NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING

GeoNet's Shaking Layer Tool: Generation of near-real time ground shaking maps for post-event response

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ABSTRACT

Information on ground shaking following an earthquake is important for many applications from emergency response, engineering assessments, infrastructure management, insurance claim estimation and research. GeoNet, GNS Science along with the RCET Endeavour programme, is developing a tool, named Shaking Layers, that produces maps of ground shaking across New Zealand in the minutes after an earthquake. Shaking Layers uses the USGS ShakeMap software to create maps of PGA, PGV, MMI and Sa(T) for M4.0 and above earthquakes. The model combines observed ground motions from strong motion stations with ground motion models to produce spatial estimates of ground shaking for a range of intensity metric types. The first maps are available within 10-20 minutes of an earthquake. The maps are automatically generated and updated in the first instance, and can be manually updated by GNS Science seismologists if new information is available, such as a fault rupture model, earthquake tectonic type, moment tensor solutions and felt reports. This paper will give an overview of GeoNet's Shaking Layer Tool and outline to the NZSEE community how they can access Shaking Layer information through the GeoNet website, the Shaking Layer data website, and an API.

1 Introduction

Following a significant earthquake, there is a need for rapid information on the level of ground shaking and the potential for damage. Emergency managers seek to know if there was any damage and, if so, where it is concentrated so they can prioritise the deployment of rapid response teams. Engineers require estimates of ground motion that may have affected structures of interest to trigger inspections. Infrastructure providers are interested in knowing if certain ground motion thresholds were exceeded, so that they can mobilise technicians and engineers to assess the damage and repair if necessary or to stop services to prevent damage. The insurance sector want to know the scale of damage and loss and the number of potential claims. The general public and media are also increasing their demand for information about the intensity of an earthquake and where the strongest shaking was experienced. They often want to validate their own personal experiences or to see what friends and families in different locations may have experienced.

GeoNet is New Zealand's geohazard monitoring programme, run by GNS Science. At present, earthquake shaking intensity and ground motion information is available from disparate sources within GeoNet and is only available at certain locations where strong motion stations are located or felt reports are reported. The GeoNet strong motion network has an average station spacing of a few kilometres in urban areas, such as Wellington and Christchurch, but a spacing of tens to hundreds of kilometres in rural areas. Ground motions can vary significantly over these inter-station distances resulting in uncertainty for end users making decisions based on the currently available earthquake shaking information.

Since 2014 GNS Science seismologists have been manually producing maps of shaking across New Zealand following significant earthquakes using the ShakeMap software developed by the United States Geological Survey (Horspool et al. 2015). However, recent consultations with GeoNet and GNS Science stakeholders has revealed the need for shaking maps to be produced faster and automatically, with less reliance on individual response scientists. Furthermore, the ability to update these automatic maps as science evolves in a large earthquake response is considered a useful feature.

For this reason, GeoNet, GNS Science and MBIE Endeavour project R-CET (Rapid Characterisation of Earthquakes and Tsunamis), have collaboratively developed Shaking Layers, a tool that provides near real-time shaking intensity maps following a magnitude 3.5 or above event in New Zealand.

2 Shaking Layer System Overview

This section provides an overview of the Shaking Layer system. It outlines the system design, processing workflow, and versioning.

Shaking Layers is the name of the system that generates shaking information (data and maps) following earthquakes and delivers it through the GeoNet website. *ShakeMap* is the scientific software used to combine shaking information from the GeoNet sensor network, and scientific models and understanding from across GNS Science, to produce estimates of shaking across the region (Wald et al 1999, Wald et al 2022).

2.1 System Overview

The Shaking Layer system runs on the GeoNet cloud based architecture at tier level 2 which means the product is supported 24/7. The overview of the Shaking Layer system is shown in Figure 1.

The GeoNet sensor network is continuously streaming seismic waveform data to the automatic earthquake location system at GeoNet. The GeoNet SeisComp3 earthquake location system automatically detects earthquakes and determines the initial solution (i.e. epicentre, depth, magnitude). This solution is given an 'automatic' quality tag. After a few minutes the automatic solution(s) will be reviewed by a Geohazard Analyst within the National Geohazards Monitoring Centre (NGMC) and the earthquake quality tag will be 'preliminary', at which point the Shaking Layer system will initiate. If the earthquake meets the event criteria set by Shaking Layers (see below) it will automatically trigger a ShakeMap processing job.

