Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Progress Towards Hybrid Broadband Ground-Motion Simulation of Megathrust Earthquakes on the Hikurangi Subduction Zone

Michael Dupuis[1,4*], James M. Paterson[2], Robin L. Lee[3], and Brendon A. Bradley[3]

[1]PhD Candidate, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand
[2]Software Engineer, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand
[3]Professor, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand
[4]Senior Engineer, Geosyntec Consultants, Davis, CA, USA
[*]michael.r.dupuis@gmail.com (Corresponding Author)

ABSTRACT

The Hikurangi Subduction Zone in New Zealand can produce very large megathrust earthquakes similar to the 2004 Sumatra M_w9.2, 2010 Maule M_w8.8, and 2011 Tohoku M_w9.0 earthquakes. Although the associated ground motions would pose significant seismic hazard to much of New Zealand, the last known large earthquake of this type in New Zealand occurred around 1855 and therefore no observed ground-motion records are available. In this study, we present progress towards simulation of realistic ground motions from megathrust earthquakes along the Hikurangi Subduction Zone using physics-based hybrid broadband ground-motion simulation. Although ground-motion simulations have been previously performed for megathrust earthquakes on the Hikurangi Subduction Zone, this study is the first to incorporate simulation models validated using observed ground motions from subduction interface earthquakes in New Zealand. Ground-motion simulations will be conducted for probable scenarios to produce a distribution of ground-motion estimates of various intensity metrics for locations throughout New Zealand. Ground-motion sensitivity to rupture characteristics such as hypocentre location, subevent location, rupture velocity, and variation of subfault slip will be investigated and quantified. It is hoped that the interface-specific simulated waveforms and estimated ground-motion intensities will be useful for seismic hazard analysis, risk mitigation, and disaster preparedness.

Keywords: Ground Motion Modeling, Hikurangi Subduction Zone, Subduction Interface Earthquake, Megathrust Earthquake, New Zealand

INTRODUCTION

The Hikurangi Subduction Zone in New Zealand (NZ) has been identified as being capable of producing very large magnitude subduction megathrust earthquakes [1]; however, because this type of earthquake has not occurred in NZ since records began, likely rupture scenarios are relatively unconstrained and realistic ground motions are poorly quantified. The 2004 Sumatra M_w9.2, 2010 Maule M_w8.8, and 2011 Tohoku M_w9.0 megathrust earthquakes resulted in great loss of life, significant and widespread destruction of infrastructure, and provide the impetus to assess probable impacts from megathrust earthquake ground motions in NZ. In this paper, progress towards ground-motion simulation of megathrust earthquake scenarios on the Hikurangi Subduction Zone using physics-based ground-motion simulation and a compound rupture model is presented.

BACKGROUND

Hybrid Broadband Ground-Motion Simulation

This study uses the hybrid broadband ground-motion simulation approach [2]. Hybrid broadband ground-motion simulation is a physics-based method which combines a comprehensive 3D wave propagation solution at low frequencies with a simplified physics solution at high frequencies. The low- and high-frequency components are combined using a perfectly-matched 4th order Butterworth filter to produce a broadband ground motion.

Empirical ground-motion models could alternatively be used to provide estimates of earthquake ground-motion intensity metrics; however, these empirical models are based on global ergodic assumptions, limited datasets (which tend to be dominated by small-to-moderate magnitudes), and don't include explicit treatment of important features of megathrust ruptures. Meanwhile, physics-based ground-motion simulation can leverage improved characterization of salient source, path, and site characteristics validated on small- and moderate-magnitude earthquake ground motions, making it particularly useful for megathrust earthquake ground-motion prediction.

Subduction Megathrust Simulations in Published Literature

Both forensic simulation studies, which aim to recreate salient characteristics of past events (e.g., [3,4]), and scenario simulation studies, which aim to forecast likely characteristics for future events (e.g., [5,6]), have been conducted for global megathrust earthquakes. These studies generally implement various forms of a compound rupture model wherein the rupture model is comprised of a typically high-slip background rupture and smaller typically deep subevents with shorter rise times. Background and subevent rupture model properties for selected examples are summarized in Tables 1 and 2, respectively.

