Incorporating simulated Hikurangi subduction interface spectra into probabilistic hazard calculations for Wellington

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ABSTRACT: Holden et al. (NZSEE Conference, 2013) modelled ground motions in Wellington from large magnitude (M_w 8.1 to 9.0) Hikurangi subduction interface earthquakes. Their results highlighted potential deficiencies in the current design levels for Wellington and the need for in-depth modelling of the interface. Their preliminary physically-based simulated motions depend strongly on the Brune stress-drop parameter. This paper presents the potential impact of such events on the probabilistic seismic hazard calculations of the National Seismic Hazard Model (NSHM) based on a modification of its ground-motion equations for subduction interface earthquakes, including accounting for stress drop.

Hazard spectra for Wellington have been re-estimated for the NSHM using stress drops of 3 MPa to 15 MPa for interface events, covering most large subduction interface events worldwide. The spectra increased from the standard NSHM estimates for return periods of 500 years and longer for spectral periods exceeding 1.5s for low stress drops (3 MPa), and for all spectral periods for moderate to high (9-15 MPa) stress drops. For the 500-year motions, a high stress drop subduction interface earthquake becomes potentially the dominant contributor to Wellington's hazard.

This is a major change from the current perception that surface rupture of the Wellington-Hutt Valley segment of the Wellington Fault is the main scenario of concern for strong damaging earthquake motions in the region. Clearly, it is critical to assess these results by improving our understanding and modelling of potential large magnitude earthquakes on the Hikurangi subduction interface, including their recurrence intervals, magnitudes and associated ground motions.

1 INTRODUCTION

Potentially the largest magnitude earthquakes in the Wellington region are those caused by the Pacific plate spasmodically slipping under the over-thrusting Australian plate on the shallowly dipping Hikurangi subduction interface, at a shortest distance of about 23 km from much of Wellington City and the Hutt Valley. Current magnitude estimates of such interface earthquakes in the Wellington region are in the range of about moment magnitude M_w 8 to 8.5, or even up to magnitude 9 for a megathrust event rupturing the interface from the southern Cook Strait to north of East Cape (e.g., Stirling et al., 2012). These magnitudes are much larger than the Mw 7.5 associated with the rupture of the Wellington-Hutt Valley segment of the Wellington Fault between its termination in Cook Strait and Kaitoke, the earthquake scenario that is usually considered for representing strong damaging earthquake motions in Wellington and the Hutt Valley. Current estimates (e.g. Stirling et al., 2012) of the recurrence intervals for the M_w 8 to 8.5 subduction interface rupture scenarios in the Wellington region are 550 years to 1000 years, with about 7000 years for M_w 9.0 megathust events, although admittedly all these recurrence intervals are poorly constrained. The two shorter recurrence intervals bracket the average long-term recurrence interval of 840 years associated with rupture of the Wellington-Hutt Valley fault segment, and also the current equivalent Poisson rupture interval of 1000 years estimated taking into account the elapsed time since its most recent rupture.

Obviously, the ability to accurately estimate the ground-motions that may be associated with these great subduction interface earthquakes is of fundamental importance for the estimation of earthquake hazard in central New Zealand. However, there are very few records world-wide of earthquake ground shaking from subduction interface events at distances as short as Wellington from the Hikurangi interface, let alone for magnitude 8 or larger events.

As they reported at the 2013 NZSEE Conference, Holden et al. (2013) attempted to overcome the lack of real-world recorded motions for such large earthquakes by computing synthetic strong ground motions from physics-based finite fault simulations of Hikurangi interface rupture scenarios. The study reported here allows the results of Holden et al. to be incorporated into seismic hazard analyses for the Wellington urban area by representing the response spectra of the synthetically-derived motions for large interface earthquakes with simple modifications to the McVerry et al. (2006) ground-motion prediction equations (GMPEs) that are used in GNS Science's National Seismic Hazard Model (NSHM) for probabilistic seismic hazard analyses (PSHAs). The synthetic motions were produced for rock site conditions.

