Ground motion modelling of a large subduction interface earthquake in Wellington, New Zealand

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ABSTRACT: The Wellington region is cut by a number of major right-lateral strike slip faults, and is underlain by the currently locked subduction interface between the Pacific Plate and the Australian Plate. A potential cause of significant earthquake loss in the Wellington region is a large magnitude (perhaps 8+) subduction earthquake on the Australia-Pacific plate interface, which lies ~23 km beneath Wellington City.

"It's Our Fault" is a project involving a comprehensive study of Wellington's earthquake risk. Its objective is to position Wellington city to become more resilient through an encompassing study of the likelihood of large earthquakes and the effects and impacts of these earthquakes on humans and the built environment. As part of the "It's Our Fault" project, we are working on estimating ground motions from potential large plate boundary earthquakes.

First we characterise the potential interface rupture area based on previous geodetically-derived estimates of slip deficit on the interface. Then, we entertain a suitable range of source parameters, including various rupture areas, moment magnitudes, stress drops, slip distributions and rupture propagation directions. Our comprehensive study also includes simulations from historical large world subduction events translated into the New Zealand subduction context.

The resulting rupture scenarios all produce long duration shaking, and peak ground accelerations that typically range between 0.2-0.7 g in Wellington city. Many of these scenarios also produce long-period motions that are currently not captured by the current NZ design spectra.

1 INTRODUCTION

The Wellington region is crossed by a number of major right-lateral strike slip faults, and is underlain at 23km depth by the currently-locked, west-dipping subduction interface between the Pacific Plate and over-riding Australian Plate (Fig. 1). The subduction zone is known as the Hikurangi subduction zone. In the short historic period of European settlement (ca. 160 years), the region has been impacted by large earthquakes on one of the strike-slip faults, but has not yet experienced a subduction interface rupture directly beneath the capital city.

As part of the "It's Our Fault" project, we are working on estimating ground motions from potential large plate boundary earthquakes. The "It's Our Fault" project is a comprehensive study of Wellington's earthquake risk (http://www.gns.cri.nz/Home/IOF/It-s-Our-Fault). The main project objective is to make Wellington city more earthquake-resilient, through an encompassing study of the likelihood of large earthquakes, and the effects and impacts of these earthquakes on humans and the built environment (Van Dissen et al., 2010). We model not only time histories but also response spectra, which are relevant to the engineering community.

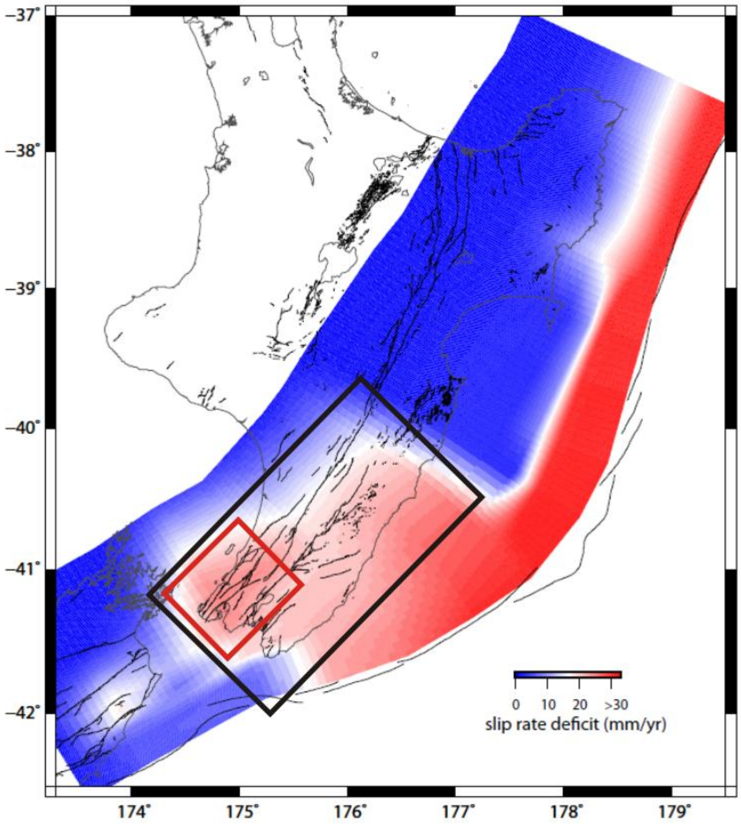

Figure 1: Subduction interface interseismic coupling results (in terms of slip rate deficit) for the Hikurangi subduction thrust from Wallace *et al. (*2012). The large rectangle represents a potential rupture area for a Mw 8.4 scenario. The small rectangle represents a potential rupture area for a Mw 8.2 asperity.