Table 1. Background rupture model properties of selected ground-motion simulation studies using compound rupture models: 2003 Tokachi-Oki M_w8.3 [4]; 2010 Maule M_w8.8 [3]; 2011 Tohoku M_w9.0 [7]; Cascadia M_w9.0 [6,8]; and Hikurangi M_w8.6 [5].

Background Rupture Model Property	2003 Tokachi-Oki M_w8.3	2010 Maule M_w8.8	2011 Tohoku M_w9.0	Cascadia M_w9.0 Scenario	Hikurangi M_w8.6 Scenario
Dimensions	100x100 km	150x530 km	200x380 km	-	120x630 km
Rupture velocity	3.5 km/s	2.5 km/s	2.2-2.8 km/s	2.3 km/s	80% V_s
Slip correlation	40x20 km	100x500 km	15x15 km	200x500 km	δ_{slip}=85%
Slip velocity	-	1.3 m/s	-	0.65 m/s	-
Peak slip	-	10 m	60 m	-	-

Table 2. Subevent rupture model properties of selected ground-motion simulation studies using compound rupture models: 2003 Tokachi-Oki M_w8.3 [4]; 2010 Maule M_w8.8 [3]; 2011 Tohoku M_w9.0 [7]; Cascadia M_w9.0 [6,8]; and Hikurangi M_w8.6 [5].

Subevent Rupture Model Property	2003 Tokachi-Oki M_w8.3	2010 Maule M_w8.8	2011 Tohoku M_w9.0	Cascadia M_w9.0 Scenario	Hikurangi M_w8.6 Scenario
Number	3	4	3	5	4
Magnitudes	M_w7.0-7.2	M_w7.9-8.2	M_w8.0	M_w8.0	M_w7.0-7.5
Areas	4-9x10^2 km^2	5-10x10^3 km^2	-	-	2-6x10^3 km^2
Location	Deep	Deep	-	Deep	Deep
Slip correlation	Smaller	50x50 km	15x15 km	50x50 km	δ_{slip}=85%
Slip velocity	Increased	5.4 m/s	15.0 m/s	5.4 m/s	-
Relative slip	Increased	Increased	-	Increased	Increased

PROGRESS TOWARDS HIKURANGI SCENARIO SIMULATIONS

Validated Simulation Models for Interface Ruptures

Subduction-specific simulation models validated for small- and moderate- magnitude subduction interface earthquake ground motions will be implemented as the median properties for the source rupture models. Stress parameter (bar), $\Delta\sigma$, for the background rupture will be modelled with linear dependence on depth (km), D: $\Delta\sigma = 10 + 1.25D$. Kinematic rupture velocity will be set as 75% of the shear wave velocity, V_s, at each subfault. Hypocentre depth will be located 10% of the rupture width down-dip from mid-depth. The coefficient of variation of slip across subfaults will be specified as 85%. These interface-specific rupture properties are compared with those validated for crustal [9] and slab earthquakes in Table 3.

Table 3. Selected median source rupture properties for interface ground-motion simulation compared with reference values for crustal and slab ground-motions.

	Interface	**Crustal**	**Slab**
Stress parameter (bar)	10+1.25D	50	50+2D
Rupture velocity (% of V_s)	75%	80%	90%
Hypocentre depth	10% down-dip	Mid-depth	Mid-depth
Coefficient of variation of slip (%)	85%	75%	75%

Source Generation for a Cascadia Megathrust Rupture Scenario

Although extensive physics-based ground-motion simulations have been done for earthquakes in New Zealand, these have generally considered small- to large-magnitude earthquakes. Megathrust earthquakes present several challenges. They need very large rupture models which require significant computational resources to generate and visualize. They have non-planar rupture geometries which are not accurately represented with planar fault segments due to their large size. Furthermore, there are high stress drop asperities which have been shown to have a dominant effect on strong ground motion generation [4] and require special treatment.