2 COMPARISON OF SPECTRA FROM GMPE AND SIMULATED MOTIONS

2.1 Hikurangi subduction interface earthquake scenarios

Holden et al. (2013) generated simulated earthquake ground motions for rock site conditions for ten large earthquake scenarios on the Hikurangi subduction interface under Wellington. The synthetic motions were produced using the EXSIM code of Motazedian & Atkinson (2005), a finite-fault stochastic modelling approach. Atkinson & Macias (2009) performed extensive validation of EXSIM simulations for subduction interface events against recorded motions from the M8.1 Tokachi-Oki earthquake of 2003 and four of its aftershocks. Six of the scenarios considered in Holden et al. (2013) involved simulation of the moment magnitude M_w 8.4 Hikurangi - Wellington maximum event of the National Seismic Hazard Model (Stirling et al., 2012). The M_w 8.4 scenario is modelled as rupturing a 220 km length of the interface from near Cape Campbell to near Cape Turnagain over a width of 144 km across the part of the interface between 5 km and 30 km depth with an average recurrence interval of 1000 years. Some rupture parameters were modified systematically, with low (3 MPa), medium (9 MPa) and high (15 MPa) values of the Brune (1970, 1971) stress-drop parameter that controls the low-frequency corner of the Fourier amplitude point-source spectrum. The stress-drop range of 3 to 15 MPa corresponds to that selected by Atkinson & Macias (2009) for developing simulations for interface earthquakes in Cascadia, based on values from earthquakes in Alaska, Chile, Japan and Mexico. Four medium stress-drop scenarios involved systematic variation of the hypocentres near the north-east, north-west, south-east and south-west corners of the source area. The low and high stress-drop scenarios had random selection of parameters such as the hypocentres and slip distributions. The same rupture zone was involved for an asperity scenario, with a 9 MPa stress-drop on the 90 km x 90 km asperity and 2.3 MPa elsewhere, and a lower magnitude of Mw 8.2. The final three scenarios were generated by placing the slip distributions of three historic earthquakes on the Wellington segment of the Hikurangi subduction interface (M_w 8.3 Tokachi-Oki, Japan earthquake of 2003) or in the mega-thrust region (M_w 8.8 Maule, Chile earthquake of 2010 and M_w 9.1 Sumatra earthquake of 2004 truncated in length to a magnitude 8.9 event).

Multiple simulations (between 20 and 200 for various scenarios) were performed for each identified scenario. The resulting spectrum for each scenario was the average of its multiple simulations. The range in magnitude values considered was narrow, 8.2 to 8.9, and as the motions were developed for a single location in Wellington, the shortest distances to the modelled rupture areas were virtually the same, from 21.6 km to 23.2 km.

2.2 Comparison of spectra

Figure 1 shows the simulated spectra for each of the ten ground-motion earthquake scenarios, together with 50-percentile predictions for the magnitude 8.4 and 8.9 scenarios from the McVerry et al. (2006) GMPE. The GMPE uses only the magnitude, shortest rupture-to-site distance and centroid depth as prediction parameters for a particular site class, so the two GMPE spectra shown represent seven of the ten scenarios for which ground motions were simulated, all except the asperity, Tokachi and Maule scenarios. The GMPE does not include stress-drop as a parameter, so its 50-percentile predictions do not reflect the systematic variations in the scenario motions caused by variation of this parameter. The spectra are plotted up to 3s period, the maximum defined for the McVerry et al. GMPE. Also, the simulation procedure used by Holden et al. (2013) has difficulty in modelling longer periods.

The main features of Figure 1 are (a) the strong effect of the Brune stress-drop parameter, which is not a parameter in the GMPE, on the simulated motions, with the medium and high stress-drop spectra lying well above the low stress-drop spectrum; and (b) the much less rapid reduction with period beyond 2s of the spectra of the simulated motions than those from the GMPE. Note also that the GMPE provides a close match to the low stress-drop (Brune stress-drop parameter of 3 MPa) spectrum from 0.5s to 1.5s, but departs from the low-stress drop simulations at short spectral periods to give more strongly-peaked spectra. At very short periods less than 0.1s and at periods longer than 2s, the GMPE spectra are considerably reduced from the spectra of the simulated motions.

