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Dynamic Shaking Layer models for large New Zealand earthquakes (M6.5+): from rapid source characterization to landslide and impact forecasting

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ABSTRACT

When a large earthquake occurs, rapid information about the earthquake, its shaking and potential impact can help emergency responders quickly gain situational awareness, and target resources where they are most needed. Advances in physical science and technology have now unlocked pathways to deliver increasingly sophisticated information immediately post-event, but the science remains challenging, particularly for very large and complex earthquakes.

Small-to-moderate earthquakes can be represented by a ‘point source’, i.e. a hypocentre where the earthquake begins and a magnitude. This allows us to generate first shaking maps (GNS Shaking Layers; Horspool et al. 2023) automatically based on GeoNet earthquake solutions. These maps are now routinely available to the public within 10 – 20 minutes.

For large earthquakes (M6.5+), a ‘point-source’ is a poor representation of the earthquake, which can rupture tens to hundreds of kilometres of the earth. First Shaking Layers based on ‘point sources’ could severely underestimate shaking in areas far from the epicentre, but close to fault rupture. Rapid 3D characterization of the rupture area, even if approximate, has the potential to significantly improve shaking estimates, and allow meaningful first impact forecasts to be generated.

The New Zealand R-CET Endeavour programme has been developing a suite of tools that characterize New Zealand earthquakes and their shaking in near real-time. These tools include FinDer (Andrews et al. 2023). RTEQcorrscan (Chamberlain et al. 2020; Warren-Smith & Chamberlain 2022) and w-phase (Fry et al. 2022). A key goal is to allow meaningful rapid shaking, cascading hazard and impact forecasts to be generated for large (M6.5+) New Zealand earthquakes.   Here we present an overview of such a rapid earthquake impact forecasting scheme based around these tools, and explore example outputs for the Kaikōura earthquake, including residential loss estimates and landslide forecasts. Our results show the importance of including rapid source characterization as a key component of our earthquake response systems, to underpin quality scientific advice for emergency responders.

1 INTRODUCTION

Following a significant earthquake, there is a need for rapid information on the level of ground shaking and the potential for damage. This information is used by emergency managers and infrastructure providers to scale and target response resources where there is greatest need. The public are also increasingly expecting timely information in an increasingly digital world.