We have utilized a compound source rupture model which has been used previously for megathrust rupture scenarios on the Cascadia Subduction Zone [6,8]. This rupture model generator can handle very large and non-planar rupture geometries and includes explicit treatment of asperities by including high stress drop subevents surrounded by a larger background rupture.

We have modified the median properties for this rupture generator to include the interface earthquake ground-motion simulation models for hypocentre location, stress parameter, and rupture velocity validated on small- and moderate-magnitude interface earthquakes in NZ. A compound model for a median rupture scenario on the Cascadia Subduction Zone was developed in the Standard Rupture Format [10] for compatibility with the hybrid broadband simulation approach [2]. An example compound rupture model for Cascadia, which is comprised of single background rupture and five subevents, is shown in Figures 1 and 2.

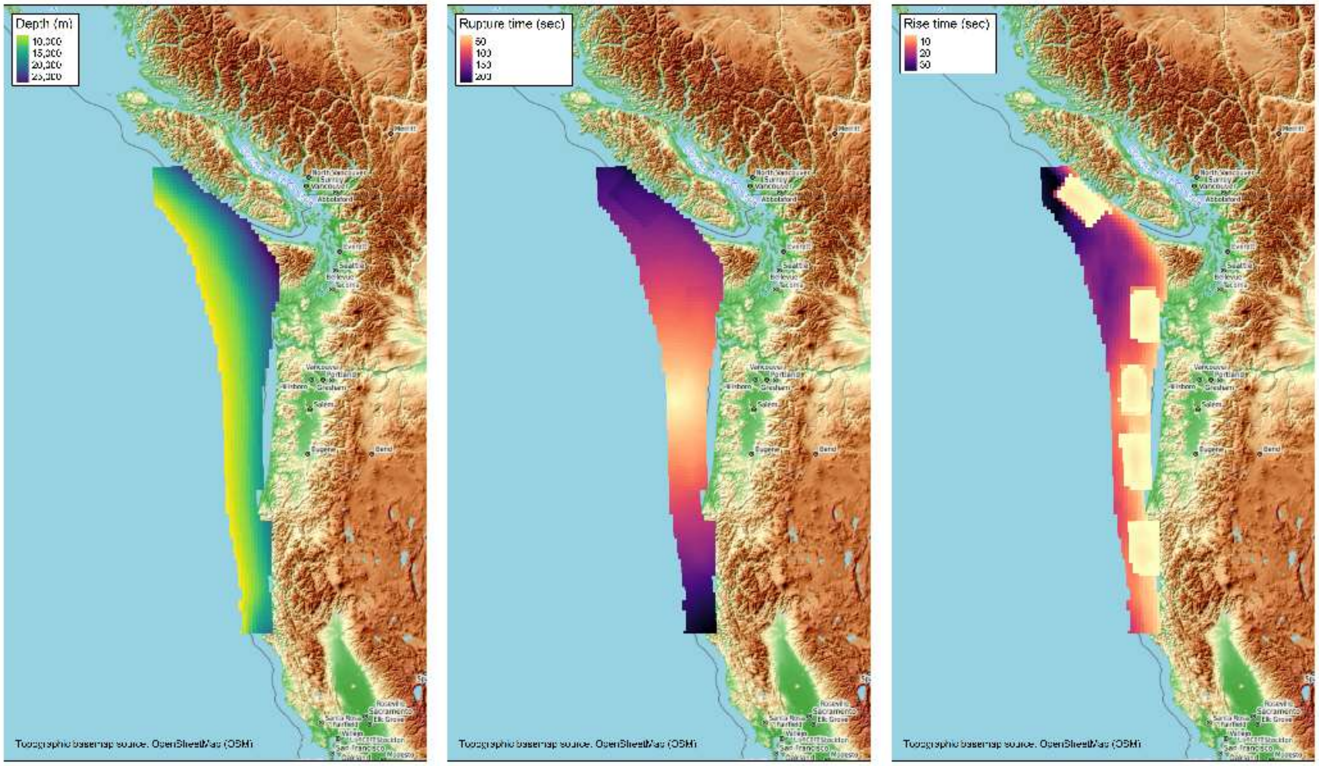
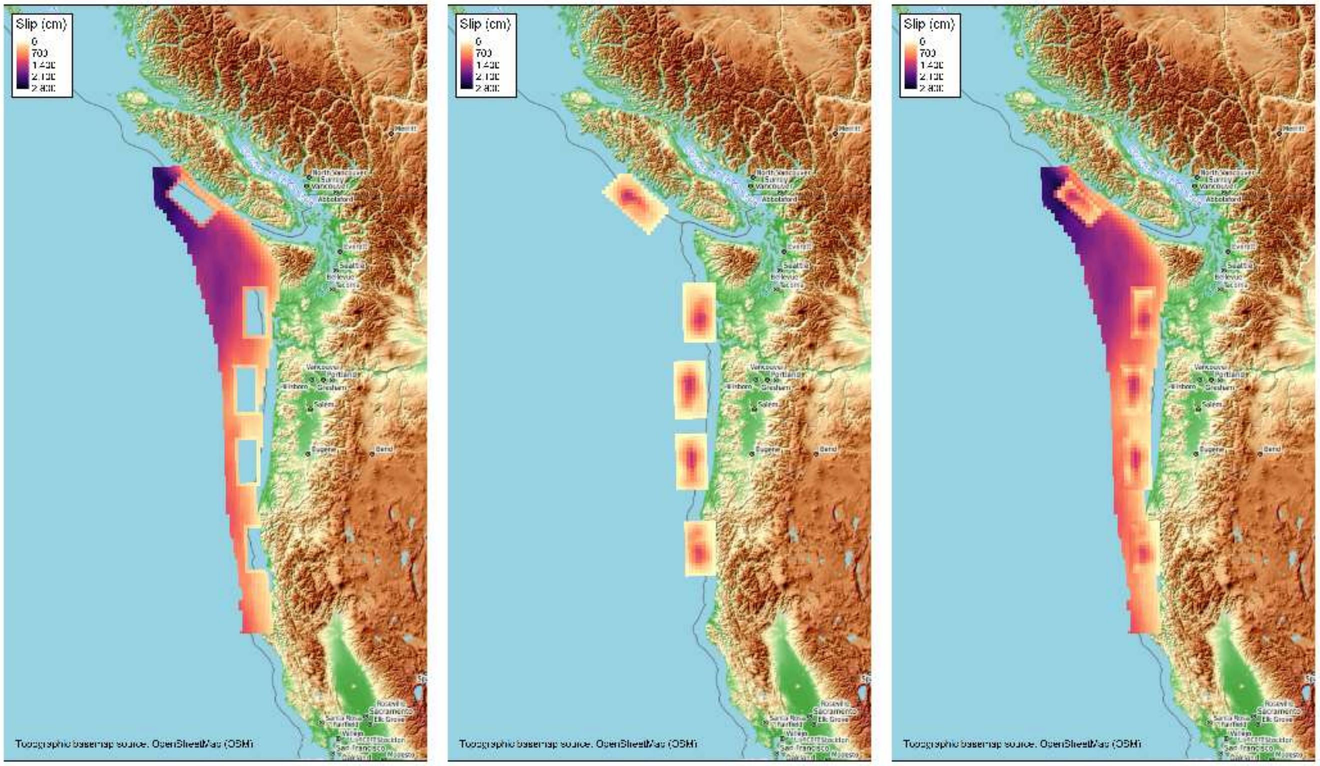


Figure 1. Depth (left), rupture time (centre), and rise time (right) for an example compound rupture model along the Cascadia Subduction Zone [6,8] in the Standard Rupture Format [10].



Topographic basemap source: OpenStreetMap (OSM)

Figure 2. Slip for the background (left), subevent (centre), and combined (right) rupture components for an example compound rupture model along the Cascadia Subduction Zone [6,8] in the Standard Rupture Format [10].