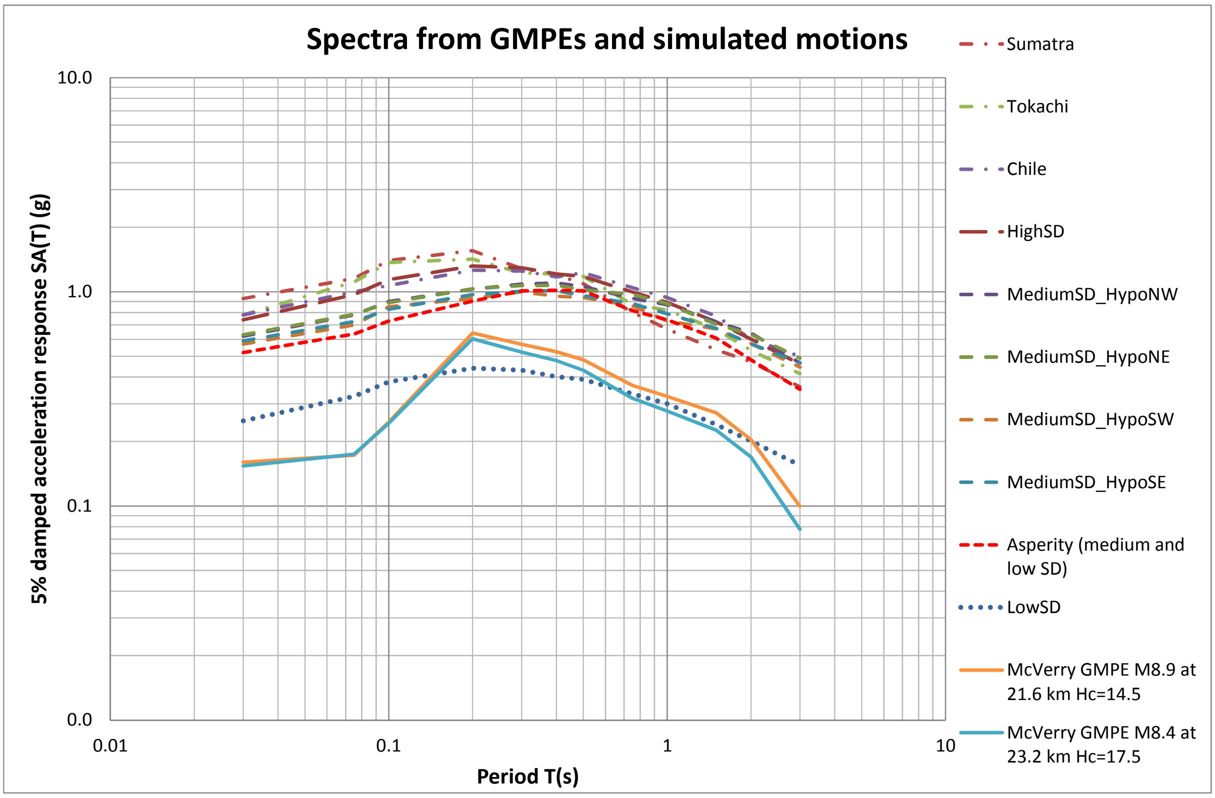

Figure 1. The average spectra for the ten ground-motion simulation scenarios and 50-percentile estimates from the McVerry et al. (2006) GMPE for M_w 8.4 and 8.9 events. The spectra for the McVerry GMPE (solid curves) lie close to the simulated spectrum for the low stress-drop scenario (dotted curve) for some spectral periods, but well below the medium (small dashes) and high stress-drop (large dash) simulations, and the three simulations based on the slip distributions for historic earthquakes (dash-dot).

Figure 2 shows the dependence on the Brune stress-drop parameter of the differences (residuals) in the logarithms of the spectral accelerations between the simulated motions and the McVerry GMPE for the ten scenarios. It uses different symbols and colours for peak ground acceleration (labelled as 0.03s) and 5% damped response spectral accelerations for periods of 0.2s, 1s and 3s. There is an obvious systematic dependence on stress-drop, at least for stress drops up to about 10 MPa. The dependence on magnitude (not shown) and other parameters is much weaker. For example, the variation in the results caused by these other parameters for any particular period (i.e., one type of symbol) across the five scenarios with 9 MPa stress-drops are much smaller than the total variation with stress drop for the same period.