Recent studies of large plate-boundary earthquake modelling include stochastic modelling of Cascadia earthquakes (Atkinson et al., 2009), finite-element and finite-difference modelling of subduction zone events for the Tokyo metropolitan area (Miyake et al., 2008) and hybrid modelling (deterministic for low frequencies and stochastic for high frequencies) for rupture scenario for Japan (Sekiguchi et al. 2008) and Peru (Pulido et al., 2012). To model ground motions for potential large Hikurangi events, we employ the Motazedian and Atkinson (2005) finite-fault stochastic modelling approach.

The absence of large historical subduction earthquakes in the region means that the current estimates of ground motions from such an event are based on modelling and inference from worldwide subduction events. In this study, we seek to overcome this lack of data by synthesising ground motions through broadband modelling of a comprehensive and realistic range of source processes.

2 COMPUTING SEISMOGRAMS WITH A STOCHASTIC METHOD

To model synthetic seismograms and the corresponding response spectra we employ the EXSIM code developed by Motazedian and Atkinson (2005). EXSIM is a finite fault stochastic modelling code that takes into account source as well as regional parameters, and generates realistic broadband seismograms. In the stochastic approach, the moment of the modelled earthquake controls the low frequency part of the spectra, and the stress drop controls the high frequency part. The stochastic method shows limitations in modelling the very long periods (5 seconds and longer) and realistic phases (e.g. Atkinson et al., 2009). However, considering that a large percentage of the current Wellington building stock has a maximum period of a few seconds, we are confident that this method is relevant for our study.

The stochastic approach requires a well-defined source model, attenuation model, and quantification of site effects. In this study we model synthetics for rock site conditions, and therefore ignore variable site effects. These will eventually be included based on a recent detailed 3D model of the Wellington basin (Fry et al., 2010; Boon et al., 2011) and a study of regional site effects (Kaiser et al., 2012).

Wallace et al. (2009) provide a comprehensive description of the Hikurangi subduction interface. We infer a simplified fault plane model with the interface beneath Wellington striking 230° with a dip of 10°. Based on this geometrical model, we consider various detailed source models.The attenuation model used in the study is constructed on the work on a 3D attenuation model for the lower North-Island by Eberhart-Phillips et al. (2005). Their model is built on inversion of earthquake data from the central North Island of New Zealand.

3 HIKURANGI SUBDUCTION SCENARII FOR WELLINGTON

3.1 A Mw 8.4 earthquake source model with random slip distribution

Stirling et al. (2012) recently provided an update to the National Seismic Hazard Model for New Zealand. Regarding the Hikurangi interface they have decomposed the Hikurangi interface into potential rupture areas distributed along strike. In particular, they describe three potential rupture scenarios for the Wellington region: a Mw 8.1 scenario rupturing a 220 by 58 km area beneath Wellington and up to 15 km deep with an associated 550y recurrence interval; a Mw 8.4 scenario rupturing a 220 by 144 km area beneath Wellington and rupturing all the way up to the seafloor (estimated 1000y recurrence interval) and; a mega-thrust earthquake Mw 9.0 rupturing a 620 by 117 km area of the Hikurangi interface (i.e. the entire Hikurangi subduction zone along the eastern margin of the North Island; Fig. 1) with an estimated 7000y recurrence interval. In this study we choose to model the Mw 8.4 event (large rectangle on fig. 1) as a compromise between higher likelihood and larger impact on Wellington. Modelling the other scenarios, especially the Mw 9.0, will be the focus of future studies. The dimensions and moment magnitude of the Mw 8.4 event are fixed but we vary stress-drop values and rupture initiation points.

First we model a range of stress-drop values from as low as 3 MPa to as much as 15 MPa following Atkinson et al. (2009) study of the variability of stress drop on worldwide subduction events. Since Wellington is located on the southernmost part of the fault plane, the rupture initiation location matters. The hypocentre location controls the shaking intensity through rupture-directivity effects if the rupture starts at the northern end of the interface. It also controls the shaking intensity through near-source effects if the rupture starts at the southern end. We therefore entertain also four rupture scenarios where rupture starts from each corner of the fault plane.

