Simulation-based ground motion prediction of historical and future New Zealand earthquakes and consequent geohazard impacts

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ABSTRACT

The utilization of end-to-end simulation for ground motion and consequent geohazard prediction in New Zealand (NZ) is presented. Validation of recent damaging earthquakes, as well as a large number of small-to-moderate magnitude earthquakes, illustrates that physics-based ground motion simulation methods can presently provide prediction accuracy and precision that is comparable to, and often exceeding, those from conventional empirical models. This predictive confidence enables the possibility of simulation-based probabilistic seismic hazard analyses, for which recently-commenced work is presented. These simulation-based ground motions are subsequently used to quantify the consequent liquefaction and landslide geohazards using geospatial models, including the computation of geohazard risk over a certain exposure period. The efficacy of geospatial liquefaction models in NZ is discussed through comparison with observations and predictions from conventional geotechnical liquefaction methods and the ability to combine multiple methods via ensemble modelling.

PHYSICS-BASED GROUND MOTION SIMULATION

Earthquake-induced ground motion prediction is presently under-going a paradigm shift from the empirical prediction of ground motion intensity measures (IMs, e.g. PGA, SA), based on regression analysis of observed IMs from past earthquakes, toward the use of physics-based simulation methods that directly predict the ground motion time series (i.e. multi-component acceleration as a function of time). This paradigm shift is occurring as a result of (Bradley 2017): (i) diminishing returns offered from the continual efforts in empirical ground motion modeling; (ii) recent well-recorded earthquakes illustrating that, even now, physics-based simulation methods provide predictions that are comparable to, or even superior than, those from empiricallybased predictions; and (iii) the physics-based nature of such simulations provides a natural framework within which a substantially greater volume of data from seismological observations can be synthesized, enabling the seamless incorporation of region and site-specific features, and thus promising appreciable improvements in the ability to reduce prediction uncertainties in the coming years, and realizing the flow-on benefits in the seismic design and assessment of built infrastructure. Three significant recent earthquakes are used below to illustrate the comparative performance of such simulations relative to conventional empirical models.

The 2010 Darfield and 2011 Christchurch earthquakes (as part of the Canterbury earthquake sequence) and the 2016 Kaikoura earthquake, whose locations are noted in Figure 1, are the most significant earthquake events to occur over the past decade in NZ. Because of their geographical proximity, rupture complexity, and the dense network of strong motion stations in the region, these events also provide a significant opportunity for the examination of ground motion features and validation of ground motion prediction methods.

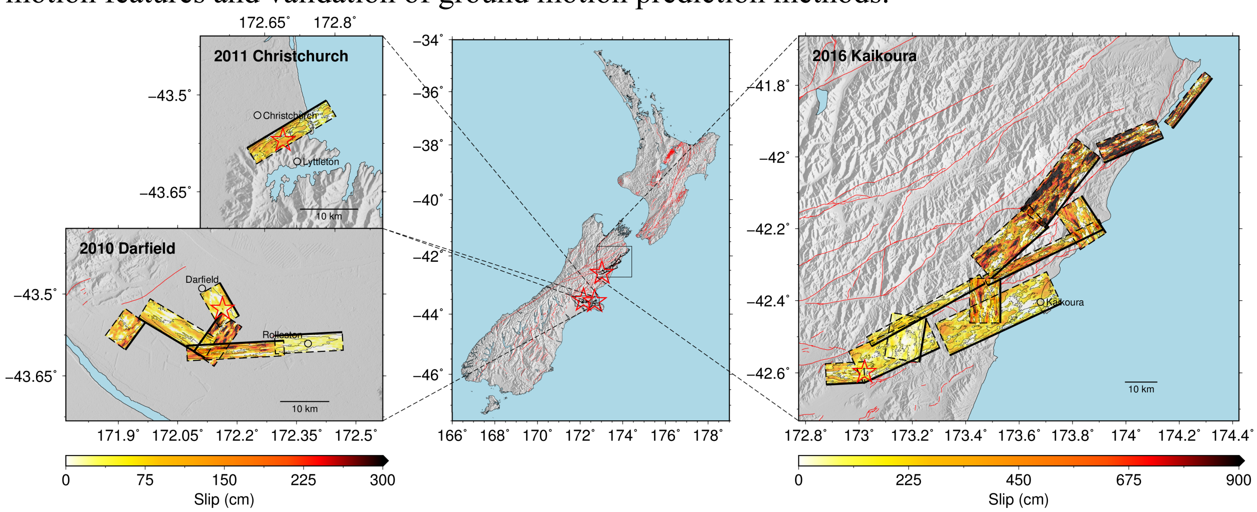

Figure 1. Location of the 2010 Mw7.1 Darfield, 2011 Mw6.2 Christchurch, and 2016 Mw7.8 Kaikoura Earthquakes. Slip amplitudes for the 2010 and 2011 events have the same color scale, but a different scale is used for the (larger) Kaikoura event.

Ground motion prediction using empirical and physics-based methods have been previously presented for these three events (Bradley et al. 2015, 2017; Razafindrakoto et al. 2017), to which the reader is referred, and here attention is restricted to a summary of the insights from such validation.

Physics-based ground motion predictions for these three earthquakes (Bradley et al. 2015, 2017; Razafindrakoto et al. 2017) utilized the Graves and Pitarka (2010) methodology, a 'hybrid' approach in which the low frequency (LF) waveforms are ‘comprehensively’ computed by solving the elastodynamic equation in a 3D crustal model domain, while the high frequency (HF) waveforms utilize a phenomenological ‘simplified physics’ approach. The seismic source is prescribed via kinematic rupture generator (Graves and Pitarka 2010), with extensions to consider multi-segment ruptures for the 2010 Darfield and 2016 Kaikoura earthquakes, as described in the aforementioned references. Importantly, the same modelling parameters are used for all simulations, and the seismic source is described based on only the fault geometry, hypocenter and magnitude (i.e. no slip inversion information is utilized), in order to ensure that retrospective validation is consistent with that which would be used in prospective prediction.