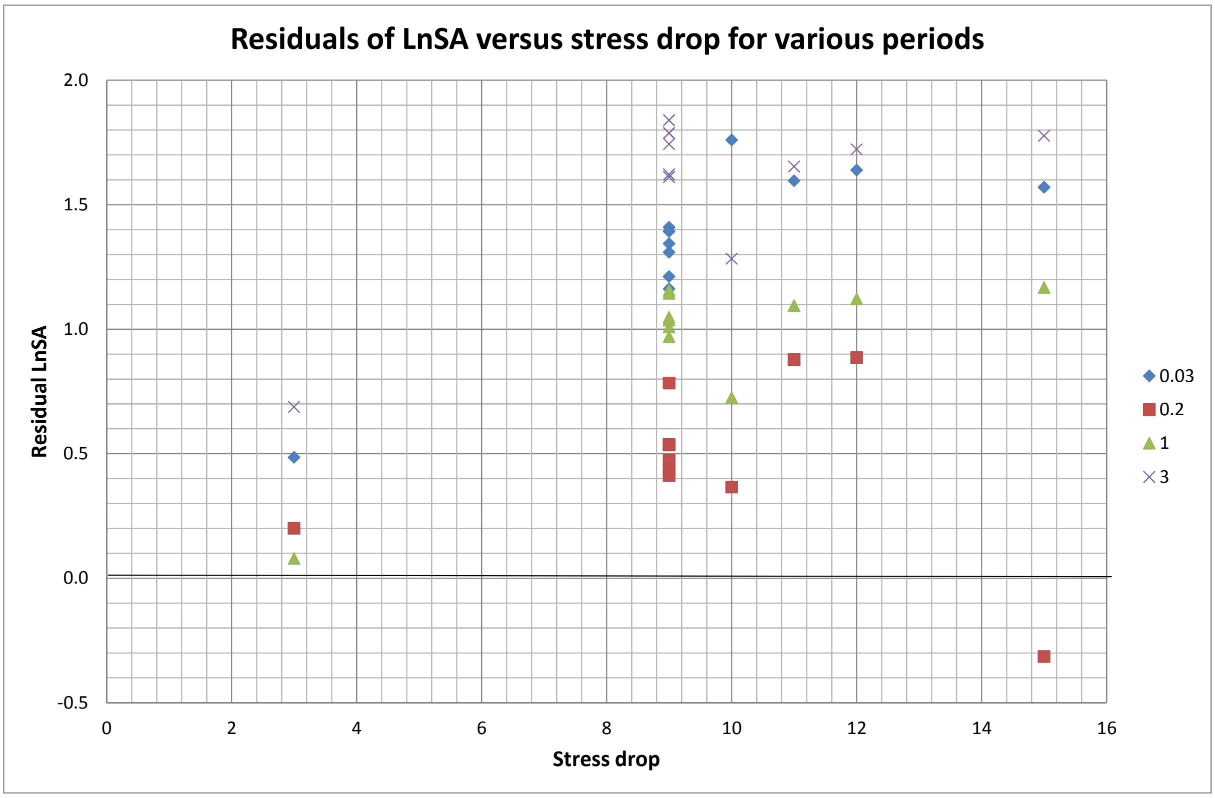

Figure 2. The dependence of residuals of ln(peak ground accelerations) (labelled as 0.03) and ln(spectral accelerations) for periods of 0.2s, 1s and 3s from the ten scenarios showing a strong-dependence on Brune stress-drop parameter.