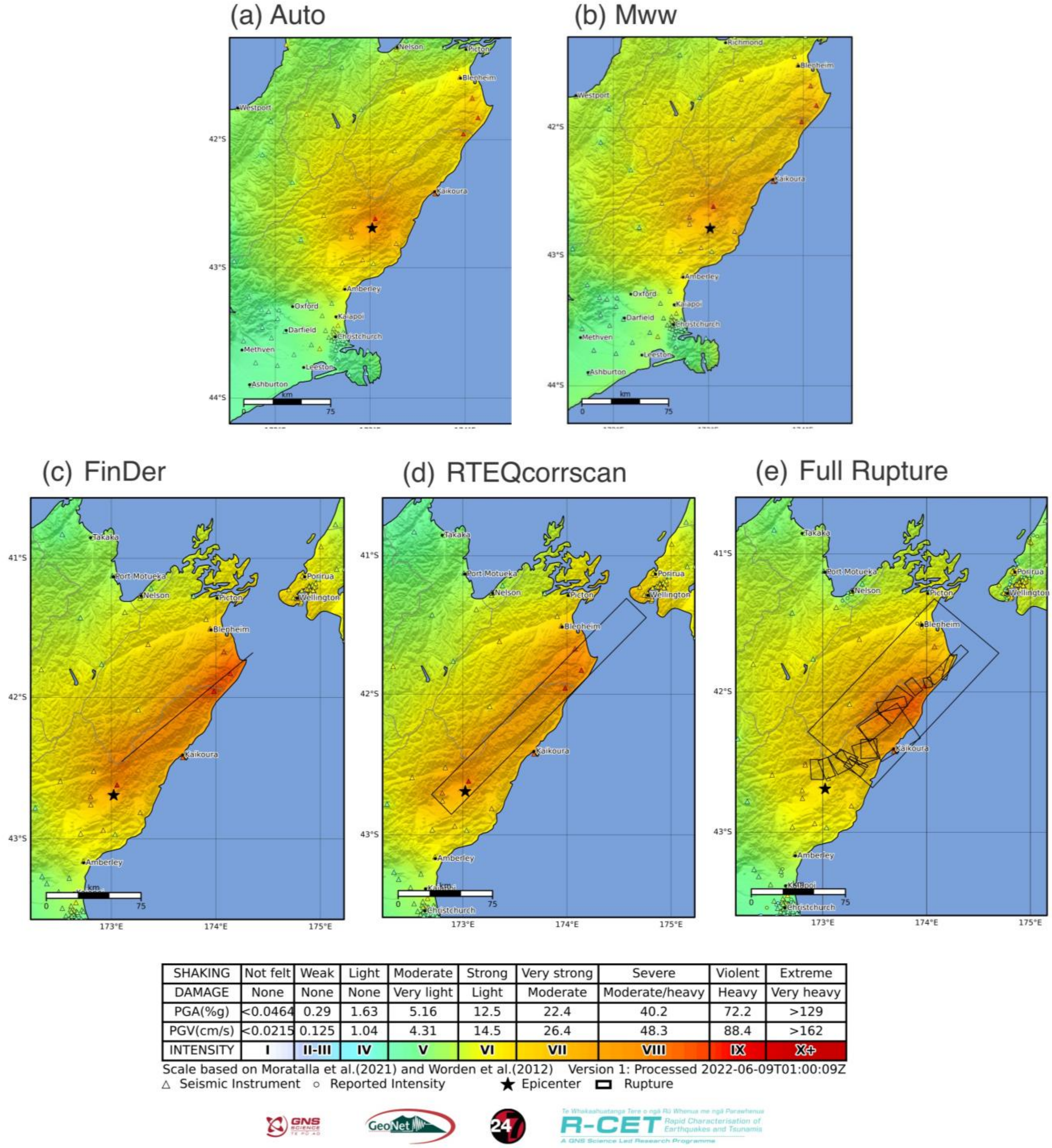
The recently launched GNS Shaking Layers tool (Horspool et al. 2023) provides automated models of shaking for the whole of New Zealand directly to the public and emergency responders (GNS Science, 2023). These maps, generated with USGS ShakeMap software (Wald et al. 2021) are routinely available within 10 – 20 minutes of the event for earthquakes of magnitude greater than 3.5.

For small-to-moderate sized earthquakes (M < 6.5), the automatic Shaking Layer models are considered robust. These earthquakes can be reasonably represented by a point source model, i.e. the hypocentre location and an earthquake magnitude. This means, at locations where we don't have seismometer recordings, Shaking Layers uses the distance to the hypocentre within empirical ground motion models to estimate the background shaking and its uncertainty (process described in Horspool et al. 2023).

However, for larger earthquakes (M6.5+) that can rupture tens to hundreds of kilometres of the crust, a point source model is only a poor representative of the earthquake. For example, the 2016 Mw 7.8 Kaikōura earthquake initiated at the hypocentre close to Waiau in North Canterbury, before rupturing northwards and releasing the majority of its energy in Marlborough, and terminating in the Cook Strait (Kaiser et al. 2017). In this case, based on the hypocentre alone, the first automatic Shaking Layer models would be unlikely to capture the full extent of strong shaking. Figure 1a illustrates the 'best case scenario' automatic Shaking Layer model for the Kaikōura earthquake. This model shows a strong mismatch between several strong motion recordings (triangles) and the background shaking model estimates, which arise from the point source assumption. It has also previously been illustrated that such uncertainties associated with post-event shakemaps can significantly affect post-event landslide forecasts (Allstadt et al. 2018).

