

THE SHAKING LAYERS PROJECT: NEAR-REAL TIME SHAKING INTENSITY MAPS FOR NEW ZEALAND EARTHQUAKES: PROJECT OVERVIEW

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ABSTRACT

Following a damaging earthquake, emergency managers and decision-makers require reliable shaking information to be able to make decisions and prioritise interventions. Until now, in New Zealand, these decisions needed to be made with incomplete geographical information, relying solely on observed data points from either strong-motion stations or felt reports. The New Zealand Shaking Layers project has been designed to fill that gap. Using the ShakeMap software, configured to satisfy New Zealand's characteristics, a tool is now available to end-users that provides shaking intensity maps for Peak Ground Acceleration, Peak Ground Velocity, Modified Mercalli Intensity and spectral acceleration at different periods. The Shaking Layers tool covers the entire country, helping decision-makers make better-informed decisions. The maps are generated for magnitude 3.5 or above earthquakes in New Zealand and use strong-motion data from the GeoNet network, as well as intensity derived from felt report data, and fault rupture information when available. To ensure scientific robustness, the tool has been developed with the support of a Science Advisory Panel and has been designed with similar configuration as the updated 2022 National Seismic Hazard Model. Moreover, to ensure the tool is fit-for-purpose, it has been co-designed with an End-User Advisory Panel comprising emergency managers, response engineers, city councils, risk analysts, duty officers and Civil Defence, amongst others. This paper provides the project overview, as well as the tool's main components and functionalities.

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INTRODUCTION

Following a damaging earthquake, emergency responders, decision-makers, scientists, and loss/risk companies, amongst others, require quick access to shaking intensity maps depicting the shaking distribution. This helps them gain situational awareness, prioritise interventions, including building inspections, and develop evacuation and rescue procedures. Until now, in New Zealand these decisions needed to be made using point observations such as Peak Ground Accelerations (PGA) from a strong-motion network, or Modified Mercalli Intensity (MMI) from felt reports, sourced from GeoNet, New Zealand's national geohazards data and monitoring platform (geonet.org.nz), a programme within GNS Science. Thus, decision-makers did not have high quality derived shaking maps covering the entire country, making decisions related to hazard and public safety difficult at locations far away from the observations. Since 2014, GNS Science seismologists have been manually producing maps of shaking across New Zealand following significant earthquakes [1]. Consultations with GeoNet and wider GNS Science end-users 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 more information becomes available is essential in an earthquake emergency

response. With these requirements, the *Shaking Layers* (SL) tool development was initiated in 2021. The project is a collaboration between GeoNet/GNS Science and the Ministry of Business, Innovation and Employment (MBIE) funded Endeavour programme "Rapid Characterisation of Earthquakes and Tsunamis" (R-CET; 2020-2025). R-CET is a large public initiative to better prepare for and respond to natural disasters in New Zealand, under which a suite of near real-time earthquake and tsunami analysis tools is being tested and operationalized [2-4].

The SL tool is now operational and has been producing automatic Shaking Layers since May 2022 for all events of magnitudes 3.5 or above within New Zealand (within the boundary of longitude 160E and 170W and latitude 15S and 55S) and 5.0 or above in the outer New Zealand region, with a total of 1,490 events of magnitudes 3.5 to 6.4 by 8 April 2024. It is called Shaking Layers due to the different output layers it produces. The different naming from the USGS ShakeMap, will help users looking for the New Zealand version to find the correct tool. Outputs include PGA and Peak Ground Velocity (PGV) maps, MMI maps and spectral acceleration maps at different periods. Results can be visualized as static or dynamic maps, downloaded, or added to datasets via an API. The well-known and highly tested software ShakeMap®, developed by

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the US Geological Survey [5], underpins this tool, with configuration settings for New Zealand features, including 1) a shear-wave velocity model (V_{s30}) for New Zealand [6], that is used to approximate site effects, 2) the New Zealand based Ground Motion prediction equation (GMPE) logic tree recently adopted by the 2022 National Seismic Hazard Model [7,8], 3) a New Zealand based Ground Motion to Intensity conversion equation (GMICE)[9], 4) a New Zealand specific tectonic regime configuration [10,11], and 5) the use of GeoNet's strong-motion data (<https://doi.org/10.21420/X0MD-MV58>). New Zealand-specific rupture extent models [e.g. 3,12] and felt report data [13-15] can also be included in the Shaking Layers when available [3,10].

Shaking Layers was developed with two main objectives: to be scientifically and technically robust, and to be fit-for-purpose for the decision-makers who will use it. To ensure scientific robustness, the New Zealand configuration has been set up to be compatible with the 2022 update of the New Zealand National Seismic Hazard Model [7] and with new supporting science from the R-CET programme [3,10-12]. In addition, all scientific decisions related to the tool have been approved by a Science Advisory Panel (SAP), a key part of the project. To ensure the tool is fit-for-purpose, it has been co-created with an End-User Advisory Panel (EUAP) which has been approving and making decisions throughout the project. Public feedback from a national survey was also integrated into the tool's development.