3 MODIFIED GMPE EXPRESSIONS

The examination of spectra of the simulated ground motions and comparisons with median predictions of the McVerry et al. (2006) GMPE suggested the need for a period-dependent adjustment of the overall level of the spectra from the GMPE and the introduction of a term dependent on the stress-drop parameter in the Brune spectral source model. Accordingly, the following modified GMPE has been investigated for Hikurangi interface earthquakes.

$$\ln SA_{modGMPE}(T) = \ln SA_{McV}(T) + a(T)\, ln\left(\frac{\Delta\sigma}{\Delta\sigma_{ref}}\right) + b(T) \qquad (1)$$

$SA_{modGMPE}(T)$ and $SA_{McV}(T)$ are the median predictions of the 5% damped response spectral acceleration at period T from the modified and McVerry et al. (2006) GMPE. They depend on parameters such as magnitude, shortest source-to-site distance, centroid depth and site class. $\Delta\sigma$ and $\Delta\sigma_{ref}$ are the stress-drop and a reference stress-drop in consistent units. The coefficients a(T) and b(T) are found by least-squares fitting of the natural logarithms of the spectra of the modified GMPE to those of the ground-motion simulations.

The stress-drop term tackles a strong dependence of the simulated motions on the stress-drop parameter of the Brune source model, which was not accounted for in the original model. The modification involves a simple power-law dependence of SA(T) on the stress-drop parameter $\Delta\sigma$, corresponding to $SA(T) \propto (\Delta\sigma)^{a(T)}$. This form of stress-drop modifier was used by Atkinson & Boore (2006) for larger magnitudes in a GMPE developed for eastern North America, where stress drop has a strong influence on ground-motions. The selection of $\Delta\sigma_{ref}$ is arbitrary; different values will affect the fitted coefficient b(T), but not the predicted values of SA(T).

The effect of the coefficients b(T) of the modified McVerry et al. subduction interface expressions for the log of the 5% damped spectral acceleration SA(T) is to correct under-estimates of long-period motions (periods exceeding 1.5s) with respect to the simulation results and to change the spectral shapes for periods less than 0.75s, including adjusting the peak ground accelerations (pgas).

No attempt has been made to modify the dependence of the GMPE on magnitude or distance, because there are only small variations in these parameters for Hikurangi subduction interface sources for locations around the Wellington urban area for both the simulated motions and for the New Zealand NSHM in which it is intended to apply the modified GMPE. Later work may produce simulated motions for a grid of sites across the lower North Island, allowing investigation of the distance dependence of the simulated motions compared to that of the GMPE.

4 MODIFIED SPECTRA FOR THE SCENARIO MOTIONS

Figure 3 compares the average spectra from the simulated motions for the high (15 MPa) and low (3 MPa) stress-drop magnitude 8.4 scenario events with the 50-percentile spectra from the original unmodified GMPE (which was independent of stress drop) and the modified high and low stress-drop GMPEs. Also shown are the +/- sigma error bounds on the modified GMPE using the estimated sigmaln(T) values. These indicate the uncertainties in the median estimates rather than the overall scatter in the GMPE models. Both the high and low stress-drop spectra are estimated well by the modified GMPE across the whole period range from 0s (plotted at 0.03s) to 3s.