Subsequent runs will also take place as outlined below. These may either be automatic updates to Shaking Layers with new GeoNet data and/or the latest earthquake solutions, or updates from GNS seismologists that incorporate new data, scientific understanding and advanced models of the earthquake.

With each run, the Shaking Layer data is then automatically published to a database which is used by four data delivery streams (Figure 1).

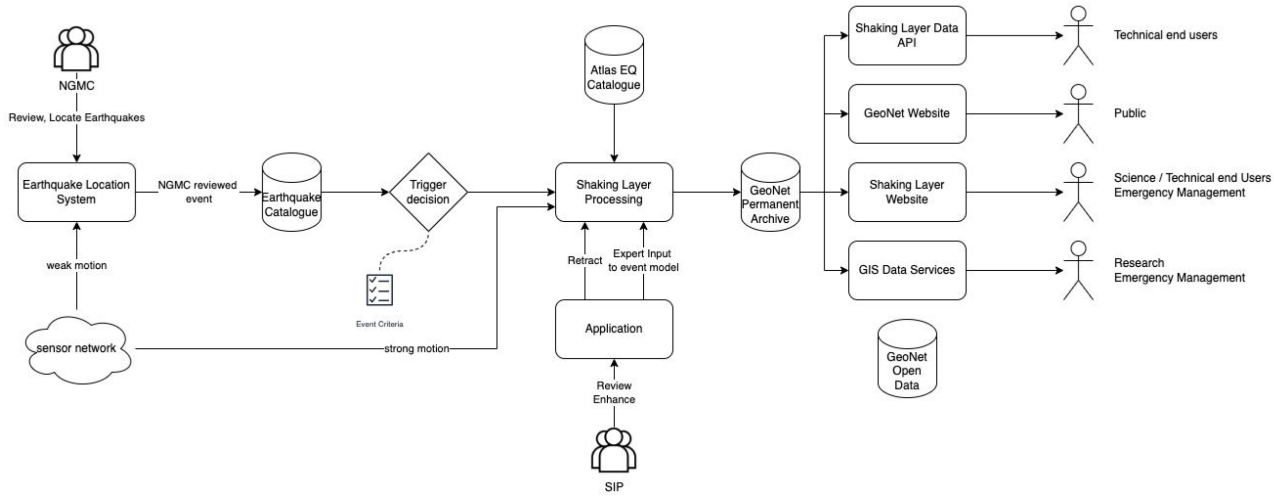

Figure 1. Shaking Layer system overview diagram. Shaking Layer processing is undertaken using the ShakeMap software. NGMC is the National Geohazards Monitoring Centre based at GNS Science, and the SIP is the Seismology Intelligence Panel which can be activated in response to significant earthquakes.

2.2 Criteria For The Generation Of Shaking Layers Maps

At present, Shaking Layer maps will be generated using the following criteria:

- Earthquakes with a GeoNet magnitude of M3.5 or above with an epicentre location within 100km of the New Zealand coast. This region is defined as 'onshore New Zealand'.
- Earthquakes with a GeoNet magnitude of M5.0 or above with an epicentre location further than 100km from the New Zealand coast. This region is defined as 'offshore New Zealand'.

These criteria was developed in consultation with the "Shaking Layer" project Science and End-User Advisory Panels and was approved by both panels.

2.3 Shaking Layer Versions

Shaking Layer is a dynamic product that is updated over time with increasing data and scientific knowledge (Figure 2). There are four different Shaking Layer versions. These are

- *Automatic*
- *Unreviewed*
- *Reviewed*
- *Revised*

The first version is *automatic* and is usually available 10-20 minutes following an event. An *automatic* version has not been reviewed or updated by seismologists. The system will then trigger subsequent *automatic* versions based on two criteria: if the GeoNet earthquake solution changes (i.e. epicentre, depth, magnitude), and at fixed times following an event (30 minutes, 1 hour, 3 hours, 6 hours, 24 hours), which allows additional strong motion data to be included if communications to relay this data back to GeoNet are delayed.