3.2 An asperity source model

The potential interface rupture area is based on geodetically-derived estimates of slip rate deficit on the interface or degree of coupling (Wallace and Beavan, 2010). We identify an area of stronger coupling beneath Wellington (fig. 1) as being a potential asperity. A study by Irikura and Miyake (2011) suggests that strong ground motions are generated from asperities while ground motions generated from the rest of the fault rupture area are negligible. Following the Irikura and Miyake (2011) recipe, we infer an asperity-like source model for a Hikurangi subduction earthquake. The recipe is based on a source model for large earthquakes that uses three parameters: outer parameters describing the source size and magnitude, inner parameters describing heterogeneities on the fault (asperity size and stress drop) and extra parameters describing the rupture initiation and velocity. We fix the rupture initiation in the central part of the asperity-area and a constant rupture velocity of 2.1 km/s.

The source and asperity areas are defined by the large and small rectangles respectively in Figure 1. Outer parameters describe the size and geometry of the target event. From Stirling et al.'s (2012) parameterization of the seismogenic sources, we assign to the model a rupture area of 220 by 144 km, a magnitude Mw 8.4, a moment of 5.22x1021 Nm and an average slip value of 5.5 m. Inner parameters describe the asperity-source characteristics. From the study of Murotani et al. (2008) we estimate an asperity area of 90 by 90 km. We locate the asperity in the area with the strongest coupling. The average slip on the asperity is 12.10 m (Murotani et al, 2008). The moment release for the asperity is 2.87*1021 Nm, equivalent to a Mw 8.2 earthquake with a stress drop of 9 MPa (Madariaga, 1979).

3.3 **Modelling historical sources**

The Hikurangi subduction zone constitutes a unique situation worldwide as it combines low plate convergence rates, old plate ages, and shallow depths of the subduction interface. In order to model realistic sources for the Hikurangi subduction interface, we included in our study large past plate boundary events. These were selected to cover a range of event sizes and for the availability of a detailed source model. They are the 2003 Mw 8.3 Tokachi-Oki Japan earthquake, the 2004 Mw 9.1 Sumatra earthquake and the 2010 Mw 8.8 Maule Chile earthquake. We transposed each slip distribution history onto the Hikurangi margin with the following constraints: no slip beyond the margin; no slip south of the Marlborough fault system and; location of an asperity-like slip near Wellington.

For the Tokachi-Oki source model, we used the slip distribution from Koketsu et al. (2004) (fig. 2). For the Sumatra source model, we used the slip distribution from Ji (2005) based on broadband teleseismic data (fig. 3). It is worth nothing that only the first 220 seconds could be constrained in the inversion, hence the solution represents a fault plane equivalent to a Mw 8.9 event. For the Maule source model, we used the slip distribution from Sladen (2010) obtained from inversion of broadband teleseismic data (fig. 4). A more detailed description of the source parameters for the selected historical subduction earthquakes can be found in Table 1.

Table 1 Source characteristics for the selected historical subduction earthquakes

Earthquake	**Reference**	**Rupture area (km^2)**	**Max slip (m)**	**Stress drop (MPa)**
Mw 8.3 Tokachi- Oki 2003 (Fig. 2)	Koketsu *et al.* (2004)	120 by 100	7 m	12 (Murotani *et al.,* 2008)
Mw 8.9 Sumatra 2004 (Fig. 3)	Chen Ji (2005)	400 by 180	19.82 m	10 (Buehler 2005)
Mw 8.8 Maule 2010 (Fig. 4)	Sladen (2010)	570 by 180	8.25 m	11 (Atkinson *et al.,* 2009).

4 SYNTHETIC TIME HISTORIES AND RESPONSE SPECTRA

Figure 5 and Figure 6 show respectively the synthetic time histories and response spectra computed for the various source models. Figure 6 includes the current spectral shape design levels for rock site condition in Wellington for the 500yr return period (normal structures, NZS1170) and 2500 yr return period (structures with special post-disaster function or dangerous activities). The average recurrence interval assigned to a magnitude 8.4 interface event in the NZ NSHM is 1000 years, although this value is subject to considerable uncertainty given the lack of large historical interface earthquakes in the region. For an average recurrence interval of 1000 years, the median ground motions associated with this event should have an average return period of at most 2000 years or less than this when the contributions of other earthquake sources are considered.