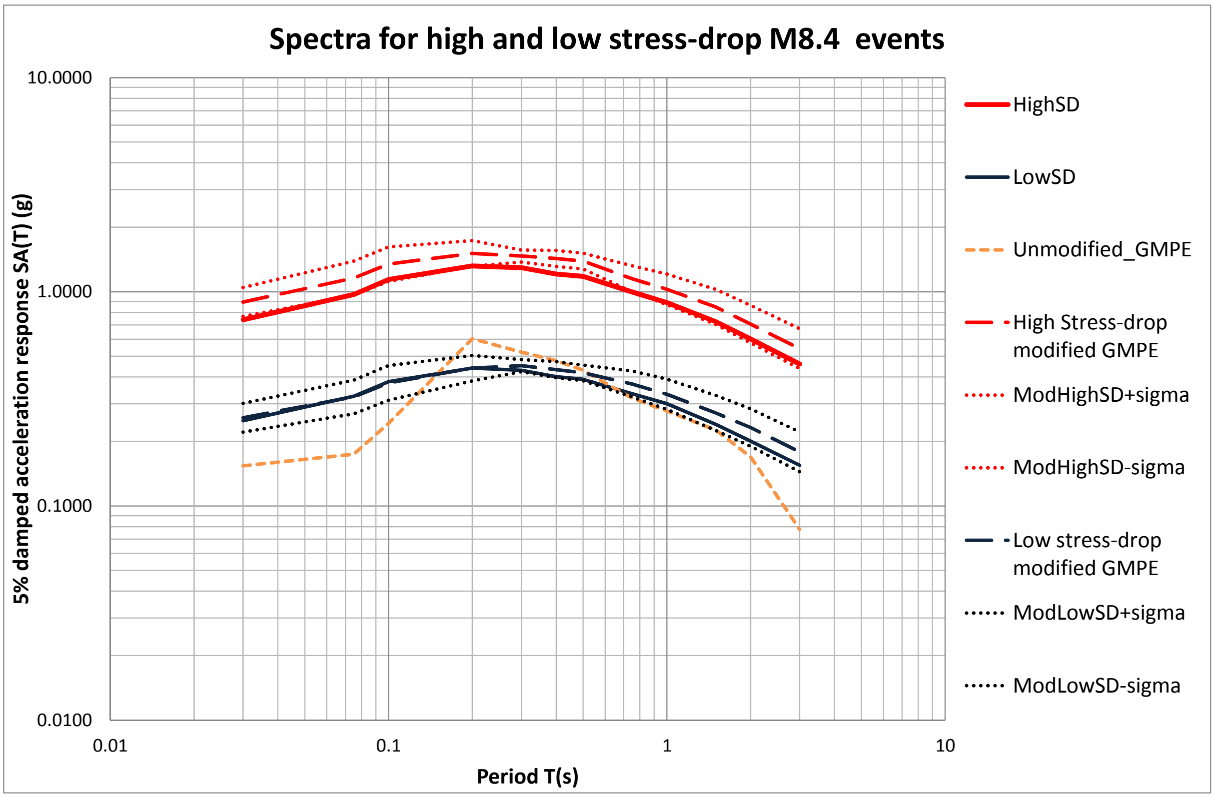

Figure 3. The spectra of the simulated motions for the low- and high stress-drop magnitude 8.4 events (solid black and red lines) compared with the median spectra (dashed lines) and their +/- standard deviation bands (dotted lines) from the modified GMPE. Also shown is the spectrum (dashed orange line) from the unmodified GMPE, which does not depend on stress-drop.

5 EFFECTS ON PSHA RESULTS FOR WELLINGTON

The next stage of the study was to determine the effect of the modified GMPE for the Hikurangi subduction interface sources on hazard spectra estimated for Wellington using the National Seismic Hazard Model (Stirling et al., 2012). This was undertaken by calculating the hazard spectra for NZS1170.5:2004 Class B rock site conditions for a Wellington site using the unmodified GMPE, and then with the modified GMPE for the subduction interface sources, for stress drops of 3 and 15 MPa, while retaining the unmodified GMPE for crustal and subduction slab sources. These stress drops were selected by Atkinson & Macias (2009) as near-minimum and near-maximum values worldwide for large magnitude interface earthquakes, and were chosen to investigate the possible range of outcomes for the currently unknown distribution of stress drops for Hikurangi interface events. Figure 4 shows the results for return periods of 25 years (blue curves), 500 years (black curves) and 2500 years (red curves). The three GMPEs are indicated by solid curves (unmodified standard GMPE), dotted curves (3 MPa stress-drop) and large dashed curves (15 MPa stress-drop).