If the earthquake is significant, Shaking Layer may be updated manually by seismologists to capture evolving scientific knowledge. These maps contain the most up-to-date scientific models at the time of creation, and will be available as *reviewed* versions and through the Shaking Layer tool. *Reviewed* versions are generated and published by the GNS Science Seismology Intelligence Panel (SIP), a group of seismology experts who provide science advice and support following significant earthquakes. SIP may modify parameters (e.g. the earthquake tectonic type, magnitude, mechanism etc) or add additional data (e.g. the geometry of the fault rupture, felt reports etc) to improve the latest Shaking Layer version. When SIP triggers a new run an *unreviewed* version is first created. A SIP member will undertake a quality assessment of the *unreviewed* version then approve this version to be published as a *reviewed* run. An end user will never see an *unreviewed* version but is noted here to show the review and quality control process..

SIP may allow the last *reviewed* run to be automatically updated with any further GeoNet earthquake solutions or strong motion data that become available. If a *reviewed* version is updated automatically it is called a *revised* version, and has not been reviewed by a seismologist. Alternatively, SIP may stop automated updates to the *reviewed* run and manage updates manually. These concepts are shown illustratively in Figure 2 and Figure 3.

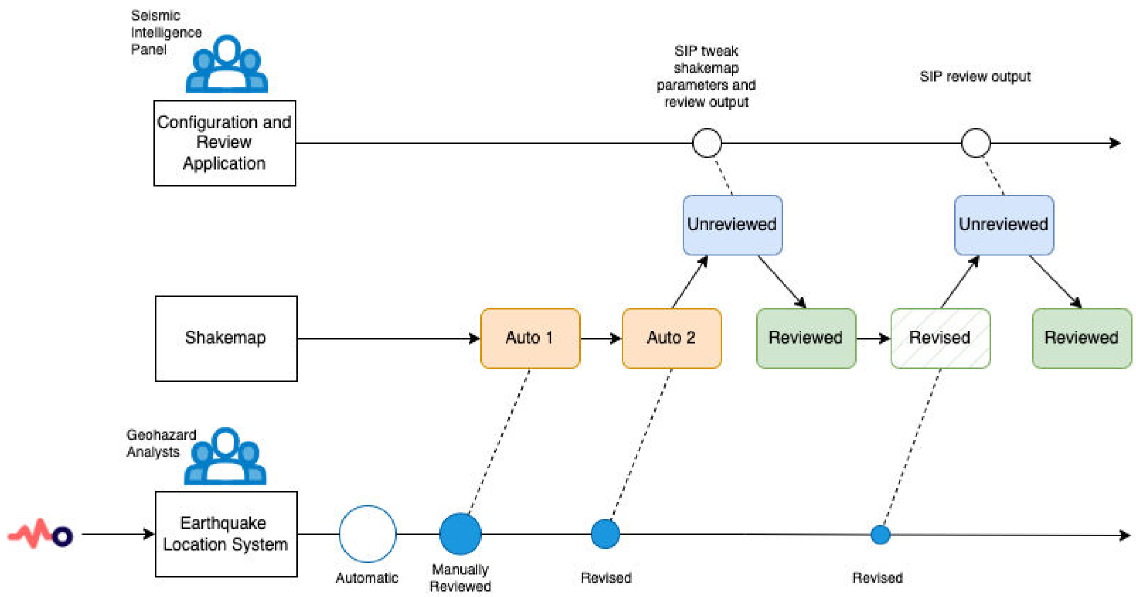

Figure 2. Schematic diagram showing the concept of different Shaking Layer versions over time.

2.4 Shaking Layer Data Delivery Streams

Shaking Layers are delivered through GeoNet. There are four data streams where an end user can get Shaking Layer information (data and maps). These are:

- GeoNet Earthquake Event Website
- GeoNet Shaking Layer Data Website
- GeoNet Shaking Layer Data Automatic Programming Interface (API)
- GeoNet Shaking Layer GIS Webservice

2.4.1 GeoNet Event Website

Shaking Layer maps are available on the main GeoNet website (https://geonet.org.nz) on an earthquake event page. Users can visualise the Shaking Layer maps on an interactive map which shows shaking intensity contours, shaking intensity heat map, or GeoNet station data. The map can be panned and zoomed, and users can click on the Shaking Layer data to extract the shaking intensity at the click location. Users can also screen shot the maps to create a static map. Users can also access the Shaking Layer Data website via the technical tab on GeoNet website.