Figure 2 illustrates the spatial distribution of simulated peak ground velocity for the three events which, in particular, highlights the importance of source directivity and sedimentary basin effects on amplifying surface ground motions. The role of source directivity is least pronounced in the 2011 Christchurch earthquake because of its moderate magnitude and general misalignment of the direction of rupture propagation and slip vectors (Bradley and Cubrinovski 2011). Directivity in the 2010 Darfield earthquake was most pronounced in central and northern Christchurch as a result of the west-to-east rupture of the Greendale fault (Bradley 2012). Finally, while the 2016 Kaikoura earthquake was the result of an exceptionally complex multi-segment rupture, strong directivity effects were present in the north eastern part of the South Island and the Wellington region as a result of the general south-to-north rupture propagation direction (Bradley et al. 2017).

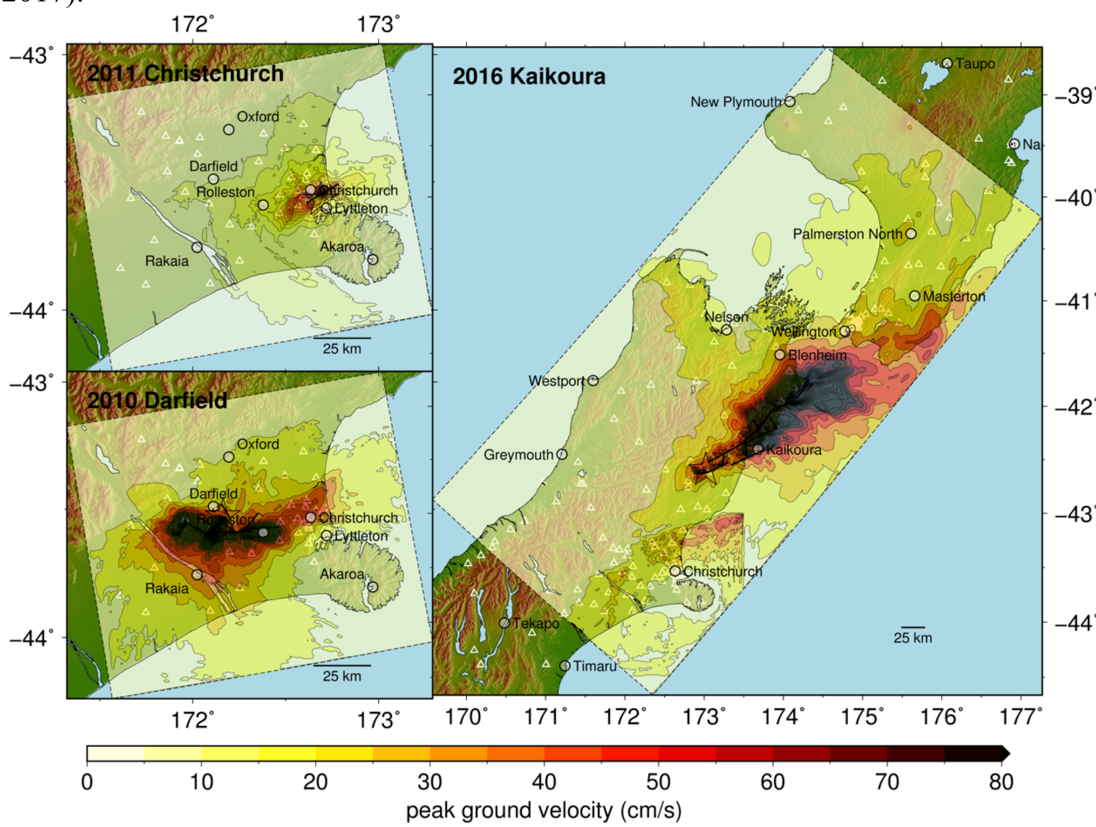

Figure 2. Simulated peak ground velocities for the 2010 Darfield, 2011 Christchurch, and 2016 Kaikoura events. Strong motion station locations, which recorded the consequent ground motions, are shown in white triangles.

Simulation validation

Validation is central to develop confidence in the predictive capability of computational simulations, and the validation for each of the aforementioned three simulated events are presented in detail in their respective references. As a summary of the predictive capabilities, Figure 3 illustrates the mean, and ± one standard deviation range of the prediction residuals for each of the three earthquake events as a function of pseudo-spectral acceleration vibration period. The residual is defined as the logarithm of the observations divided by the ground motion model (GMM; either the physics-based or empirical prediction). For the 2011 Christchurch and 2010 Darfield events it can be seen that the physics-based and empirical residuals have a similar mean at short vibration periods (T<1s), for which the physics-based prediction is dominated by the HF 'simplified physics' portion of the simulation. At long periods (T>1s) in these two events, the physics-based prediction tends to outperform the empirical prediction, illustrating the benefit of the 'comprehensive physics' in the LF portion of the simulation. Finally, in the 2016 Kaikoura event it can be seen that the physics-based simulation performs better than the empirical prediction at short periods (T<1s), principally because of its ability to consider the amount of slip on each of the multiple fault segments, whereas the empirical model simply uses the source-to-site distance based on the nearest fault segment (Bradley et al. 2017). At long periods (T>2s) it can be seen that both physics-based and empirical predictions exhibit bias, in opposite directions, principally due to the uncertainty in the source characterization of this recent event.

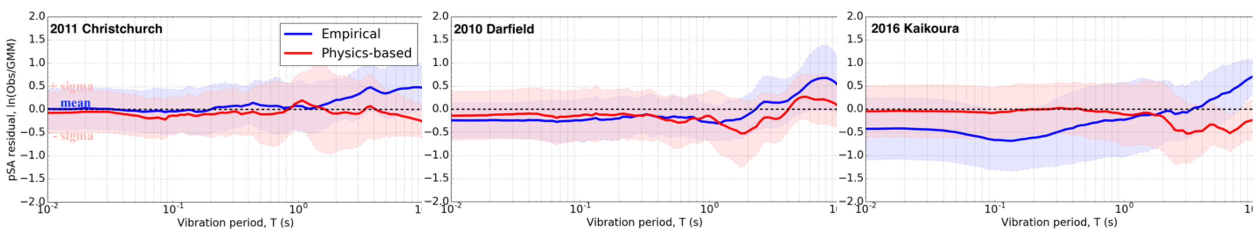

Figure 3. Comparison of spectral acceleration residual distribution as a function of vibration period for the three considered events based on physics-based and empirical ground motion predictions. The solid line represents the mean of the residual distribution and the shaded region the ± one standard deviation range.