Hikurangi Source Rupture Model Generation

The next step in this study will be to develop compound source rupture models for megathrust ruptures along the Hikurangi Subduction Zone. Interface geometry for the Hikurangi interface [11], will be used to generate the rupture surface geometry. The up- and down-dip rupture extents will be guided by the seismogenic depths determined for the Hikurangi Subduction Zone [12].

Due to knowledge uncertainty of the on-fault stress and strength distribution, the source characteristics for a megathrust event are impossible to know in advance. To explore sensitivity of the simulated ground motions to various possible rupture characteristics, the main features of the rupture, which have been shown to significantly affect simulated ground motions (e.g., [4]) will be varied. This will result in a suite of multiple rupture scenarios that will be considered. Important rupture characteristics which will be explored in sensitive studies, as shown in Table 4, include: hypocentre location, rupture velocity, stress parameter, subevent location, and subevent magnitude.

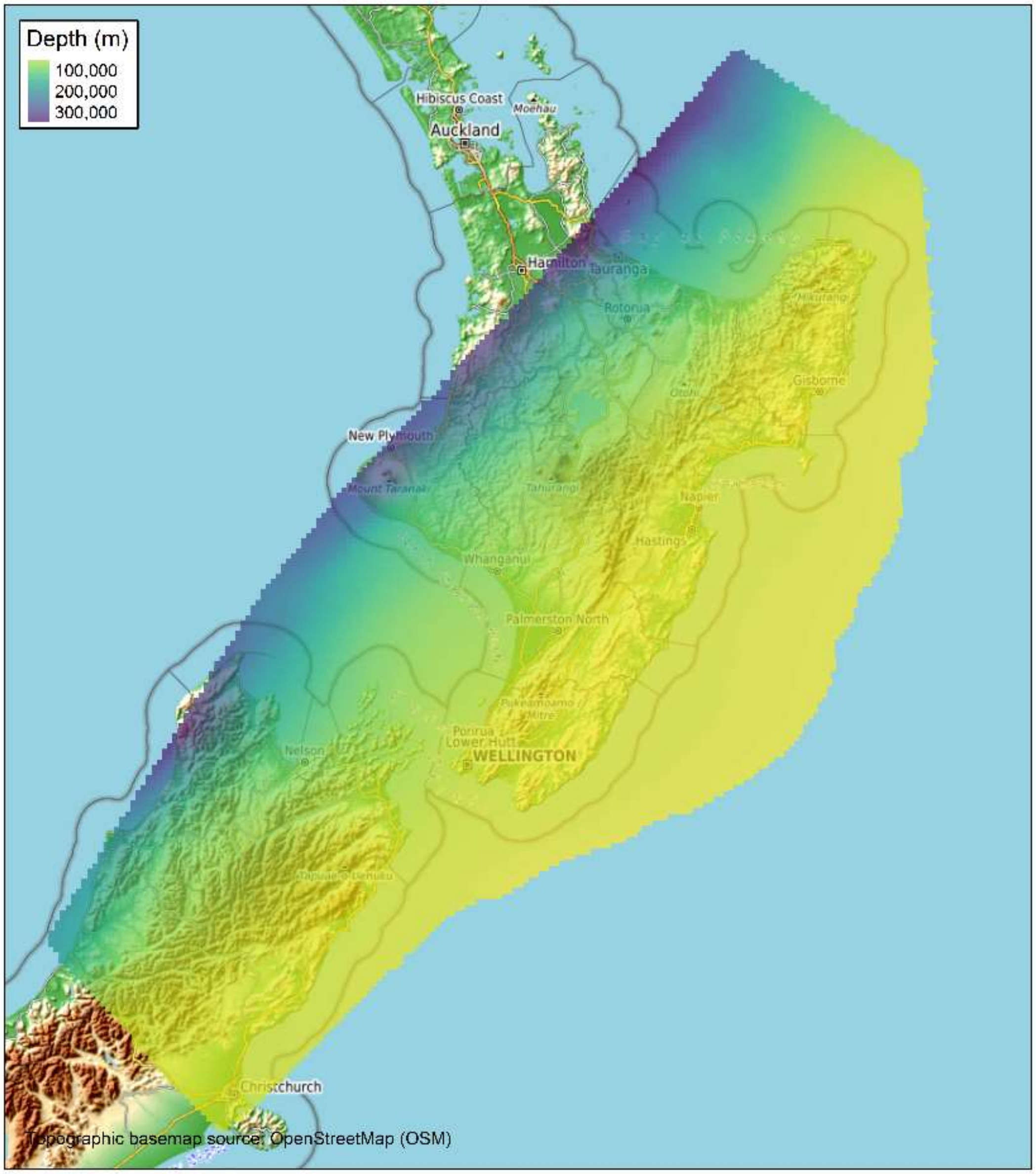
Table 4. Rupture characteristics to be investigated in sensitivity studies of multiple rupture scenarios where depths are relative to top of rupture as a percentage of rupture width, W, and positions are relative to the centre of the top of rupture as a percentage of rupture length, L.