2.4.2 GeoNet Shaking Layer Data Website

The Shaking Layer Data Website is the location to manually download data files. Users can download individual files or all files for a Shaking Layer event and version. The Shaking Layer website is available at https://shakinglayer.geonet.org.nz/ Uses can search earthquakes by their GeoNet event ID or year, sort recent events by their magnitude, depth, region or time.

2.4.3 GeoNet Shaking Layer Data Automatic Programming Interface (API)

The Shaking Layer Data API provides a way external applications can access Shaking Layer data through URL based queries. The Shaking Layer Data API guide is located at https://shakinglayer.geonet.org.nz/api. The API allows querying events that have Shaking Layer data, versions available for events, files available for versions, and to download specific files or all files.

2.4.4 GeoNet Shaking Layer GIS Webservice

The Shaking Layer GIS webservice allows users of GIS systems to access Shaking Layer data through their GIS software.

2.5 Shaking Layer Data Products

This section describes the different data products produced by the Shaking Layer System and which data stream they are available from.

2.5.1 Shaking Intensity Metric Types

There are a number of ways to describe the shaking at a location based on different intensity metric types. There are three main types produced by Shaking Layers; intensity, acceleration, velocity.

2.5.1.1 Intensity

Shaking intensity is a description of shaking as perceived by people and the effect on their environment. Shaking intensity is measured through the Modified Mercalli Intensity (MMI, Dowrick et al., 2008). The MMI scale ranges from 1 to 12, and is often represented in roman numerals (e.g. I to XII). Each MMI level also has an intensity descriptor related to the perceived shaking level (e.g. light, moderate, strong). Both of these units are used by GeoNet to describe shaking intensity. Shaking intensity information is collected through Felt Reports ("Felt RAPID", or "Felt Detailed", GNS Science, 2016) on the GeoNet website. Shaking Layers produces intensity data in the MMI scale units (i.e. 1 to 12). An example intensity map is shown in Figure 3.

2.5.1.2 Peak Acceleration

The peak (or strongest) accelerations are another intensity metric type used to describe shaking. There are a number of ways to express acceleration. Peak ground acceleration (PGA) is the largest acceleration from an event, whereas Peak Spectral Acceleration (PSA or SA) is the acceleration for a defined frequency (inverse of period) of shaking. Spectral acceleration is related to how buildings of different heights respond to shaking. The taller a building, the longer the period of spectral accelerations it is sensitive too.

Shaking Layers produces data on PGA, and SA at 0.3s, 1.0s, and 3.0s periods. Units are in fraction of acceleration due to gravity (g), where 1.0 g is 100% the force of gravity. The available SA periods will be expanded in the future to allow ShakeMap spectra to be estimated.

2.5.1.3 Peak Ground Velocity

Peak ground velocity (PGV) is a metric that describes the peak (or strongest) velocity observed. Units are in cm/s.

2.5.2 Format Types

The different intensity measure types are available in a number of different file and spatial formats.

- Raster grids in geotiff format (.tif) with a spatial resolution of 1km (e.g. Figure 3)
- Generalised contours in geojson format (.json)
- Contour polygons in ESRI shapefile format (.shp)

For each intensity measure type an uncertainty raster in geotiff format is also available. This represents the standard deviation of the shaking estimates. An addition json file is available that contains metadata for the version.