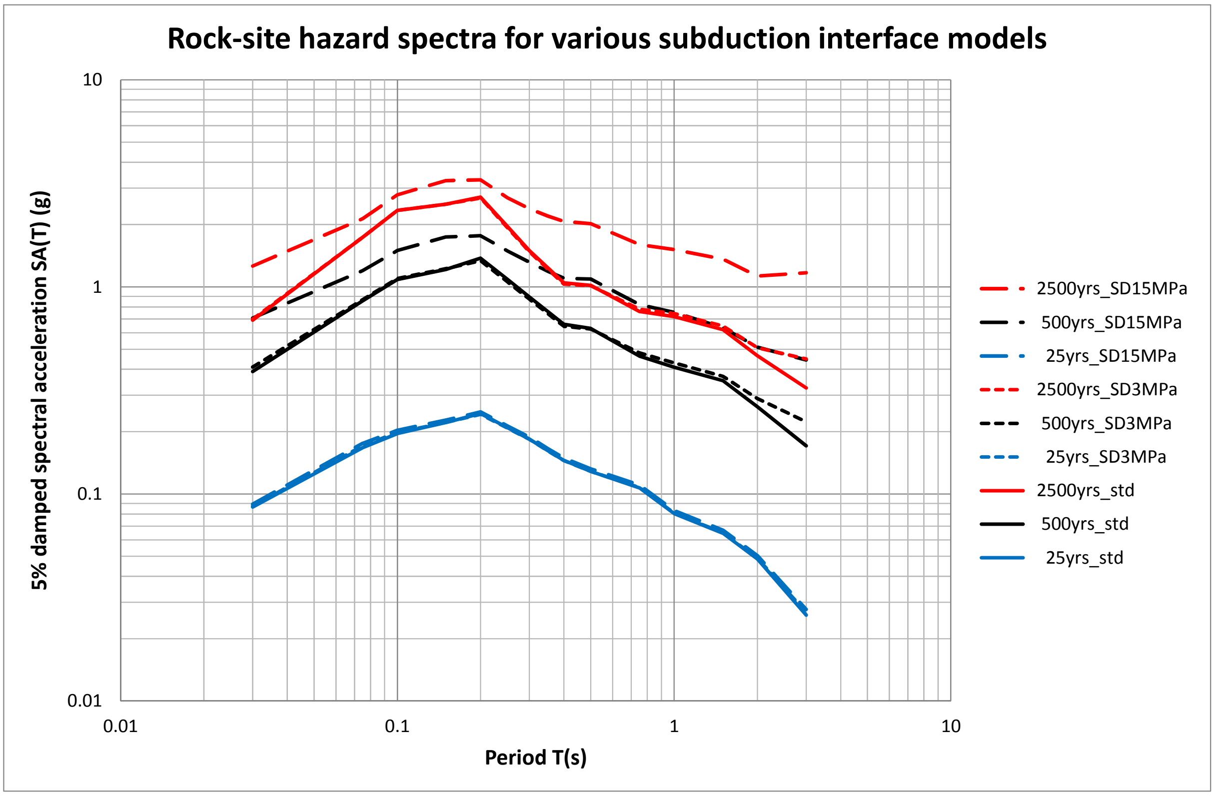

Figure 4. Hazard spectra for a Wellington rock site for return periods of 25, 500 and 2500 years, using the standard GMPE and the modified GMPE for subduction interface sources for stress drops of 3 and 15 MPa.

The 25-year spectrum is insensitive to the choice of GMPE for the interface sources, as these sources contribute little to the estimated motions for this return period. For return periods of 500 and 2500 years, the modified GMPE with a 3 MPa stress-drop gives virtually unmodified spectra for periods up to 1.5s, with the modified spectra then becoming increasingly stronger as the period increases from 1.5s to 10s. This is in line with the difference between the scenario spectra from the unmodified GMPE and the low-stress drop GMPE shown in Figures 1 and 3. For the scenario spectra, the unmodified model considerably underestimates the low stress-drop spectra both from the simulated motions and the modified GMPE for periods up to about 0.15s. This does not occur in the hazard spectra, as the interface sources are significant contributors to the hazard only for longer periods. For a stress-drop parameter of 15 MPa, the 500-year motions from the new model are higher than those from the unmodified model by factors of between about 1.3 to 1.8 in the 0s (pga) to 1.5s period range, before becoming increasingly stronger at longer spectral periods, to a factor of 2.6 at 3s period. The estimated 500-year pga values for a rock site increase from 0.39g to 0.71g.

6 DISCUSSION

Simulations by Holden et al. (2013) of ground shaking for major earthquakes on the Hikurangi interface showed that the response spectra at periods longer than 1.5s are likely to be stronger than given by previous ground-shaking models for all feasible stress drops. If the stress drops are moderate to high (9-15 MPa), the shaking will be stronger than given by previous models at all spectral periods.

The representation of the results of the simulations by a modified GMPE as presented here allowed assessment of the effect of the stronger subduction interface motions on earthquake hazard spectra for

Wellington. The hazard spectra estimated using the modified GMPE increase for return periods of 500 years and longer for spectral periods longer than 1.5s for the low stress-drop interface model, and for all spectral periods for the high stress-drop model.