	Property	**Median**	**Lower Limit**	**Upper Limit**
Subevents	Along-strike position	Mid-strike	-10% L	+10% L
	Along-dip depth	75% W	65% W	85% W
	Magnitude, M_w	7.9	7.7	8.1
Hypocentre	Along-strike position	Mid-strike	-50% AS	+50% AS
	Along-dip depth	60% W	0% W	100% W
Rupture	Rupture velocity (% of V_s)	75%	60%	90%
	Stress parameter (bar)	10+1.25D	5+0.625D	15+1.875D

Other rupture characteristics, such as lateral extent of the background rupture, number of subevents, and seismogenic depth have been shown by others (e.g., [4]) to have little effect on strong ground motion; therefore, only a single background rupture extent will be implemented and all scenarios will have 4 subevents similar to previous Hikurangi megathrust simulations [5].

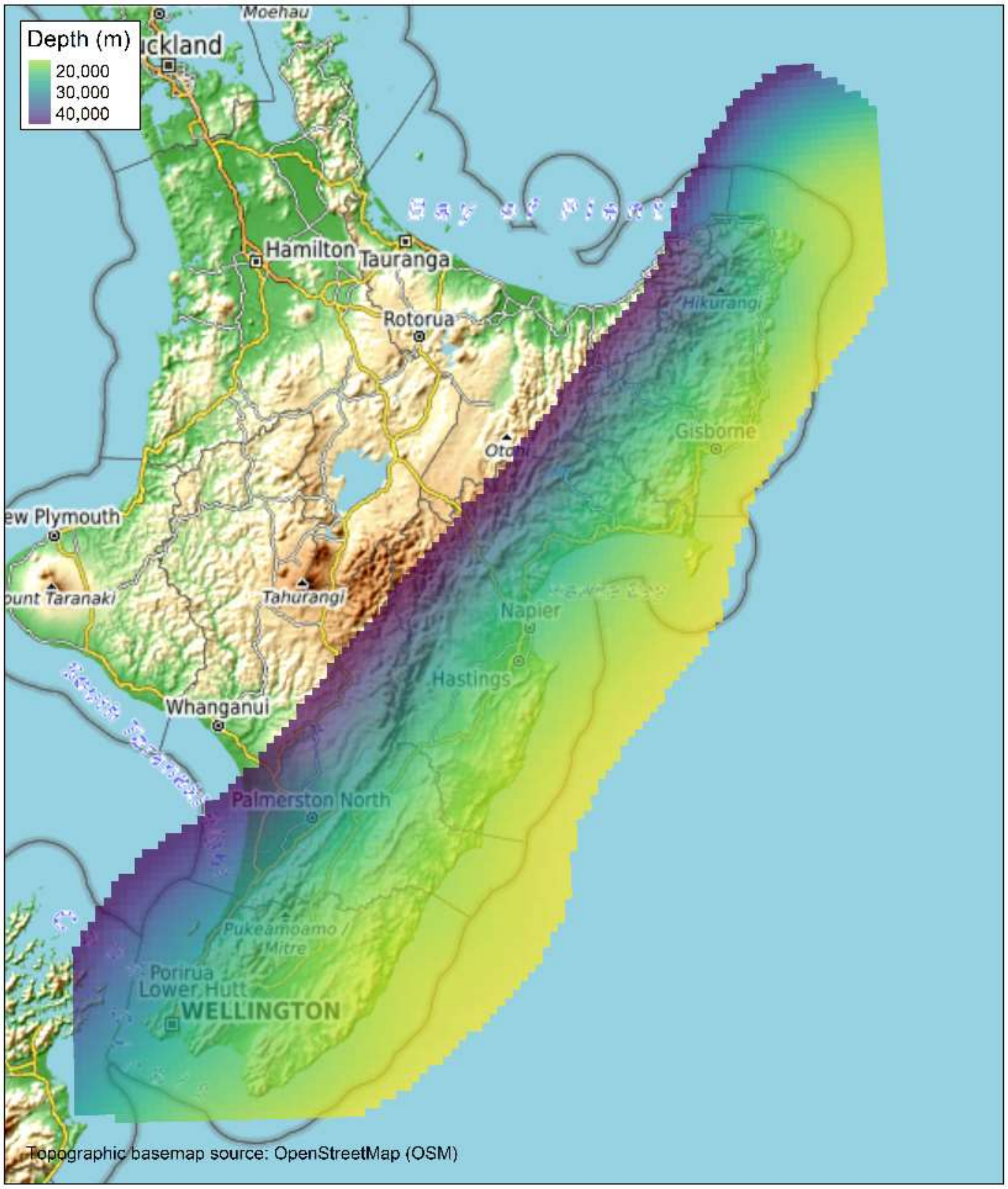
The southern rupture extent of the background rupture is likely bounded by the transition zone between the Marlborough fault system and the Hikurangi Subduction Zone due to fault system interactions at this transitional plate boundary [13]. The southern extent of the region of inter-seismic coupling for the Hikurangi Subduction Zone has been determined to be approximately along the Cook Strait which separates the North and South Islands [14]. In this study, the southern and eastern extent of the background rupture is set at the latitude and longitude of Lake Grassmere, respectively; this is a convenient selection which is close to the Cook Strait and Marlborough fault system transitions. The exact delineation of the southern rupture extent is expected to have only a small effect on the simulated ground motions [4].