In recognition of this challenge, the Shaking Layers tool, developed jointly by GeoNet and the R-CET (Rapid Characterisation of Earthquakes and Tsunami) Endeavour programme, also includes an application that allows GNS seismologists to update Shaking Layers as more sophisticated models of the earthquake (and/or additional data) become available. R-CET have also been developing and testing a suite of rapid earthquake characterisation tools for New Zealand. Several of these tools, including FinDer (Andrews et al. 2023, 2024), RTEQcorrscan (Chamberlain et al. 2020; Warren-Smith & Chamberlain et al. 2022) and w-phase (Fry et al. 2022) are running in-house in real-time, and together form a key underpinning toolkit for large earthquake response. As appropriate to the scenario, the tool outputs can be used to improve Shaking Layer models and feed a diverse range of other cascading hazard and impact assessments, if a large earthquake occurs.

Here, we present one example of a rapid post-event forecasting scheme, from rapid source characterisation to shaking to residential loss estimates and landslide forecasts, illustrated using the Mw7.8 Kaikōura earthquake.



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.29	1.63	5.16	12.5	22.4	40.2	72.2	>129
PGV(cm/s)	<0.0215	0.125	1.04	4.31	14.5	26.4	48.3	88.4	>162
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1 Shaking Layer MMI models re-constructed for the 2016 Mw 7.8 Kaikōura earthquake using different input earthquake source information. (a) The 'best-case' automatic shaking model generated from GeoNet point-source earthquake solutions within 10 – 20 minutes. (b) – (d) Shaking models after inclusion of rapid source characterisation: (b) Mww from w-phase solutions, (c) real-time FinDer rupture model, (d) rapid RTEQcorrscan rupture model. (e) Shaking model based on a detailed rupture model (Hamling et al. 2017) available weeks after the earthquake.

2 RAPID SOURCE CHARACTERISATION

Shaking Layer models (and many other hazard and impact forecasting methods) require a model of the earthquake as a starting point to estimate shaking and follow-on impacts. This requirement can be dropped, only if the forecasting method relies on sufficiently dense observational data (e.g. instrumental recordings of shaking and/or felt reports). Here, we summarise a suite of models that could be included within Shaking Layers.

2.1 Robust earthquake magnitude (Mww) and focal mechanism from w-phase

The W-phase method (Duputel et al. 2012) is considered the most robust method to derive rapid moment magnitude (Mw) for large earthquakes. Whereas standard local magnitude calculations (e.g. ML) can be derived more quickly, ML tends to saturate (i.e. underestimate the magnitude) when earthquakes become very large. The w-phase method inverts for the source moment tensor using very long period seismic waves that arrive shortly after the P-wave at regional teleseismic distances (Duputel et al., 2012). In New Zealand, the W-phase method has been implemented to provide automatic, real-time solutions for earthquakes in the south-west Pacific region within 18 - 30 minutes of earthquake origin time, if prescribed quality criteria are met (Fry et al. 2022).

2.2 FinDer

The Finite-Fault Rupture Detector (FinDer) algorithm (Böse et al., 2012) was originally designed to very rapidly detect earthquakes and estimate their rupture position, extent, orientation and evolution, with the aim of improving shaking estimates for earthquake early warning. The algorithm works by matching the spatial pattern of high frequency ground motions (peak ground acceleration) to a suite of pre-computed templates with associated rupture parameters. In New Zealand, the FinDer method has been implemented to provide automatic, real-time solutions within a few minutes of earthquake initiation, for M4.5+ onshore or near-shore events using region-specific ground motion templates (Andrews et al., 2023, 2024). Although the tool provides only simplified, approximate rupture estimates, these can be highly valuable if available almost immediately, to understand and model the first-order effects of the earthquake.

2.3 RTEQCorrScan

RTEQcorrscan (Chamberlain et al. 2020) is a real-time application of the matched filter detection code EQcorrscan (Chamberlain et al. 2018) that uses template matching to detect earthquakes with similar waveforms. The algorithm can rapidly (within minutes) detect aftershocks which may have been missed within the wavetrain of larger events and use these to improve aftershock catalogues in space and time. Development of the tool is underway to extract dynamically evolving spatial rupture extent estimates (length, azimuth, scaled magnitude) from rapidly-relocated early aftershock hypocentres (Warren-Smith and Chamberlain, 2022). In the example shown for the Kaikōura earthquake in Figure 2, the results for rupture azimuth stabilise within ~10 minutes post-earthquake, and stable estimates of magnitude and length are available within 1 hour. Using this information, a preferred rupture plane of the w-phase moment tensor can also be identified (Figure 2, top panel).