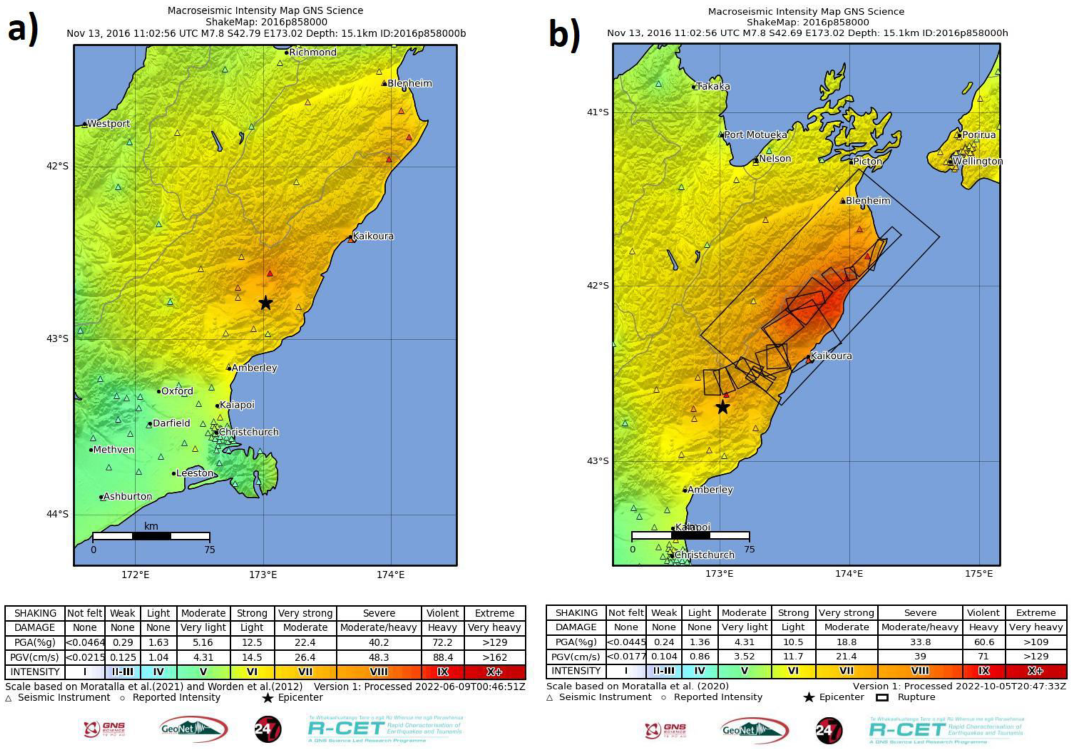

Figure 3. Example of how maps can evolve over time with additional input, from the initial epicentral based map (a) to an updated map with estimated rupture geometry (b)

3 Configuration Of The ShakeMapNZ

This section describes the New Zealand specific models, equations and configuration files included in Shaking Layers to make it a tool specifically designed to be used for New Zealand earthquakes, using the latest geological, seismological and geotechnical information for New Zealand. The configurations are implemented in the ShakeMap software. To distinguish between the software (ShakeMap), and the USGS implementation of ShakeMap (also ShakeMap), we refer to the New Zealand implementation of ShakeMap as ShakeMapNZ.

3.1.1 Ground Motion Models (GMM)

Ground motion models (GMM) are equations that estimate ground motions given a number of variables such as earthquake magnitude, distance from site to fault rupture, soil conditions, or the tectonic type of earthquake, amongst others. The GMM used in ShakeMapNZ are the same as that of the 2022 New Zealand National Seismic Hazard Model (NSHM). The NSHM has recently undergone a significant update, which included evaluating, selecting and developing new GMM for seismic hazard assessments. The details on selection of GMM for modelling in New Zealand is present in the NSHM reports by Gerstenberger et al. (2022) and Bradley et al. (2022).

3.1.2 Intensity Prediction Equation (IPE)

Intensity prediction equations (IPE) are a type of GMM that estimate macroseismic intensity instead of engineering based ground motions. IPE are not used in the NSHM so there is no recommended model to use for New Zealand. ShakeMapNZ uses the Allen et al (2012) Intensity Prediction equation. The IPE estimates shaking intensity aligned with the New Zealand's Modified Mercalli intensity (MMI) scale (Dowrick et al., 2008). This is a global model which includes macroseismic intensity data from earthquakes around the world as well as over 100 events from New Zealand. Testing of this model against GeoNet Felt Report data shows that this model performs well at near to intermediate distances (<150 km) but does attenuate (estimates lower intensities) faster than what is observed from the Felt Report data, which appears to 'flatten out' at larger distances. Work on developing an updated New Zealand specific Intensity Prediction equation is in progress, and inclusion of this new model in ShakeMapNZ will be considered in the near future.

3.1.3 Ground Motion To Intensity Conversion Equation (GMICE)

Ground motion to intensity conversion equations (GMICE) convert between different intensity metrics, such as macroseismic intensity (e.g. MMI) and engineering based parameters including peak ground acceleration (PGA), peak ground velocity (PGV) and spectral acceleration (SA), and vice versa.

They are used in ShakeMap to convert between different intensity metrics so that all types of shaking data (e.g. strong motion recordings and felt reports) are able to be used to generate maps.