For variable stress-drop values (orange) there is a gradual increase in shaking intensity with increasing stress drop. Peak ground accelerations range from 0.2 to 0.6 g for stress drop of 3 and 15 MPa respectively. For low values of stress drop, the modelled response spectra are below the lowest level of design spectral shape for periods up to 2 seconds. However for larger stress-drop values, the design level at 2500yr is showing deficiencies for periods of 0.5 seconds and beyond. In this study, the

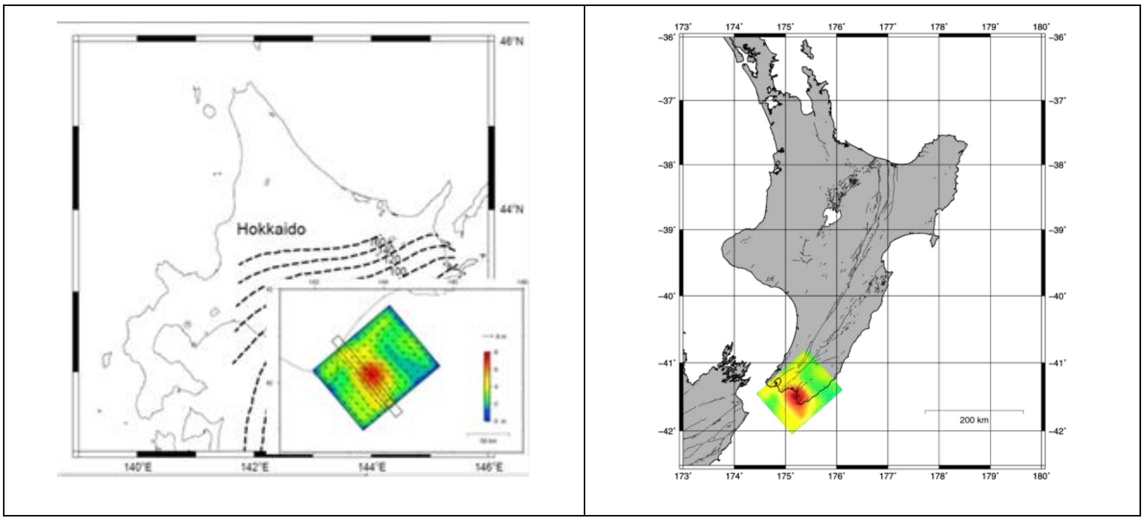

Figure 2: left: slip distribution of the 2003 Mw 8.3 Tokachi-Oki (Koketsu *et al.*, 2004); right: the same slip distribution pasted on the Hikurangi interface.

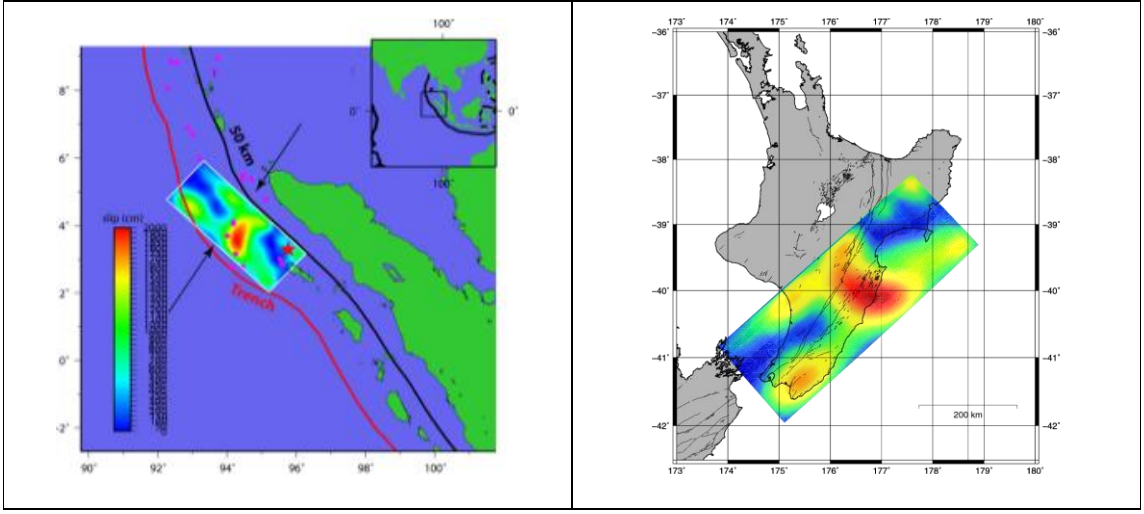

Figure 3: left: slip distribution of the M 9.1 (Mw 8.89) Sumatra earthquake (Ji 2005); right: the same slip distribution pasted on the Hikurangi interface.