2.4 Detailed rupture models

The first rapid rupture models generated for earthquake response are approximate single-fault-plane estimates. Although they are useful in illuminating the approximate extent of rupture, they don’t capture the rupture detail or complexity of events such as the 2016 Mw 7.8 Kaikōura earthquake. This still requires detailed post-event modelling (e.g. Hamling et al. 2017) based on seismic, geodetic (including InSAR) and/or field mapping data. The data that feeds this modelling may not be available for hours to days, or even weeks to months following an earthquake. In the following sections, we also test the full Kaikōura rupture model of Hamling et al. (2017) in our workflows, to show what is possible with longer response timelines.

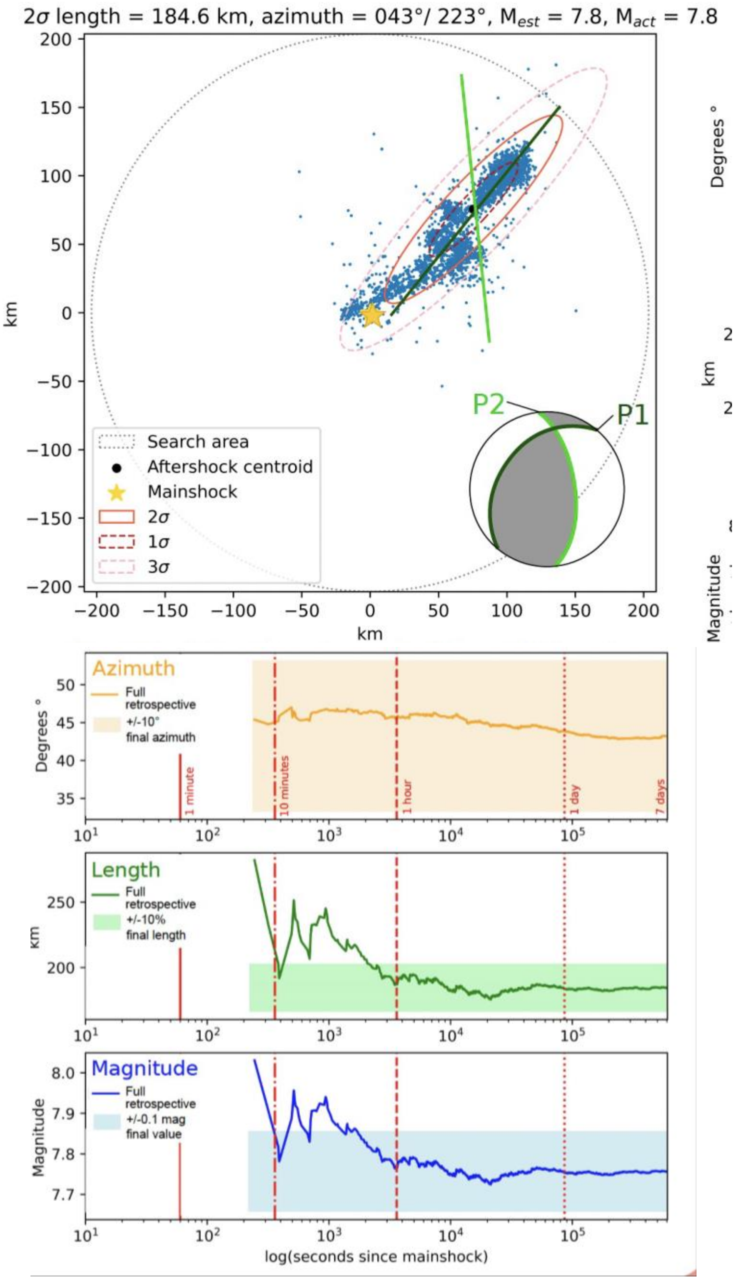


Figure 2 Example of a simulated RTEQcorrscan output for the Kaikōura earthquake. (a) Aftershocks and ellipse fitting for the full Kaikōura declustered catalogue (Chamberlain et al. 2021). Two planes of the regional moment tensor solution (Ristau et al. 2013). (b) Evolution of geometry estimates with time. 'Final azimuth/length/mag value' refers to values calculated 1 week after mainshock, which are assumed to be most representative.

