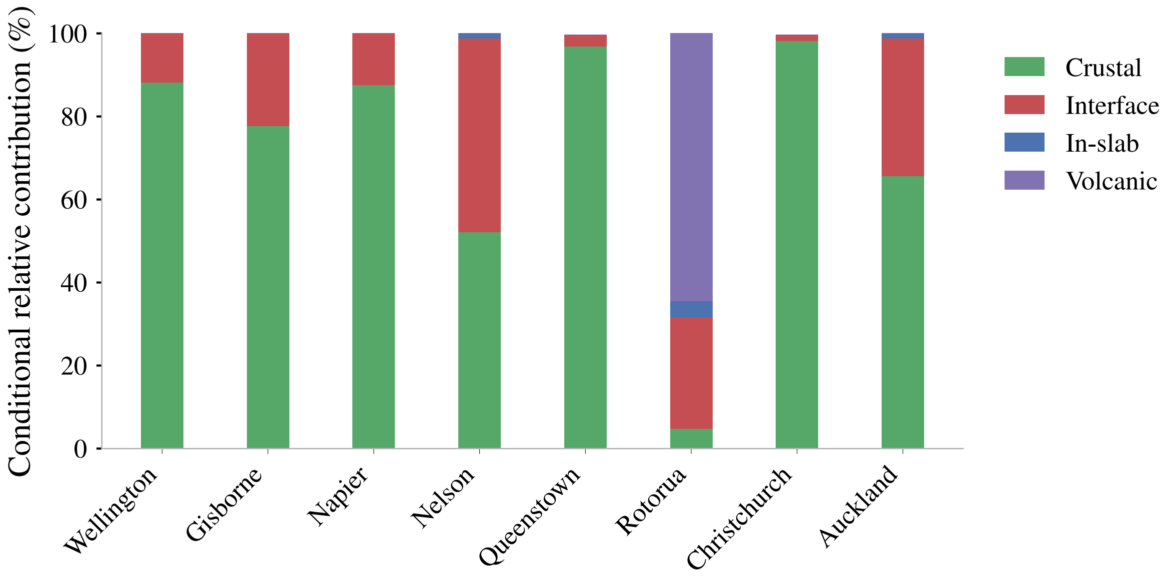

Figure 3: Relative contribution of each type of seismic source to the 2 % in 50 year exceedance probability of $S_a(1.0\,\mathrm{s}, 5\,\%)$.

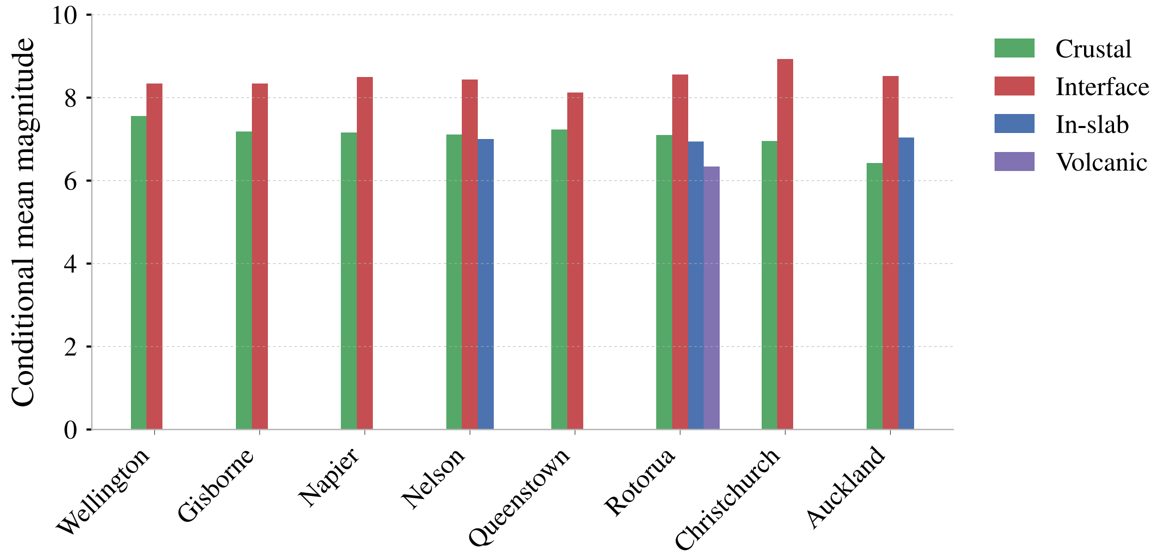

Figure 4: Mean magnitude of earthquakes from each type of seismic source conditional on the 2 % in 50 year exceedance probability of $S_a(1.0\,\mathrm{s}, 5\,\%)$.