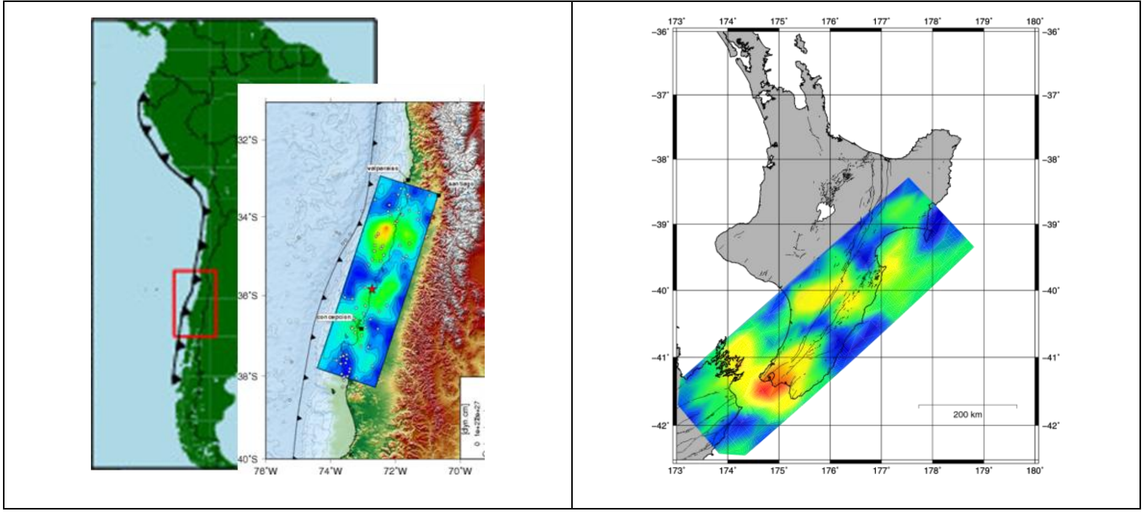

Figure 4: left: slip distribution of the 2010 Mw 8.8 Maule earthquake (Sladen 2010); right: the same slip distribution pasted on the Hikurangi interface.

models show that stress drop has a strong influence on shaking intensities and on the design levels of infrastructures. With no historical large earthquakes on the Hikurangi interface, it is currently difficult to assess stress drop values for future earthquakes, and therefore necessary to entertain all possible values.

For variable hypocentre locations (shades of pink), synthetic seismograms in Wellington show various characteristics in shaking intensities and durations: long durations but smaller intensities (0.33 and 0.43 g) for ruptures starting south of the fault plane, shorter durations and larger intensities (0.48 and 0.53 g) for ruptures starting north of the fault plane. However in terms of response spectra, the spectra for various hypocentre locations are very similar and highlight deficiencies in the 500yr design level for periods of 0.2 seconds and beyond, and deficiencies in the 2500yr design level for periods of 1 second and beyond.

For the asperity model (black), the peak synthetic acceleration is 0.47 g, which is consistent for a 9 MPa stress drop modelled event, and falls between a low stress-drop model and high stress-drop model of a Mw 8.4 event (orange colour). The synthetic response spectrum is showing deficiencies in the 500y and 2500y design levels for periods longer than 0.2 and 0.8 seconds respectively.

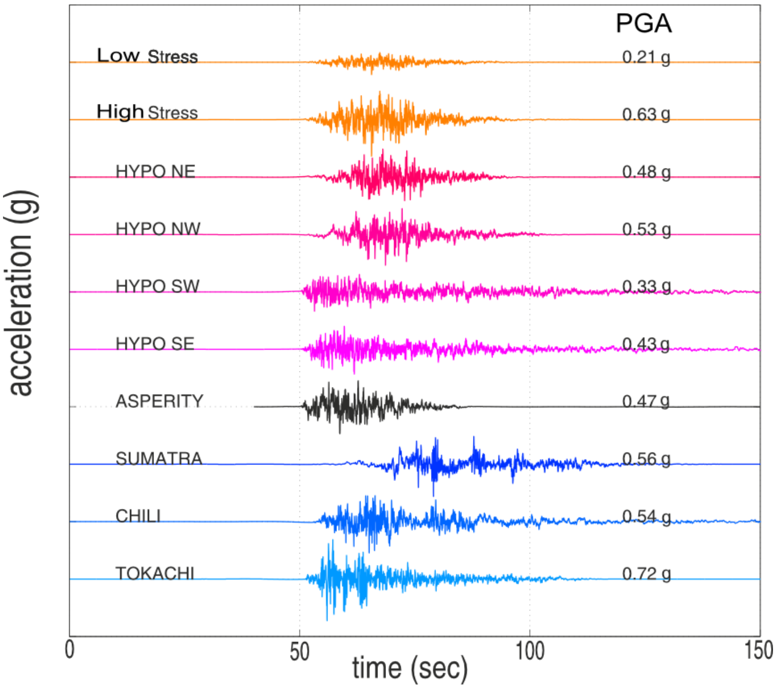

Figure 5: synthetic acceleration time-histories (g) for various rupture scenarios of the Hikurangi interface