2.5 Felt reports

Felt reports submitted by the New Zealand public can also play a role in improving Shaking Layer models. GNS seismologists can use 'Felt Detailed Reports' (GNS Science, 2016) to derive community intensity values to supplement strong motion seismometer recordings. These additional data points do not alone directly address the problem of the point source assumption for large earthquakes. However, if sufficiently dense they can mitigate its effects by reducing the weight of the background ground motion model predictions in Shaking Layers. This makes them useful as a supplementary tool to rapidly assess the scale of urban ground shaking.

3 KAIKŌURA EARTHQUAKE EXAMPLE – EVOLVING SHAKING LAYER MODELS AND IMPACT FORECASTS

3.1 Evolving Shaking Layer Models

In Figure 1 we present Shaking Layer models for the Mw 7.8 Kaikōura earthquake that could be generated post-event as follows:

(a) The 'best case scenario' automatic Shaking Layer model that assumes (i) all strong motion station recordings are available in real-time (note in reality, several outages occurred at stations close to the rupture) and (ii) M 7.5, which represents the automatic summary magnitude calculated from playbacks of the event within the GeoNet earthquake detection software (SeisComP; Helmholz Center Potsdam GFZ 2008).

(b) – (d) Shaking Layer models that could be rapidly generated by experts during the first hours of response using near real-time R-CET tool outputs

(e) Shaking Layer model using the full complex rupture model of Hamling et al. (2017) derived in the weeks following the earthquake from detailed geodetic data (including InSAR) and field rupture mapping.

Each of the models above use all available strong motion data, making them 'best case' estimates that would be possible only if the GeoNet seismic network is fully operational after the event.

Including a robust magnitude (Mww 7.8) with the point source assumption (Figure 1b) yields only minor improvements in the result. This is because the underpinning USGS ShakeMap software (Wald et al. 2021; Worden et al. 2020) already includes a magnitude bias correction to apply a bulk adjustment to ground motion model predictions based on observed station recordings. However, including a first rapid rupture model, even if approximate, provides a substantially more realistic Shaking Layer model (Figure 1c-d), similar to the full rupture model (Figure 1e). This is also illustrated through a better match of shaking recording at instruments (triangles) with nearby background shaking predictions. No model captures very fine-scale spatial shaking patterns, given that Shaking Layers does not (yet) account for variations in slip and energy release across the complex rupture.

3.2 Residential Loss estimates

The RiskScape software (Paulik et al. 2022) uses shaking model inputs to calculate a range of different loss and damage metrics. Hence, these loss estimates are sensitive to input earthquake source and shaking models, as well as the vulnerability and exposure data that form the basis of risk modelling.

In Figure 3, we show an example of residential loss estimates calculated from each of the Shaking Layer models in Figure 1. For New Zealand as a whole (top left panel), mean loss estimates can vary by factor of four depending on the source input model. Furthermore, uncertainty in these loss estimates is most likely underestimated when using the automatic Shaking Layer model, given that the uncertainty in the earthquake source is not fully captured within these uncertainty estimates. This is also illustrated in the Wellington region results (bottom left panel), where the automatic model yields predictions of zero loss, due to the location far from the earthquake hypocentre. In contrast, loss estimates for Canterbury remain relatively stable, due to the fact the 'distance to source' is similar, whether a 'point-source' model or full rupture model is adopted. These results help to illustrate that uncertainties in source models are one key source of uncertainty that should be considered in rapid impact forecasting applications.