The interface geometry for the Hikurangi Subduction Zone and the rupture extents within the seismogenic zone is shown in Figure 3 and 4, respectively.



Topographic basemap source: OpenStreetMap (OSM)

Figure 3. Interface geometry of the Hikurangi Subduction Zone [11].



Topographic basemap source: OpenStreetMap (OSM)

Figure 4. Interface geometry [11] within the seismogenic zone [12,14] for the compound rupture model to be used for megathrust rupture scenario simulations along the Hikurangi Subduction Zone.

CONCLUSIONS

Following the development of compound rupture models for various rupture scenarios, ground-motion simulations will be conducted for NZ. Ground motions from the Hikurangi rupture scenarios are expected to produce significant ground motions throughout New Zealand. This study will offer an opportunity to investigate several important considerations with implications for NZ and ground-motion prediction for megathrust subduction earthquakes:

- Comparison of simulated ground motions (median and standard deviation) with maximum historical ground-motion intensities across NZ.
- Comparison of median simulated ground motions with predictions from empirical ground-motion models for subduction earthquakes.
- Investigation of the most severe rupture scenarios for cities across NZ and discussion of the ground-motion-driving rupture characteristics for each region.

ACKNOWLEDGMENTS

Thanks to Erin Wirth and Art Frankel for generously assisting with the implementation of the compound rupture model for the Hikurangi Subduction Zone and for sharing their code for generation of compound rupture models in Cascadia.

This project was supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded centre, and the Commonwealth Scholarship and Fellowship Plan funded by the Government of Canada. High performance computing resources were provided through the NeSI merit allocation.

REFERENCES

[1] Wallace, L.M., Reyners, M., Cochran, U., Bannister, S., Barnes, P.M., Berryman, K., Downes, G., Eberhart-Phillips, D., Fagereng, A., Ellis, S. and Nicol, A. (2009). "Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand". *Geochemistry, Geophysics, Geosystems*, 10(10).