While ground motions from larger magnitude events at small source-to-site distances are of principal focus, because they typically dominate the seismic hazard in active regions, the consideration of ground motions from smaller magnitude events naturally enables a significant increase in the observational data which can be utilized for simulation validation. The appropriateness of using ground motion records from small magnitude earthquakes for 'testing' the applicability of empirical ground motion models for larger magnitude events has long being a topic of debate. However, the physics-based nature of ground motion simulation methods provide a rational framework in which to evaluate the predictive capability of various model 'components'. Of course, the use of small magnitude earthquakes for validation offers limited (if any) ability to examine kinematic source rupture or nonlinear near-surface site response modelling, but observational data can be used for validation of the considered crustal (velocity) model.

Despite this obvious need, extensive region- and site-specific simulation validation has not yet become commonplace. Figure 4a provides one example from Lee (2017), in which 144 Mw=3.5-5.0 earthquakes in the Canterbury, NZ, region were used to validate the commonlyadopted Graves and Pitarka (2015) simulation method. This validation dataset consisted of 1819 ground motions for validation and enabled Lee (2017) to systematically identify several simulation features that can be refined in order to provide improved predictions in this region, as well as likely biases in the adopted crustal model. Such improvements are also likely to result in improved validation outcomes for the larger magnitude event simulations that were presented in the previous section. In this regard it should be recognised that these 144 events in Figure 4a represent only about 8% of the 1731 Mw=3.5-5.0 earthquakes recorded in NZ under the GeoNet programme to date (since 2003), as shown in Figure 4b, with another 129 events for Mw>5.0. These additional events are currently being simulated by the authors. Ultimately, validation over the full spectrum of ground motion intensity levels is likely to accelerate the improvement of simulation methods themselves, as well as provide further statistical evidence of their fidelity relative to empirical prediction models.

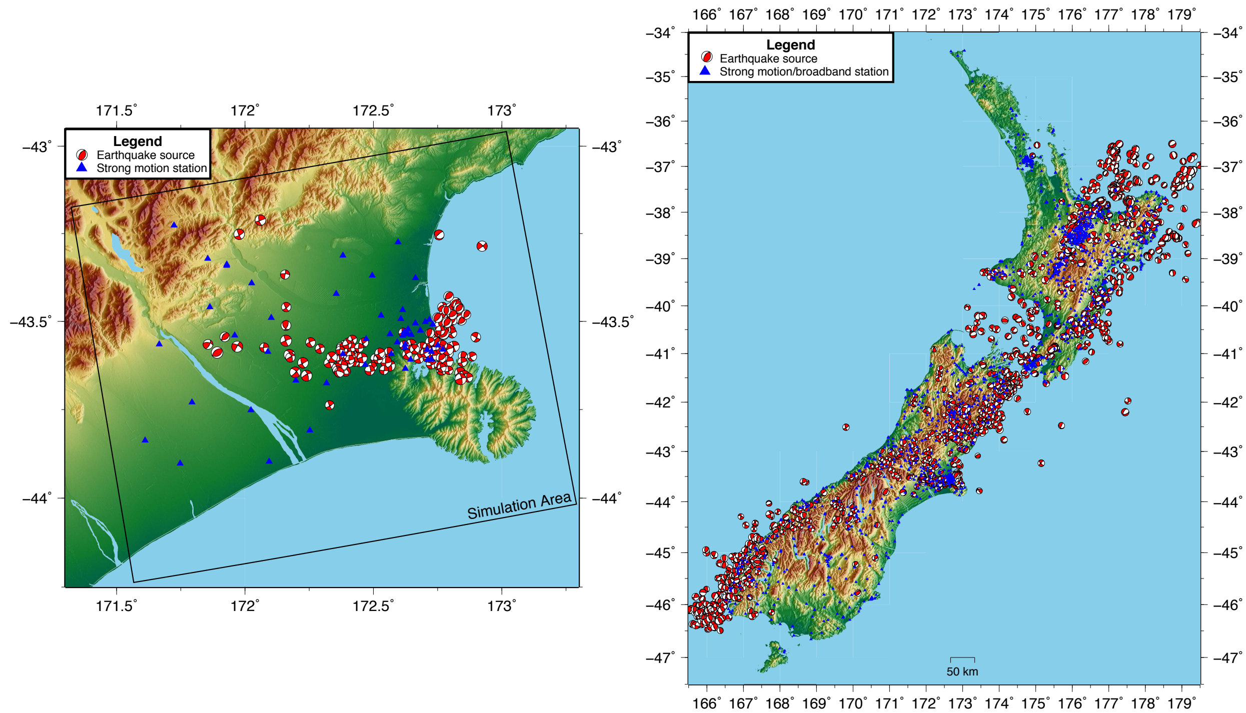

Figure 4: (a) 144 M_w = 3.5−5.0 earthquakes, providing 1819 ground motions at 53 strong motion stations, considered by Lee (2017) in simulation validation of the Graves and Pitarka (2015) method for the Canterbury, NZ region; and (b) 1731 M_w = 3.5 − 5.0 earthquakes recorded in NZ under the GeoNet programme (2003-2017 inclusive) that could be used for simulation validation.

Simulation-based probabilistic seismic hazard analysis

The demonstrated validity of physics-based ground motion simulation methods enables simulations for future earthquakes to be used for seismic hazard analysis and subsequent seismic design and assessment.

Several efforts have examined the use of simulated ground motions for probabilistic seismic hazard analysis (PSHA), most notably the pioneering 'Cybershake' work by the Southern California Earthquake Centre (Graves et al. 2011). More recently, similar Cybershake analyses have commenced in NZ. Figure 5 illustrates the active shallow crustal fault sources in NZ considered by Tarbali et al. (2018). For each fault source considered, different rupture realizations are developed based on varying the location of the earthquake hypocenter and co-seismic slip distribution over the fault surface.