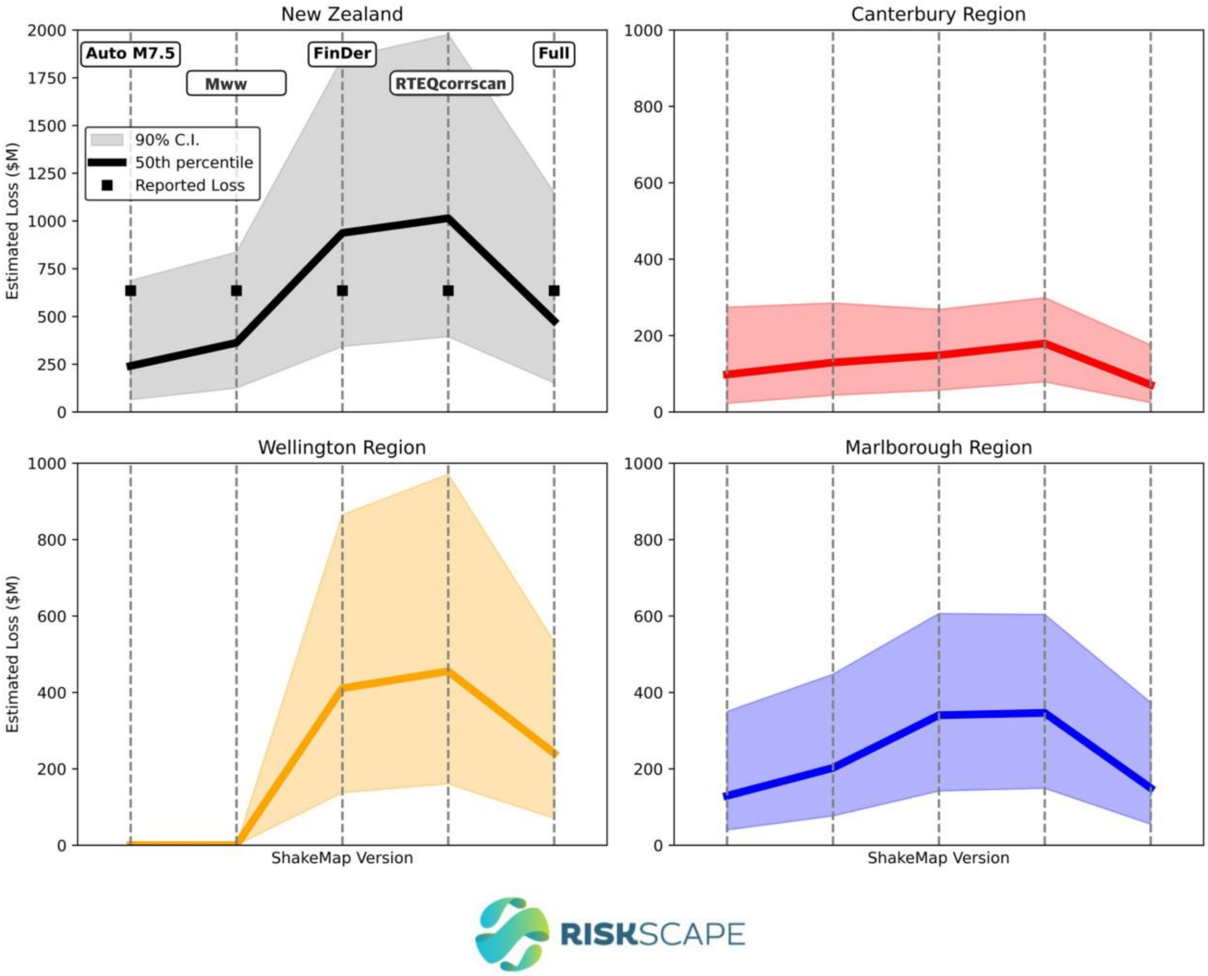


Figure 3 Residential loss estimates for the Kaikōura earthquake based on Shaking Layer models with different input source information. Loss estimates are derived from the RiskScape tool for New Zealand as a whole, as well as by region. Results show that estimates can be highly sensitive to the input source model of the earthquake.