For the worldwide historical earthquake sources (shades of blue), the synthetic seismogram for the Sumatra-like slip history shows the longest shaking duration; however the synthetic for the Tokachi-like slip history has the largest peak acceleration, 0.72 g against 0.54 and 0.56 g for Maule and Sumatra respectively. This cannot be explained from the slip distribution, as these events all present a large slip patch beneath the Wellington region. However the large acceleration can be explained from a larger stress-drop value for the Tokachi-like slip history (12 MPa against 11 and 10 MPa for the Maule and Sumatra models respectively). The synthetic response spectra both show higher response spectra than that of the 500yr design level (NZS1170) at all periods, and of the 2500yr design level for periods of 0.4 seconds and longer (fig. 6).

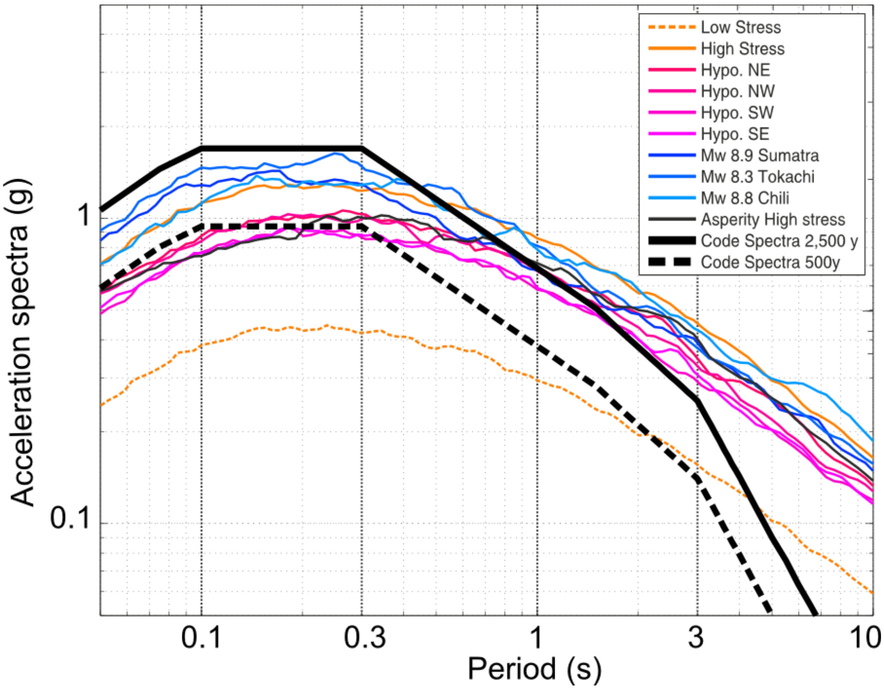

Figure 6: synthetic response spectra for various rupture scenarios of the Hikurangi interface

5 CONCLUSIONS AND FUTURE WORK

We have developed various Hikurangi subduction interface source models from physical principles, and by superimposing slip distributions from recent worldwide great subduction earthquakes onto the subduction zone. The synthetic earthquakes produced from these interface source models have been compared by way of acceleration time-histories (fig. 5) and response spectra (fig. 6). The response spectra also include the current spectral shape design levels for rock site condition in Wellington.

The resulting rupture scenarios all produce long duration shaking of 60+ seconds, and peak ground accelerations that, typically range between 0.2-0.7 g in Wellington city. Many of these scenarios also produce long-period motions that are currently not captured by the current NZ design spectra. We have found stress drop to be a major controlling factor in the ground motion models. At present, with very few records from interface events on the Hikurangi interface, we are not able to characterize stress drop directly from regional earthquakes. It is therefore necessary to entertain all possible values.

Future work will include refining the regional attenuation model using local earthquakes near the interface, defining a detailed source model based on the degree of coupling between the plates (as in Pulido, 2012), and including site effects in the ground motion estimation.

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