The GMICE of Moratalla et al (2021) is used in ShakeMapNZ as this is based on a dataset of 67,000 felt reports from 917 earthquakes since 2004.

3.1.4 Vs30 Model

ShakeMapNZ requires a national model of Vs30 (time-averaged shear-wave velocity in the uppermost 30 m of the subsurface). This is required to apply site amplification factors in ShakeMap and as a required input for GMMs. ShakeMapNZ uses an updated (unpublished but available at https://github.com/ucgmsim/Vs30) version of the Foster et al. (2019) Vs30 model. This model is the most recent for New Zealand and considered the most robust. The mean Vs30 estimates given by the two published New Zealand Vs30 models of Foster et al. (2019) and Perrin et al. (2015) can differ from one another significantly, highlighting uncertainty arising from modelling assumptions. The new update to Foster et al. (2019) appears to be a good compromise, generally providing mean Vs30 estimates similar to or in between the two published estimates. The Foster et al. (2019) model and updates are based strongly on geology and geomorphology, using geostatistical methods to incorporate a limited set of Vs30 observations. The model is developed at a grid spacing of 100 x 100m but up-sampled to 1 km x 1 km for use in ShakeMap.

Nevertheless, it should be noted that only coarse-scale regional Vs30 models are available for New Zealand with large associated uncertainties. The site amplification factors estimated from these models are approximate (e.g. discussion in Kaiser et al. 2022). Hence, ShakeMaps are models of ground motion that provide a useful regional and national overview, but are not intended to be used for site-specific applications. Further development of national Vs30 models is being undertaken and new models may be used in future versions of ShakeMapNZ.

3.1.5 Earthquake Magnitude

The initial magnitude from GeoNet is used as automated input into ShakeMap. GeoNet provides a summary magnitude (M) which is influenced by local magnitude (M_L), whereas ShakeMap requires a moment magnitude (M_w). To convert between local and moment magnitude for the automatic map generation the following equation is applied, based the average correction value between these two metrics derived by Christopherson et al (2021):

$$M_W = M_L - 0.2 \qquad (1)$$

The Shaking Layer magnitude may be updated by the Seismology Intelligence Panel in *reviewed* versions of shaking layers. For very large earthquakes, a M_{ww} derived from w-phase inversion (Duputel et al. 2012) is considered the global international standard because it provides robust magnitudes that do not saturate (i.e. are not underestimated in the largest earthquakes). W-phase inversions for New Zealand may be available from the R-CET programme (see below) or from international agencies USGS or Geoscience Australia (GA). For small to moderate earthquakes M_w may also be directly estimated from Regional Moment Tensor inversion (e.g. Ristau et al. (2014).

3.1.6 Earthquake Tectonic Type Assignment

In order to select the appropriate ground motion model for an earthquake, a tectonic type must be assigned to the earthquake and an appropriate ground motion model set used. As noted earlier there are three tectonic types applicable to New Zealand earthquakes. These are crustal, subduction interface, and subduction slab types. The NSHM has a ground motion model logic tree for each of these tectonic types. ShakeMap allows the use of a blend of tectonic types if the exact type is not known through the use of weights of each ground motion model set. Since Shaking Layer is an automated system, the tectonic type of the earthquake must be determined automatically by the system. Figure 3.2 shows the algorithm for assigning the weighting and described below:

1. Using the location of the earthquake, the tectonic zone is determined. This includes non-subduction zone, Hikurangi subduction zone, or Puysegur subduction zone.
2. If the earthquake is in the non-subduction zone area, and
    I. the depth is less than 40 km, it is assigned as a crustal earthquake and the crustal GMM set is given a weight of 1.00 and others a weight of 0.00
    II. the depth is greater than or equal to 40 km it is assigned as a subduction slab event and subduction slab GMM set is given a weight of 1.00 and others a weight of 0.00.
3. If the earthquake is in one of the subduction zones, the distance to the subduction interface is calculated. The subduction interface is represented by a mesh of points. The nearest subduction interface point to the earthquake epicentre is selected and the depth to interface extracted. The distance to interface ($DIST_{INT}$) is calculated by using the depth of the interface ($DEPTH_{INT}$) and depth of earthquake ($DEPTH_{EQ}$):

$$DIST_{INT} = DEPTH_{INT} - DEPTH_{EQ} \qquad (3.4)$$

4. Using Table 1 below the weighting for each ground motion model set is selected.
5. If the magnitude is M8.0 or above, any distance to interface rule is overridden, and the earthquake is assumed to be a subduction interface event and a weighting of 1.00 is assigned to the subduction interface ground motion model set.