This paper summarises the Shaking Layers project, including: a) the history of how the project was developed, b) the team and project structures, c) the role of the different advisory panels, d) a brief summary of the different ways to access the tool, e) the release of Shaking Layers on the GeoNet website, including communications release and webinar, f) lessons learned and challenges found along the way. Two future publications (in preparation) will provide: the science overview [11], and the Shaking Layers atlas developed as part of the tool [16]. The atlas, with a total of 65 events, includes ten large historical New Zealand earthquakes and all instrumental earthquakes of magnitude greater than 6.0 between 1968 and 2022 (a total of 51). The Shaking Layers atlas can be accessed online from the Shaking Layers website (shakinglayers.geonet.org.nz, see more details on the websites below). For clarity, we will refer to "Shaking Layers" when talking about the tool that develops shaking intensity maps for New Zealand, and "ShakeMapNZ" when referring to the ShakeMap software adapted to New Zealand specific needs.

THE SHAKING LAYERS TOOL

The Shaking Layers (SL) tool aims to provide fast near-real time shaking intensity maps following an earthquake of magnitude 3.5 or above in New Zealand, and 5.0 or above in the outer New Zealand region. The tool has been designed using ShakeMap version 4 software [17] developed by the USGS [5] and adapted to New Zealand. ShakeMap has been thoroughly tested in the last 24 years and is widely known and used internationally [e.g. 18-20]. The SL tool uses strong-motion data and felt report information as observed data, together with rupture information when available, and a series of attenuation models as well as GMICE equations and shear-wave velocity models, to produce shaking maps covering the entire country. Shaking maps are produced for PGA, PGV, MMI and spectral accelerations at different periods, currently 0.3s, 1.0s and 3.0s, other periods are planned to be included soon. They are produced using recorded and derived strong motion information provided through the near real time process "scwffparam" from the SeisComP software suite [21].

The SL tool uses the following input data and models:

- **Earthquake source parameters**, including earthquake ID, magnitude, location, depth, date and event origin time. The default source input for automatic map generation is derived from the GeoNet Catalogue (GNS Science, GeoNet New Zealand Earthquake Catalogue, <https://doi.org/10.21420/0S8P-TZ38>). Earthquake magnitude can also be updated with robust moment magnitude (M_w) solutions as they become available [3,10].
- **Strong-motion data**, including PGA, PGV and spectral accelerations, obtained near real-time from the GeoNet strong-motion dataset (GNS Science, GeoNet Strong Motion Data Products, <https://doi.org/10.21420/X0MD-MV58>). This data has been designed to be streamlined via the current New Zealand earthquake monitoring system. Although the tool can produce shaking intensity maps without strong-motion data, using all available strong-motion data received for New Zealand earthquakes significantly improves the models [10]. This is implemented through the open-source software module *scwffparam* used for rapid parametrization of waveforms data in SeisComP [21] developed by the Swiss Seismological Service and Gempa GmbH (EC-funded project NERA, with support from Geoscience Australia and GNS Science, New Zealand. In some cases, the first map produced might only have source information, producing what is called "fully predictive" maps. As soon as strong-motion data is available, the SL tool is automatically rerun (see below for details on automatic runs).
- **A New Zealand V_{s30} model**, providing time-averaged shear-wave velocity in the uppermost 30m of the subsurface on a 1 x 1 km grid [6].
- **A New Zealand based GMPE logic tree**, consistent with the 2022 NSHM [7,8].
- **A New Zealand-based GMICE** [9]
- **A global Intensity Prediction Equation** [22]. A New Zealand specific IPE is in process of being developed and will be included in the tool once ready.
- **Earthquake rupture extent**, when available [3]. This information is a critical component in producing robust maps for the largest New Zealand earthquakes [3,10] and is incorporated into Shaking Layers updates by GNS response seismologists as appropriate. Rupture estimates may be derived from near-real-time tools e.g. RCET FinDer [12] and/or developed over days to months based on detailed surface rupture mapping, seismic and/or geodetic data analysis (see [ref. [3,10] for more details).
- **Modified Mercalli Intensity data** in the New Zealand MMI scale [23] derived from GeoNet's "Felt Detailed" [14,15] felt reports, when available. Current research is under way on the potential use of "Felt RAPID" [13] felt reports in the SL tool in the future [24-26].
- The outputs produced are:
- Static maps (JPG and PDF formats) for rapid visualisation.
- Geojson files: Geojson is an open data format for representing vector geographic features. Geojson can be opened in GIS software and many internet tools.
- Json files for each output. Json is a human- and computer-readable format. Json files can be viewed in a text editor or a web browser.
- Shapefiles (vector files)
- Geotiff files: Geotiff is a raster file that can be opened in a Geographic Information System (GIS) software such as QGIS (free and open source) or ArcGIS (license required).
- Contour files
- Uncertainty data for each parameter