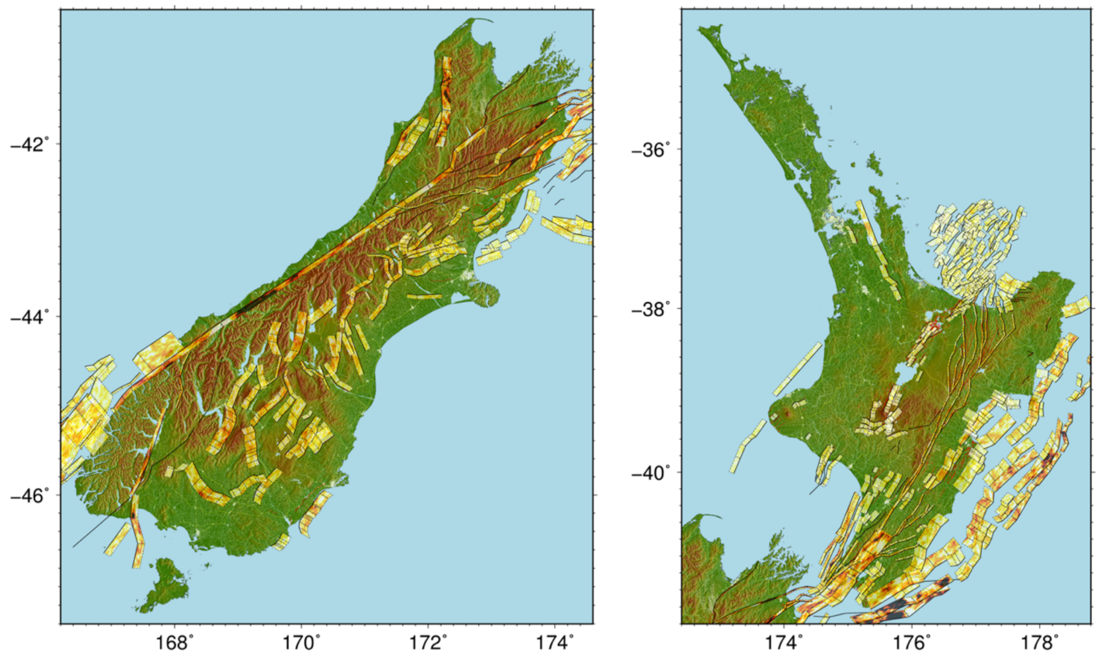

Figure 5. Shallow crustal finite faults considered in the current version of New Zealand simulation-based PSHA (after Tarbali et al. (2018)).

The output from the ensemble of ground motion simulations is aggregated to obtain PSHA hazard curves for a specific intensity measure, *IM*, in the conventional manner as follows:

$$\lambda_{IM}(im) = \sum_{n=1}^{N_{rup}} P_{IM|Rup}(im|rup_n)\lambda_{Rup}(rup_n) \qquad (1)$$

where $\lambda_{IM}(im)$ is the seismic hazard curve defining the exceedance rate of $IM > im$; $\lambda_{Rup}(rup_n)$ is the annual occurrence rate of $Rup = rup_n$; $P_{IM|Rup}(im|rup_n)$ is the probability of $IM > im$ given $Rup = rup_n$; and N_{rup} is the number of ruptures considered. For a given earthquake rupture, a uniform probability of hypocenter and slip realizations is considered such that $P_{IM|Rup}$ simplifies to the counted proportion of simulations (for that rupture) which exceed *IM*=*im* (i.e. these uncertainties, among others, give rise to the uncertain ground motion intensity for a given source rupture); see Graves et al. (2011) for further details.

It is also important to note that PSHA hazard curves can be computed that make use of both simulation and empirical GMMs. This is advantageous where computational capacity may limit the total number of simulations that can be performed; thus forcing a trade off between the number of simulations per fault to account for rupture uncertainties, and the number of different faults to simulate. In general, given that not all seismic sources comprise a significant portion of the total seismic hazard, it is logical to devote the majority of available computational capacity to those faults representing the largest hazard.

Figure 6 illustrates a seismic hazard curve from Tarbali et al. (at a location in Canterbury, NZ: Lat: -43.3759, Lon: 172.011), in which the seismic hazard is comprised of simulated ground motions from a subset of faults (Type A); and empirically-predicted ground motions from another subset of faults (Type B), and also distributed seismicity. In this case, Tarbali et al.'s result represents a work-in-progress, where eventually all Type B faults will also utilize simulated ground motions. The in-progress nature of the work by Tarbali et al. also means that the total number of hypocenter and slip realizations considered for each source rupture is not extensive (hypocenters every 20km along strike, and three slip realizations per hypocentre) – which likely leads to an underestimate in the ground motion uncertainty for a given rupture. This is the principal reason for the different 'shape' of the simulation-based hazard curve from Type A faults shown in Figure 6.

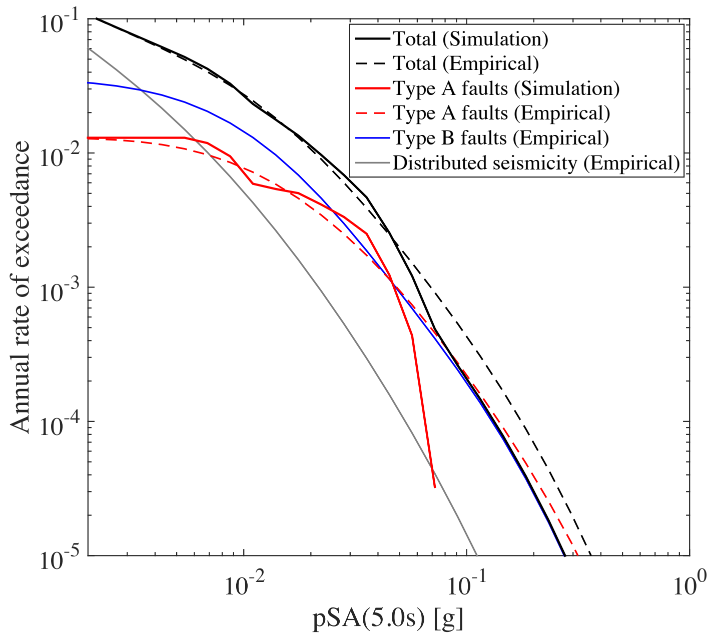

Figure 6: Illustrative seismic hazard curves based on simulation and empirical GMM, and disaggregated by fault and distributed seismicity sources (after Tarbali et al. (2018)).