For these combinations of return periods and spectral periods, the subduction interface is found to be the dominant contributor to the estimated seismic hazard for Wellington. This is a major change from the current perception that surface rupture of the Wellington-Hutt Valley segment of the Wellington Fault between Cook Strait and Kaitoke is the main scenario of concern for strong damaging earthquake motions in Wellington and the Hutt Valley.

A much larger region is likely to be impacted by strong ground shaking, landslide, rockfall and liquefaction for major subduction interface earthquakes than by rupture of the Wellington Fault. The larger impacted region results from the subduction interface earthquakes being associated with much longer rupture lengths (about 220 km for the Wellington portion of the Hikurangi subduction interface) than the 70-80 km of the Wellington-Hutt Valley segment of the Wellington Fault.

The rupture lengths associated with the subduction interface will produce long-duration motions, of over a minute. The long durations may produce a level of damage that is high even for the strength of the spectra. The simulated acceleration histories can be used in dynamic analyses of structures to assess the effect of duration combined with the strength of the motions in inducing damage.

There are many uncertainties in the hazard estimates presented here for major Hikurangi subduction interface earthquakes, from the source modelling through to the ground motions.

The current subduction interface source segmentation and the down-dip width of the rupture zone are subject to modification as more information becomes available, as are the associated rupture intervals. The magnitudes depend on the rupture area, so they will change for any modification of the segmentation of the Hikurangi subduction interface, or change in rupture width.

Stress drop is a key parameter in determining the strength of shaking. Holden et al. (2013) state: “With no historical large earthquakes on the Hikurangi interface, it is currently difficult to assess stress-drop values for future earthquakes ….”. It is likely that large Hikurangi subduction interface earthquakes exhibit a range of stress drops, but these are currently unknown and may not cover the whole 3 MPa to 15 MPa range. Once the distribution becomes known, the hazard analysis could be performed for this distribution, but in this exploratory study results are presented only for possible minimum and maximum values to show the sensitivity of the ground-motions to this parameter.

The current subduction interface GMPEs may implicitly incorporate effects of variation in stress drop in their variances. Once information on the distribution of stress drops on the Hikurangi subduction interface becomes available, ground-motion simulations may be used to modify the variances of the GMPEs as well as incorporating stress-drop dependent modifications for the median motions.

7 CONCLUSIONS

1. Adding two simple terms to the McVerry et al. (2006) GMPE allowed it to fit the spectra of simulated motions for major earthquakes on the Hikurangi subduction interface. The main modification accounted for stress drop, a key parameter of the simulated motions that does not appear in most GMPEs. The other additional term provided stronger long-period motions as well as adjusting the spectra in the short-period range to better match the simulations.

2. The modified GMPE for the subduction interface allowed the simulated motions to be incorporated in probabilistic seismic hazard estimates for a rock site about 2 km from the Wellington Fault, for a selection of possible Brune stress-drop parameters.

3. The modified GMPE affected the hazard estimates for return periods of 500 years and longer.

4. For low stress drops (3 MPa), the hazard spectra were affected only for periods longer than 1.5s. High (15 MPa) stress drops modified the spectra for all spectral periods.

5. For the return period and spectral periods affected by the changes, the subduction interface was found to be the dominant contributor to the estimated seismic hazard for Wellington according to the Holden et al. simulations

6. This is potentially a major change from the current perception that surface rupture of the Wellington-Hutt Valley segment of the Wellington Fault between Cook Strait and Kaitoke is the main scenario of concern for damaging earthquake motions in Wellington and the Hutt Valley.

7. The simulations to date are for a limited magnitude range (8.2-8.9) for sites between about 20 and 25 km from the interface.

8. Extension of the simulations to calculate motions on a grid across the lower North Island will allow further refinement of the GMPE to account for attenuation with distance from the source.

9. Values of the key stress-drop parameter are unknown for potential large earthquakes on the Hikurangi subduction interface.

10. Source parameters including segmentation length, down-dip extent of rupture and average recurrence interval are poorly constrained for the Hikurangi subduction interface.

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