Wellington, Gisborne, Napier, and Rotorua is around 10–20 %. Crustal earthquakes are, nevertheless, observed to be the primary contributors to the seismic hazard at most of the considered sites. The seismic hazard at Christchurch and Queenstown, in particular, is almost entirely dominated by $M_W \sim 7.0$ crustal earthquakes that produce ground motions of median $Ds_{5-75} \sim 7\,\mathrm{s}$. Although the ground motion at Christchurch resulting from a large magnitude interface earthquake in the Hikurangi subduction zone is likely to be of relatively long duration, with median $Ds_{5-75} \sim 40\,\mathrm{s}$, it is also expected to be of sufficiently low amplitude, and hence, of limited engineering consequence. This is reflected by the small relative contribution of interface earthquakes to the seismic hazard at Christchurch. Auckland is expected to experience relatively low amplitude ground motions at the 2 % in 50 year hazard level, as indicated by its low seismicity in Figure 2. There is, however, a probability of about 30 % that these ground motions would be produced by interface earthquakes, and as a consequence of its large distance from the Hikurangi subduction zone, they are likely to be of relatively long duration, with median $Ds_{5-75} \sim 40\,\mathrm{s}$. The contribution of in-slab earthquakes to the seismic hazard at most of the sites is seen to be relatively insignificant in comparison. Rotorua is additionally susceptible to earthquakes of volcanic origin. Since the relative contribution of interface earthquakes to the seismic hazard typically increases with the conditioning period (Chandramohan et al. 2016a), the effect of duration is expected to be more important for long period highrise buildings

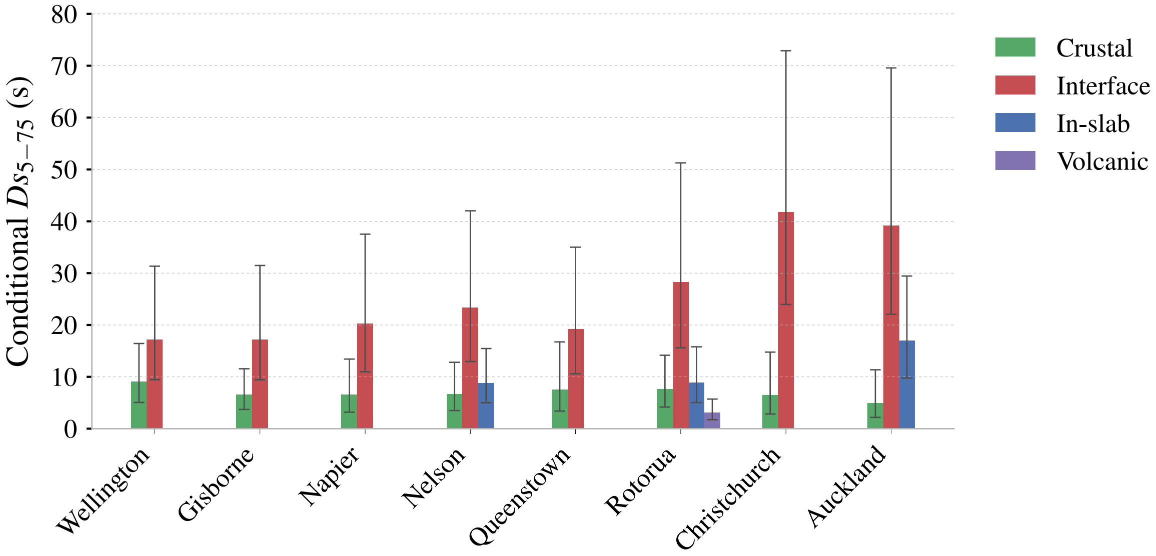

Figure 5: Median and 16th to 84th percentile error bars of Ds_{5-75} of the ground motions produced by earthquakes from each type of seismic source conditional on the 2 % in 50 year exceedance probability of $S_a(1.0\,\mathrm{s}, 5\,\%)$.

located at these sites.