3.3 Landslide forecasts

Earthquake-induced landslide forecasting tools for New Zealand (Massey et al. 2021) were developed through the Earthquake-Induced Landscape Dynamics (EILD) Endeavour programme, with new versions currently in development. The key input needed to run these tools during an earthquake response is a spatial model of peak ground acceleration (PGA). A simple PGA interpolation scheme based on seismometer recordings can be used to generate first input shaking models (see example in Figure 4 top left panel). Alternatively, Shaking Layer models are now also rapidly available for use in early response.

In Figure 4, we show the dependence of landslide forecasts on the input PGA shaking model, using the Kaikōura earthquake example. The PGA 0.2g contour (shown in black) provides a useful indicator of where strong shaking has occurred that has significant potential to trigger landsliding; the calculated landslide probabilities take into account several other key factors associated with the local slopes, including elevation/material/angle etc. Figure 5 shows a summary of the total number of forecast landslide grid cells for each model, compared to actual landslide observations.

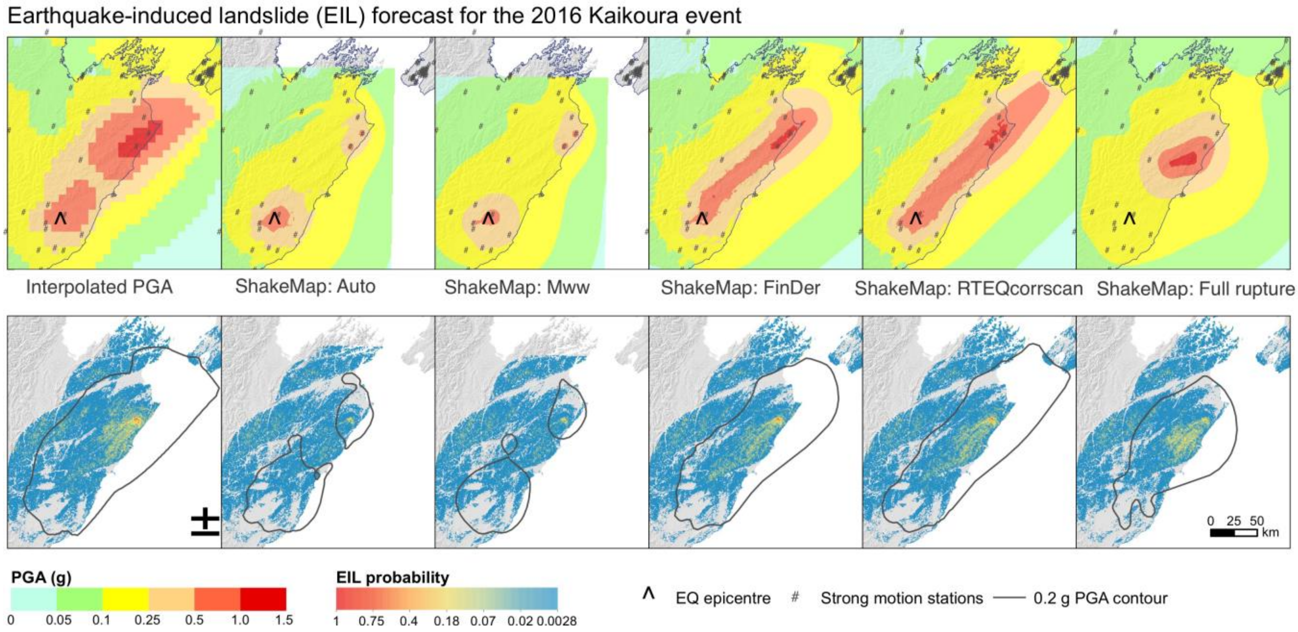


Figure 4 Earthquake-induced landslide (EIL) forecasts that would be made based on Shaking Layer models in Figure 1. (a) PGA models used as input. The PGA interpolated model is a simple PGA-interpolation option that can also be used in response. (b) Output of the earthquake-induced landslide tool (Massey et al. 2021) for each PGA model in (a). Black lines show the 0.2g PGA contour within which landslides are expected to dominantly occur.