The discussion to date between empirical and simulation-based GMMs has been purposefully adversarial to enhance comparison. However, in reality, these competing models simply represent two different approaches for the prediction of ground motions in the same manner that two different empirical GMMs also provide different predictions. Since it is conventional to consider multiple empirical GMMs in a logic tree for the purpose of ensemble modelling in PSHA, simulation-based GMMs are expected to become an increasingly important addition to conventional PSHA logic trees. The weighting (representing degree-of-belief that any given model best represents reality in comparison to the alternatives) given to each model in the logic tree should be a function of their predictive capabilities as established through validation. Thus, over time, methods with improving predictive power (which is expected for physics-based simulation methods) are expected to predominate.

REGIONAL LIQUEFACTION SIMULATION

The additional spatial resolution of ground motion prediction that can be realized via simulation-based methods can advance the ability to provide site-specific assessment of consequent geohazards. In this and the following section, ongoing research coupling simulated ground motion outputs with liquefaction and landslide modelling is presented.

Geospatial methods

Similar to empirical ground motion simulation, the majority of liquefaction assessments have used an empirical method that has remained fundamentally unchanged over the past 50 years (the so-called ‘simplified procedure’ in industry parlance, but referred to herein as ‘geotechnical liquefaction’ models). While advances in computing, numerical methods, and soil constitutive modelling have enabled an increase in the adoption of nonlinear effective stress analyses, hindrances in the necessary operator skill and input data mean they are still well below the ‘knee’ of their adoption S-curve.

In contrast to the nonlinear effective stress analyses, the explosion of geospatial datasets has enabled the rapid development and application of geospatial models for predicting liquefaction susceptibility and severity over the recent past (Baise et al. 2012; Zhu et al. 2017). Zhu et al. (2017) represents a 2nd-generation geospatial liquefaction model (and is used here for the purpose of example) which is a function of peak ground velocity, 30-m averaged shear wave velocity, V_{s30}, precipitation, distance to coast and rivers, and water table depth. Figure 7a illustrates the liquefaction susceptibility of NZ based on the Zhu et al. model (where the susceptibility categories are: very low, low, medium, high, very high), while Figure 7b and c illustrates the areal liquefaction probabilities for the 22 February 2011 Christchurch and 14 November 2016 Kaikoura earthquakes based on the PGV simulated in Figure 2.

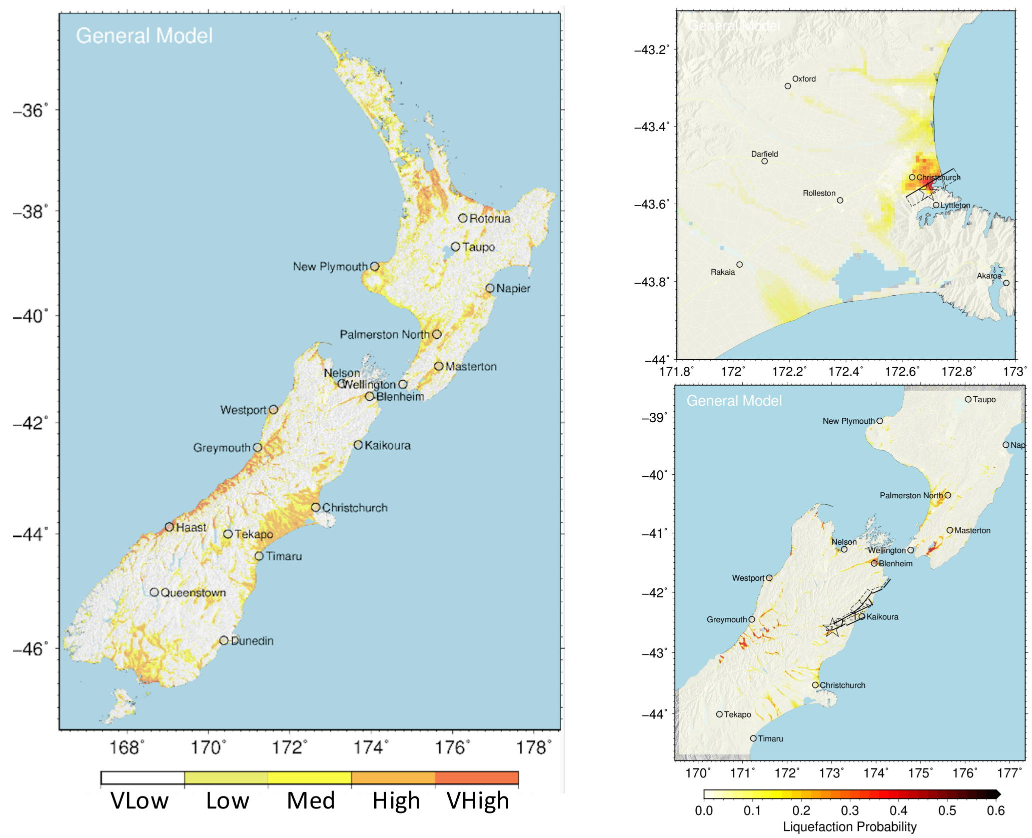

Figure 7: Liquefaction hazard based on Zhu et al.: (a) susceptibility across NZ; and areal probability in the (b) 22 February 2011 Christchurch; and (c) 4 November 2016 Kaikoura earthquakes.