This algorithm was developed based on knowledge that there is large uncertainty in the initial depth of an earthquake and so tectonic assignment based on depth should reflect this uncertainty by assigning a blend of ground motion models. The goal of this algorithm is to reduce variation between versions due to difference in tectonic type assignment. It is anticipated that the tectonic type of the earthquake will likely be updated for significant earthquakes by the Seismology Intelligence Panel, producing a reviewed run.

Table 1. Distance to interface ($DIST_{INT}$) and magnitude criteria for assigning ground motion model sets based on tectonic type. The magnitude criteria overrides any distance to interface criteria.

Distance to Interface	Ground Motion Model Set Weighting
$DIST_{INT} > 20$	Crustal: 1.00 / Subduction Interface: 0.00 / Subduction Slab: 0.00
$10 <= DIST_{INT} < 20$	Crustal: 0.66 / Subduction Interface: 0.34 / Subduction Slab: 0.00
$0 <= DIST_{NT} < 10$	Crustal: 0.34 / Subduction Interface: 0.64 / Subduction Slab: 0.00
$-10 <= DIST_{INT} < 0$	Crustal: 0.00 / Subduction Interface: 0.64 / Subduction Slab: 0.34
$-20 <= DIST_{INT} < -10$	Crustal: 0.00 / Subduction Interface: 0.34 / Subduction Slab: 0.66
$DIST_{INT} < -20$	Crustal: 0.00 / Subduction Interface: 0.00 / Subduction Slab: 1.00
Mag > 8.0	Crustal: 0.00 / Subduction Interface: 1.00 / Subduction Slab: 0.00

4 Faster Estimation Of Earthquake Source Parameters

To provide faster and more accurate Shaking Layer maps the RCET MBIE Endeavour Programme (Rapid Characterisation of Earthquake and Tsunami) is developing real-time implementation of a number of seismic analysis tools. Two of these tools, W-phase and FinDer, aim to rapidly provide source parameters for moderate- to large-magnitude earthquakes, and both will provide benefits in the calculation of Shaking Layers. The W-phase magnitude will provide a rapid, automated and reliable moment magnitude (and other source mechanism parameters) for local and regional earthquakes, while FinDer will provide initial rupture location, extent and orientation estimates. These tools are under development and being tested in a development Shaking Layer system and will be integrated in the near future.

4.1 W-Phase Centroid Moment Tensors

The W-phase method inverts for the source moment tensor using very long period seismic waves that arrive shortly after the P-wave (Duputel et al., 2012). It has the advantages of arriving early in the wave train facilitating rapid inversion, a relatively simple waveform, and using a long-period signal that is effective for characterising very large magnitude and tsunamigenic earthquakes. Originally developed for teleseismic distances, the method has since been proven successful at regional scales, providing reliable solutions within as little as 5 minutes after origin time, regional distances less than 12 degrees, and down to Mw 5.0. 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 15 minutes of earthquake origin time.

4.2 Rapid Finite Fault Estimation with FinDer

The Finite-Fault Rupture Detection (FinDer) algorithm compares the evolving spatial pattern of high frequency ground motions (PGA) to pre-computed templates to estimate rupture length, position and orientation (Böse et al., 2012). It is designed to run in real-time, in the context of earthquake early warning or rapid characterisation, and fills the information gap before more detailed rupture modelling or mapping can be carried out. FinDer solutions can be available between 8 and 60 seconds after earthquake origin time, depending on earthquake magnitude, station density and system configuration (Böse et al., 2023). Dynamic finite-fault rupture models require longer windows of data, and generally are only available after several hours. Detailed mapping of fault rupture, either through field studies or remote sensing techniques, may take days or weeks to complete. Therefore, even an approximate rupture estimate can be highly valuable if available almost immediately, as distance to fault rupture is a controlling factor on strong ground shaking, and therefore a critical input to improve the accuracy of shaking and loss estimate calculations (Wald et al., 2022). In New Zealand, the FinDer method has been implemented to provide automatic, real-time solutions for M4.5+ earthquakes onshore or near-shore using region-specific ground motion templates.

4.3 Acknowledgements

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