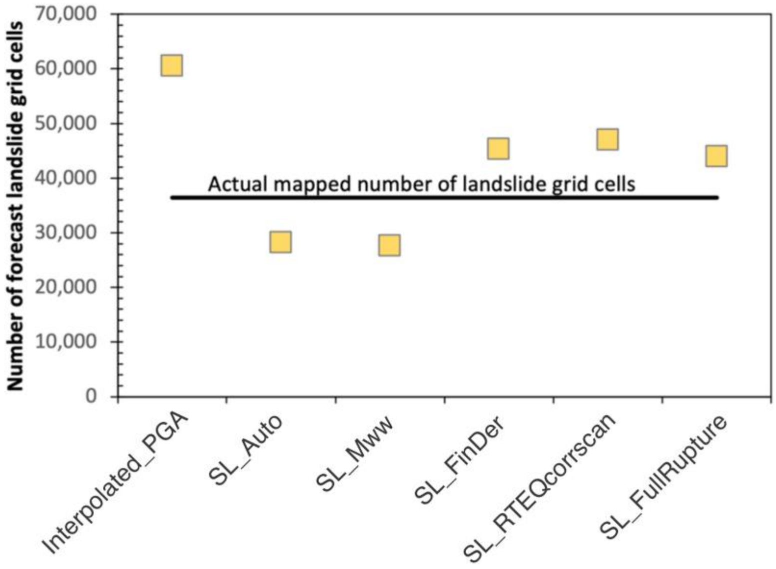


Figure 5 Total number of forecast landslide grid cells (32m x 32m) for each of the shaking models described in the text and shown in Figure 4.

The landslide forecasts based on the interpolated PGA model and the Shaking Layers that include earthquake rupture models show similar spatial patterns; they forecast higher probability of landsliding extending from North Canterbury to Marlborough in eastern coastal areas. However, the PGA interpolated model tends to somewhat overestimate landsliding in general, presumably as a result of the smearing of higher ground motions over a wider area. Notably, the first automatic Shaking Layers and Mww models based on point-source models, are limited in their ability to capture both the true extent of strong shaking and the significant probability of landslides in near-coastal regions (including State Highway 1) between Kaikoura and

Marlborough. With rapid source characterisation (e.g. FinDer, RTEQcorrscan), we have a pathway to significantly improve initial landslide forecasts early during a response.

4 DISCUSSION AND CONCLUSIONS

A suite of new near-real time rapid earthquake source modelling tools are being developed and tested for New Zealand, including FinDer (based on strong motion data) and RTEQcorrscan (based on aftershock modelling). These tools provide a rapid estimate of fault rupture extent, which is a critical input needed to generate rapid and robust shaking models (e.g. Shaking Layers) for large New Zealand earthquakes (M6.5+). In general, the larger the earthquake, the bigger the influence of the underpinning source model on shaking estimates, and the less accurate maps using basic 'point-source' assumptions will be. These innacuracies (and high uncertainty) will be propagated through rapid impact forecasting schemes and workflows.

We illustrate these points, using the Kaikōura earthquake by creating hypothetical rapid response outputs from source to shaking to cascading hazard and impact forecasting workflows. The results shows that Shaking Layers models that incorporate rapid rupture models are better able to estimate the true spatial extent of strong shaking, residential loss and landsliding. For example, in this case they could help rapidly identify potential shaking damage in Wellington and the potential landslide disruption in coastal areas around Kaikōura.

At present, real-time rupture mapping tools are run in-house through the R-CET programme, and any outputs are available for expert science responders to assess, interpret and feed into science advice, Shaking Layers and impact forecasts as appropriate. Our current and future work is focused on testing and further streamlining these processes, to optimise the scientific results in a diverse range of New Zealand earthquake scenarios.

5 ACKNOWLEDGEMENTS

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GeoNet data for analysis were downloaded through the International Federation of Digital Seismograph Networks (FDSN) webservices data service available at https://www.geonet.org.nz/data/access/FDSN (last accessed March 2023). We acknowledge the New Zealand GeoNet program and its sponsors Toka Tū Ake EQC - Earthquake Commission (EQC), GNS Science, Toitū Te Whenua Land Information New Zealand (LINZ), National Emergency Management Agency (NEMA), and Ministry of Business, Innovation and Employment (MBIE) for providing data used in this study.

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