While it is somewhat evident that geospatial models have limited ability to explicitly represent the subtle effects associated with liquefaction, conventional geotechnical liquefaction models also provide imprecise predictions. For example, in the context of the 22 February 2011 Christchurch earthquake, Figure 8 illustrates the observed liquefaction severity (Figure 8a) and that predicted in the form of LSN based on a simplified geotechnical liquefaction models. While the prediction and observations are generally consistent in a broad context, detailed location-by-location assessment reveals discrepancies between the approaches, which have been examined at length in the literature (Green et al. 2014; Maurer et al. 2014, 2015), including underlying mechanistic reasons for the discrepancies (Cubrinovski et al. 2017). Figure 7b illustrates that the geospatial prediction of high liquefaction probabilities east of the Christchurch CBD is also consistent with the area of observed liquefaction noted in Figure 8a.

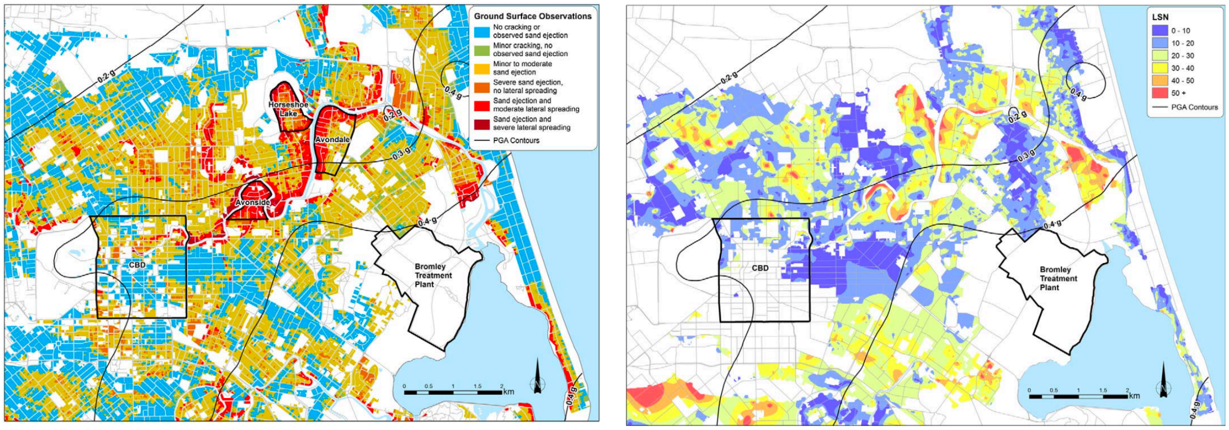

Figure 8: Liquefaction surface manifestation severity during the 22 February 2011 Darfield earthquake: (a) observed; and (b) predicted via the Liquefaction Severity Number, LSN (after van Ballegooy et al. (van Ballegooy et al. 2014))

While the development of geospatial liquefaction models are still in their infancy (models of the current form appearing as early as 2012 (Baise et al. 2012)), their ease of development has also already enabled utilization of data from 27 global earthquakes (Zhu et al. 2017), a number similar to the 23 events with data considered by most simplified geotechnical liquefaction models (Maurer et al. 2017).

Maurer et al. (2018) recently provided the first direct examination of the comparative performance of geospatial and geotechnical models on a common dataset of the 2010-2011 Canterbury earthquakes, considering two geotechnical and three geospatial models. Figure 9 presents a summary of the results of Maurer et al. based on receiver operating characteristic (ROC) analysis – which examines the rates of true- and false-positives in diagnostic models. They found that the best geospatial model (‘Regional Geospatial Model’ in Figure 9) had a predictive capability similar to the two geotechnical models, with two other geospatial models providing poorer predictions.

Due to their relative infancy, the development of detailed input data for geospatial liquefaction models is often absent. For example, Zhu et al. was developed using V_{s30} models based on a global topographic slope correlation, rather than using a region-specific V_{s30} model developed based on topographic slope, surface geology and actual V_{s30} measurements at discrete locations. The utilization of higher quality input data is likely to result in more precise geospatial liquefaction models. Of course, there is the question of the quality of the input data when actually utilizing models in a forward prediction sense, but it is important to separate the apparent aleatory uncertainty in the model predictions themselves from the epistemic uncertainty in the parameters used for forward modelling.

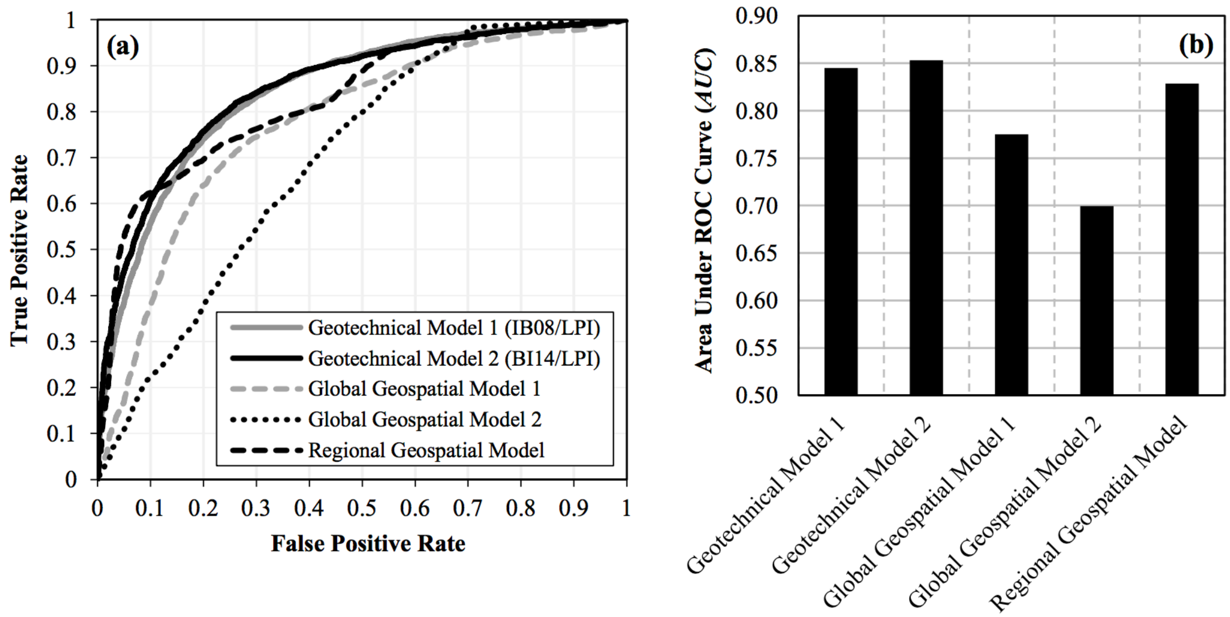

Figure 9: Liquefaction predictive capabilities of various geotechnical and geospatial models: (a) reciever operating characteristic (ROC) analysis; and (b) model performance as quantified by the area under the ROC curve (AUC) (after Maurer et al. (2018))