[2] Graves, R. and Pitarka, A. (2015). "Refinements to the Graves and Pitarka (2010) Broadband Ground-Motion Simulation Method". *Seismological Research Letters*, Vol 86. 10.1785/0220140101.

[3] Frankel, A. (2017). "Modeling Strong-Motion Recordings of the 2010 M_w 8.8 Maule, Chile, Earthquake with High Stress-Drop Subevents and Background Slip Modeling Strong-Motion Recordings of the 2010 M_w 8.8 Maule, Chile". *Bulletin of the Seismological Society of America*, 107(1), pp.372-386.

[4] Wirth, E.A., Frankel, A.D. and Vidale, J.E. (2017). "Evaluating a Kinematic Method for Generating Broadband Ground Motions for Great Subduction Zone Earthquakes: Application to the 2003 M_w 8.3 Tokachi-Oki Earthquake", *Bulletin of the Seismological Society of America*, 107(4) pp.1737-1753.

[5] Bayless, J., Skarlatoudis, A., Somerville, P. and Pitarka, A. (2019). "Rupture model of a Hikurangi M_w 8.6 megathrust earthquake". *Proceedings of the 2019 Pacific Conference on Earthquake Engineering and Annual NZSEE Conference*.

[6] Frankel, A., Wirth, E., Marafi, N., Vidale, J. and Stephenson, W. (2018). "Broadband Synthetic Seismograms for Magnitude 9 Earthquakes on the Cascadia Megathrust Based on 3D Simulations and Stochastic Synthetics, Part 1: Methodology and Overall Results". *Bulletin of the Seismological Society of America*, 108(5A), pp.2347-2369.

[7] Frankel, A. (2013). "Rupture history of the 2011 M 9 Tohoku Japan earthquake determined from strong-motion and high-rate GPS recordings: Subevents radiating energy in different frequency bands". *Bulletin of the Seismological Society of America*, 103(2B), pp.1290-1306.

[8] Wirth, E.A., Frankel, A.D., Marafi, N., Vidale, J.E. and Stephenson, W.J. (2018). "Broadband synthetic seismograms for magnitude 9 earthquakes on the Cascadia megathrust based on 3D simulations and stochastic synthetics, Part 2: Rupture parameters and variability". *Bulletin of the Seismological Society of America*, 108(5A), pp.2370-2388.

[9] Lee, R., Bradley, B., Graves, R., Paterson, J. and Motha, J. (2021). "Source modelling insights from ground motion simulation validation of moderate magnitude active shallow crustal earthquakes in New Zealand". *Proceedings of the 2021 Annual NZSEE Conference*.

[10] Graves, R. (2006). Standard Rupture Format. http://equake-rc.info/static/paper/SRF-Description-Graves_2.0.pdf

[11] Williams, C.A., Eberhart-Phillips, D., Bannister, S., Barker, D.H., Henrys, S., Reyners, M. and Sutherland, R. (2013). "Revised interface geometry for the Hikurangi subduction zone, New Zealand". *Seismological Research Letters*, 84(6), pp.1066-1073.

[12] Hayes, G.P., Moore, G.L., Portner, D.E., Hearne, M., Flamme, H., Furtney, M. and Smoczyk, G.M. (2018). "Slab2, a comprehensive subduction zone geometry model". *Science*, 362(6410), pp.58-61.

[13] Pizer, C., Clark, K., Howarth, J., Garrett, E., Wang, X., Rhoades, D. and Woodroffe, S. (2021). "Paleotsunamis on the southern Hikurangi subduction zone, New Zealand, show regular recurrence of large subduction earthquakes". *The Seismic Record*, 1(2), pp.75-84.

[14] Wallace, L.M., Beavan, J., Bannister, S. and Williams, C. (2012). "Simultaneous long-term and short-term slow slip events at the Hikurangi subduction margin, New Zealand: Implications for processes that control slow slip event occurrence, duration, and migration". *Journal of Geophysical Research: Solid Earth*, 117(B11).