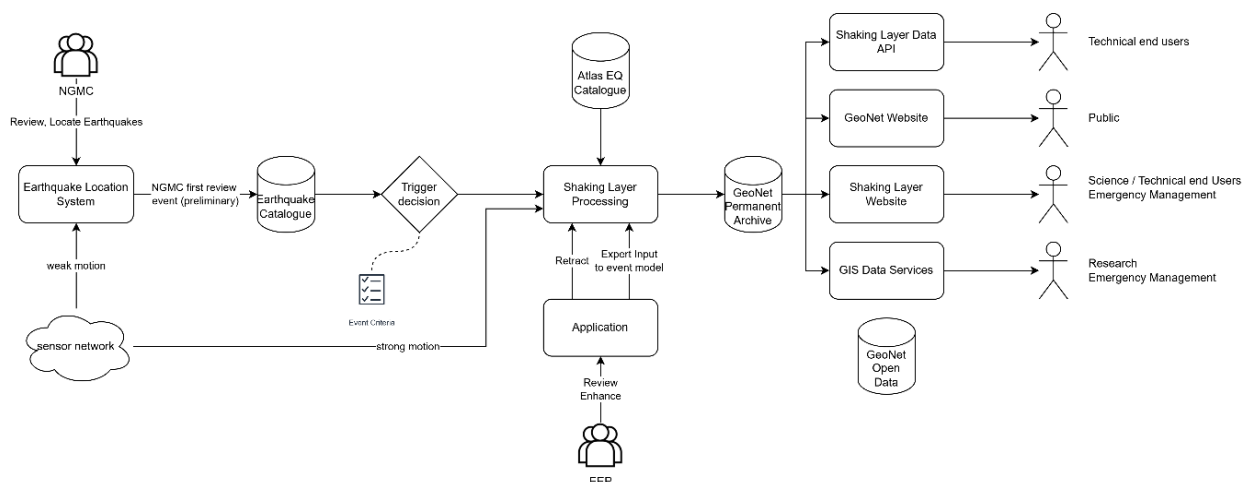


Figure 1: a) Shaking Layers system overview. Shaking Layers processing is undertaken using the ShakeMap software [5]. NGMC is the National Geohazards Monitoring Centre based at GNS Science, the EEP is the GNS Earthquake Expert Panel, which can be activated in response to significant earthquakes.

- A dynamic map with different layers to visualize each map and be able to zoom in and out. Layers include strong-motion stations, felt reports and the different intensity measures, amongst others.

HISTORY OF THE SHAKING LAYERS PROJECT: FROM SCIENCE TO OPERATIONS

Since 2014, GNS Science has been providing shaking intensity maps to end-users as needed. This was done in two different ways:

- 1) Between 2014 and 2018, GeoNet supported a website where end-users could download ShakeMap outputs specifically run with New Zealand characteristics. While end-users found them useful, the project was not well supported, and this production of Shaking Layers was turned off. Reasons for the lack of support was mostly the lack of stable funding options for GNS to keep the tool long-term. The ShakeMap version used then was 3.5.
- 2) From 2018 until 2022, the GNS Science seismologists manually ran an in-house implementation of ShakeMap version 4 [17], adapted for New Zealand (ShakeMapNZ), to provide results to end-users who would request it.

Since 2019, the need for an automatic system that provided shaking intensity maps for New Zealand earthquakes was emphasized by GNS Science scientists and New Zealand emergency managers and the engineering community. This included Toka Tū Ake Earthquake Commission (EQC) – previously a main funder of GeoNet. EQC (now the Natural Hazards Commission, NHC) used the shaking information from the USGS ShakeMap to obtain loss estimations and they needed a tool with New Zealand specific models. Support for the Shaking Layers project from EQC enabled GeoNet to begin work in 2020.

In 2020 the MBIE Endeavour project R-CET led by GNS Science started. Its main aim is to develop scientific tools to rapidly characterise the earthquake source, shaking and tsunami in the critical first hours post-earthquake. This provided a great opportunity for GeoNet and R-CET to collaborate to develop a scientifically and technically robust SL product for New Zealand. The R-CET programme is in charge of funding the science behind the tool.

The collaboration of these two programmes, and the timely revision of the 2022 NSHM which has provided the latest GMPEs for New Zealand [7,8] ensured this new SL tool is of high quality, developed with the most up-to-date science available.