Probabilistic liquefaction risk

A particularly valuable attribute of geospatial liquefaction models is their ease of application (being based on input parameters that are available everywhere), in contrast to the common problem of inadequate data for geotechnical liquefaction models. Figure 7a provides an apt illustration of this by enabling liquefaction susceptibility to be computed across the entire area of NZ. Figure 10a illustrates the distribution of NZs area by liquefaction susceptibility as shown in Figure 7a. Despite the fact that over 75% of NZs area has very low susceptibility (because of a large area of mountainous terrain), Figure 10b illustrates that the population exposed is disproportionally affected because of the tendency for dense urban areas to be located on alluvial plains and coastal regions, with over 25% of NZs population being exposed to high or very high liquefaction susceptibility.

By combining the liquefaction susceptibility and the seismic hazard (e.g. Equation (1) and Figure 6) it is possible to compute the liquefaction risk as:

$$\lambda_L = \int P_{L|IM}(im) \left| \frac{d\lambda_{IM}(im)}{dIM} \right| dIM \qquad (2)$$

where λ_L is the annual rate of liquefaction occurring at a given location (conditioning on the location is suppressed in the notation for brevity); $P_{L|IM}(im)$ is the probability of liquefaction as a function of a ground motion intensity measure (e.g. PGV in the case of the Zhu et al. (2017)

model); and λ_{IM} is the seismic hazard curve from Equation (1). In order to consider the annual rate of liquefaction in the context of service life of affected structures it can be converted to a probability of occurrence in a time period, T, through the Poisson assumption: $P = 1 - e^{-\lambda T}$.

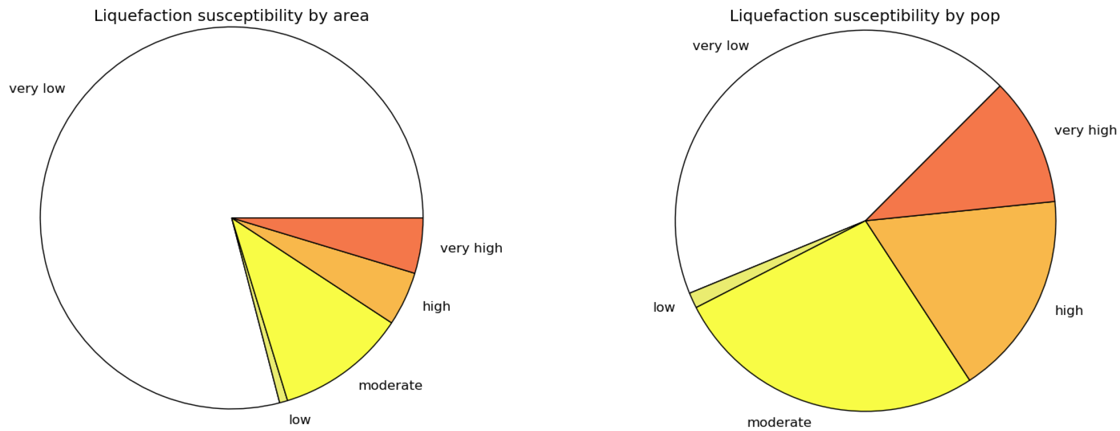

Figure 10: Distribution of liquefaction susceptibility in NZ by: (a) area; and (b) population exposed.

Figure 11 illustrates the application of Equation (2) for the South Island region of NZ. The highest probabilities occur in the West Coast region because of the high PGV hazard resulting from the proximity to the Alpine Fault. Lower probabilities are seen in the highly susceptible alluvial valleys and plains in Blenheim, Canterbury and Southland because of the lower seismic hazard.

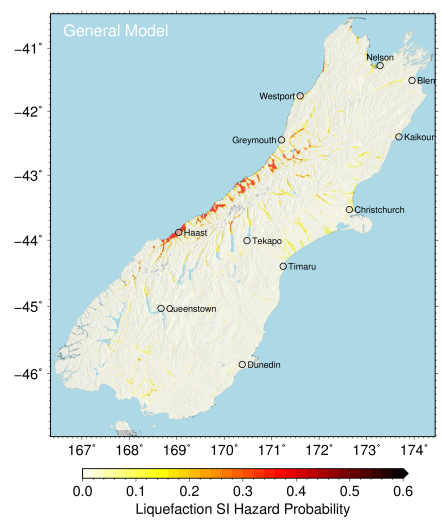

Figure 11: Probability of surface manifestation of liquefaction in 50 years in the South Island of New Zealand.

Ensemble liquefaction modelling

Despite being convention in seismic hazard analysis (because of its historical ties to seismic safety of critical facilities and therefore risk analysis), the consideration of ensemble modelling in liquefaction evaluation is not commonplace in geotechnical earthquake engineering, with it being more common to adopt a single geotechnical model rather than several, and model input uncertainties usually via a heuristic sensitivity analysis rather than through the use of probabilistic approaches. Clearly the discipline could significantly benefit from ensemble modelling, both for obtaining improved predictions and estimates of uncertainty; as well as avoiding large 'swings' in estimated performance as a consequence of changing the single adopted model.