4 IMPLICATIONS FOR GROUND MOTION SELECTION FOR STRUCTURAL PERFORMANCE ASSESSMENT

Studies like Bommer et al. (2000), Bommer and Acevedo (2004), Katsanos et al. (2010), and Tarbali and Bradley (2016) have highlighted the importance of selecting hazard-consistent ground motions for structural performance assessment. This implies selecting ground motions whose characteristics—like response spectra and duration—match those of the ground motions likely to be observed at the site. Specifically, the set of ground motions selected at an intensity level should match hazard-consistent, source-specific target distributions of response spectra and duration, conditional on that intensity level. Source-specific conditional distributions of duration (shown in Figure 5) can be computed using the procedure described in Section 2. Source-specific conditional distributions of response spectra, known as conditional spectra (Abrahamson and Al Atik 2010; Baker 2011; Lin et al. 2013b), can be computed using an analogous procedure. Additionally, the fraction of ground motions selected at an intensity level to match targets corresponding to each type of seismic source should be equal to the relative contribution of that source type to the seismic hazard at that intensity level (indicated in Figure 3).

For example, if 40 ground motions are to be selected to analyse a structure in Wellington at the $S_a(1.0\,\mathrm{s}, 5\,\%) = 0.82\,\mathrm{g}$ intensity level (corresponding to the 2 % in 50 year hazard level as per Figure 2), 35 of them should be selected to match crustal targets, while 5 of them should be selected to match interface targets. The ground motions selected to match interface targets are likely to be of longer duration compared to those selected to match crustal targets. As shown in Chandramohan et al. (2016a), the prevalent practice of selecting ground motions from the PEER NGA-West2 database (Ancheta et al. 2014) on the sole basis of their response spectra, without consideration of their durations, is likely to produce biased estimates of structural response, since the database consists of primarily short duration records from crustal earthquakes. The implicit consideration of duration via causal parameters such as magnitude and source-to-site distance was also shown to produce poor results. Satisfying the requirements to select both an adequate number of ground motions to obtain meaningful structural response statistics, and in appropriate hazard-consistent proportions corresponding to different types of sources, is expected to be challenging when only 3 to 11 of them are selected at an intensity level, as is typically the case when conducting code-based performance assessments (NZS 2004; ASCE 2017). Satisfying this requirement is relatively simpler, on the other hand, when conducting more advanced multiple stripe analyses (Jalayer 2003, Chapter 4) or time-based assessments as per FEMA (2012), where typically a larger number of ground motions are selected per intensity level, at a series of different intensity levels.

Strategies have also recently been developed to account for the effect of duration, along with response spectral shape, in structural design procedures that involve static analyses (Chandramohan et al. 2018). It has been shown in Chandramohan (2016) (Chapter 5) that consideration of response spectra and duration is generally sufficient for the collapse risk assessment of steel and concrete frames, and consideration of additional IMs is likely to produce diminishing returns, in addition to imposing further constraints for ground motion selection from a limited database. Consideration of other IMs may, however, be necessary for the assessment of other structural and geotechnical systems not considered in the study.

5 CONCLUSION

Source-specific probability distributions of the Ds_{5-75} of anticipated ground motions, conditional on the 2 % in 50 year exceedance probability of $S_a(1.0\,\mathrm{s}, 5\,\%)$, were computed for a number of sites in New Zealand. Sites in the eastern part of the North Island and the northern part of the South Island are susceptible to long duration ground motions ($Ds_{5-75} \sim$ 15–25 s) produced by $M_W \sim 8.4$ interface earthquakes in the Hikurangi subduction zone. Such long duration ground motions contribute to nearly 50 % of the seismic hazard at Nelson, and about 10–20 % at Wellington, Gisborne, Napier, and Rotorua, at the considered hazard level. Since crustal earthquakes of $M_W \sim 7.0$ dominate to the seismic hazard at Christchurch and Queenstown, they are expected to experience relatively short duration ground motions ($Ds_{5-75} \sim 7$ s). Although Auckland's low seismicity implies it is likely to experience low amplitude ground motions, there is a 30 % likelihood of them being caused by large magnitude interface earthquakes, in which case, they are expected to be of relatively long duration ($Ds_{5-75} \sim 40$ s).

When selecting ground motions at a certain intensity level for structural performance assessment, it is recommended that they are selected to match source-specific conditional distributions of response spectra and duration. Studies such as (Chandramohan et al. 2016a; Chandramohan 2016, Chapter 5) have demonstrated the nature of errors and biases that could be introduced in the estimated structural responses if ground motions are selected to match only response spectra without consideration of duration.

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