The growing predictive capabilities of geospatial liquefaction models and their ease of use is likely to drive a desire to use geospatial and geotechnical models in combination. The weighting of such models should be in proportion to their predictive capabilities as demonstrated via validation (in the same manner as discussed previously for ground motion prediction). One present challenge to this notion is that, unlike ground motion prediction, there is not consistency between the liquefaction severity/impact metrics that are used in geotechnical vs. geospatial models. The former using liquefaction severity index parameters such as LSN, LPI; while the latter using an 'areal liquefaction probability' for surface manifestation of liquefaction (but not its severity). While there is nothing preventing the development of geospatial models which predict severity index parameters, the fact that they don't exist at present is one hindrance to the application of ensemble predictions.

LANDSLIDE MODELLING

Landslide susceptibility and hazard in New Zealand were predicted using the recent global landslide model of Jessee et al. (2018). The model is a function of PGV, topographic slope, lithology, land cover, and cumulative topographic index (CTI); and was developed based on an inventory from 23 global earthquakes. Figure 12a presents the spatial distribution of landslide susceptibility of NZ, while Figure 12b and c illustrate the proportion of the discrete susceptibility classifications as a function of area and population. As might be expected, comparing Figure 12a with Figure 7a illustrates that a large proportion of regions in NZ have either a high landslide or liquefaction susceptibility (but not both) owing to the generally high rainfall, large number of rivers, and proximity to the coast. Approximately 25% of the population is subject to a moderate landslide susceptibility, and 2.5% to high or very high. In contrast, nearly 30% of NZs area is subject to high or very high landslide susceptibility, making it a principal concern for spatially distributed infrastructure that traverses NZ, such as transportation and electric power generation and transmission.

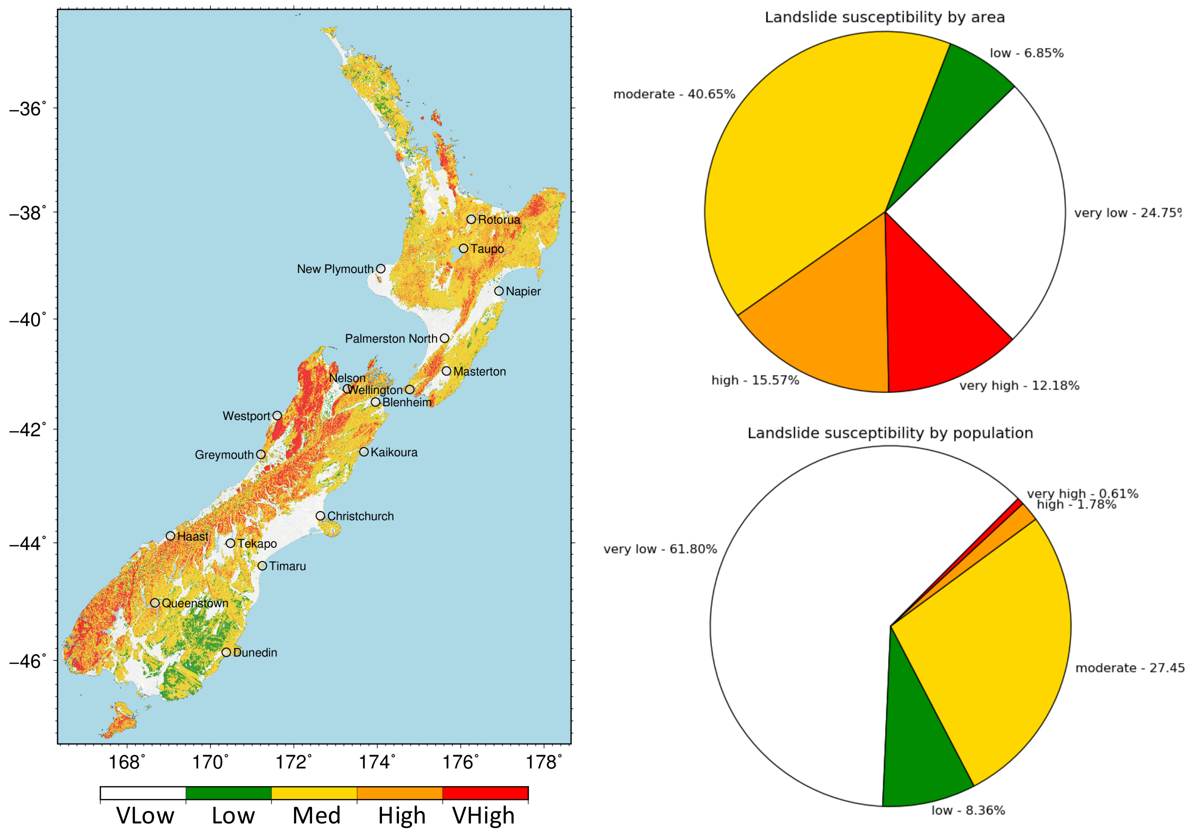

Figure 12: Landslide susceptibility based on Jessee et al.: (a) across NZ; (b) percentages based on area; and (c) percentages based on population exposed.

The NZ-specific validity of the Jessee et al. landslide model is currently being further evaluated. The model development included four moderate magnitude earthquakes in the time period 2013-2015, and therefore the 2016 Kaikoura earthquake provides further opportunity to examine the predictive capability of the model. Following this, NZ-wide landslide risk modelling can also be undertaken as discussed for liquefaction risk previously in the context of Equation (2).

CONCLUSION

This paper has examined ground motion and geohazard modelling in the context of its application in New Zealand. The on-going developments in the paradigm-shift toward physics-based ground motion simulation were presented through validation of recent historical earthquakes, as well as the application to future events to derive simulation-based probabilistic seismic hazard. Such results were then utilized in geospatial liquefaction and landslide models in order to compute the seismic geohazard susceptibility of NZ by area and exposed population, as well as its convolution with ground motion hazard in order to determine geohazard risk. Future challenges include the on-going validation of such models, as well as their combination in ensemble modelling to develop more robust prediction estimates as well as explicit uncertainty consideration. The explicit incorporation of observational data into the predictions of such models is also a major goal in order to drastically improve their near real-time utility and region-specific accuracy.

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