The Shaking Layers project is a unique project at GNS Science, developed all the way from science to operations, with a team of seismologists, engineers, geologists, risk modellers, social scientists, seismic duty officers, and developers. It has been a huge undertaking, with many positive outcomes.

From Science to Operations

The Shaking Layers tool is currently supported (e.g. any technical issues being sorted) during business hours, to minimize the risk of a technical failure preventing decision-makers from receiving the data when it is most needed. Work towards support 24/7 is being under way. Shaking Layers runs in Amazon Web Services (AWS), a collection of public cloud computing services. Each earthquake event triggers a chain of processing steps (Figure 1) which are handled by a set of containerised tasks connected by queues. Each task performs a specific job like preparing the data, processing or publishing and each triggers the next task to run by placing its output in a queue which is the input for the next task. GeoNet provides rapid automatic and manual earthquake information minutes after they occur in New Zealand. Using this information, SL processing is triggered by a human-reviewed earthquake solution coming from GeoNet's earthquake location system, which currently uses the SeisComp [27] software. Upon triggering, a series of tasks fetch data from an FDSN web service (<https://www.geonet.org.nz/data/access/FDSN>) hosted by GeoNet, pre-process the data, and then run ShakeMapNZ. The subsequent ShakeMap-created datafiles are published on AWS S3 object store which triggers downstream publishing steps and availability of the SL maps.

Developing an automatic, reliable, and robust tool from both a scientific and technical and user perspective is difficult. Best practice science and technology are not always easy to combine, especially at the speed with which both evolve, and users need to be able to access and understand the outputs, adding another dimension to development and decision-making. For the SL project, a leadership team comprising of science leaders, technical leads, and end-user leads, was crucial to the project's success. It created a forum for the group to educate each other about their different requirements and needs, to discuss technical and scientific features, and to compromise around the best practical solutions for the scientific and technical problems as they were presented.

From a technical operations perspective, this meant ensuring the tool was developed in a way that is compatible (documented, managed and integrated) with GeoNet systems and resilience requirements, especially with regards to elements

like the GeoNet website, which is specifically engineered to withstand extremely heavy traffic loads and spikes in users. The implementation needed to be done in a way that integrated the tool with GeoNet’s systems without adverse impact on the performance of other GeoNet services or applications, and that was consistent enough with other systems and products such that it could be supported by GeoNet’s 24/7 on-call Application Support team. For example, the web page end point for shaking layers was designed to be independent from the main web pages, so that it did not compromise site resilience. Data custodianship considerations – from findability, accessibility, and reusability to interoperability – also needed to be made to ensure the shaking layer outputs could be created, stored, and shared responsibly.

Integrating rapidly evolving science, monitoring networks and systems into a robust and resilient automated product was a core component of the project. To enhance scientific robustness, the Earthquake Experts Application (EEP App; Figure 2) for desktop was developed to enable GNS seismologists to have expert user interaction at any time, and be able to pause automatic shaking layer production for a specific earthquake, run new Shaking Layers with more advanced scientific inputs (e.g. finite fault solutions), review those runs, and (if appropriate) enable those more scientifically accurate outputs to be published via GeoNet. The technical decision-making to enable the development of this application for the project is the first of its kind at GNS Science. More details about the EEP app are provided in the next section.

Consideration of science is incomplete without consideration of human behavioural responses and user needs. Input from social scientific experts in this aspect of the programme was fundamental to how engagement with users was undertaken, from the project initiation to the dissemination of the outputs. From this perspective, the public perception of the shaking, via the online felt reports, is included in the SL tool as another layer of observed information, supported and designed in collaboration with the social scientists.

For effective product delivery, we first needed to identify all of the users of SL and what we already know about their user needs. There were three high level groups:

- Highly technical users (e.g. people who use SL as part of their job, mostly engineers): We define technical users as those who require either more information beyond shaking Intensity or those who use raw data in formats other than maps.
- Moderately technical users (e.g. people who use SL as part of their job, mostly emergency managers).
- Non-technical users (e.g. people who don’t use SL as part of their job, mostly general public).

The first SL outputs were released on a technical site in May 2022, which continues to provide a technical record of inputs and other required information to support technical users. In September 2023 and November 2023, a dynamic map version of SL outputs aimed more at the general public was released to the GeoNet website and mobile application, respectively. These outputs reflect the latest solutions available from the technical site but have a different look and feel aligned with the different use cases they support.

Continued maintenance and upkeep of the SL tool, both scientifically and technically, remains an ongoing challenge (see final section).

Earthquake Experts Panel App for Manual Reviews

The SL project has been designed with a workflow that takes into account several ways in which scientific inputs to SL could evolve during an earthquake event.

Automatic Updates

Automatic runs generated by the Shaking Layers system use basic earthquake source parameters and recorded strong motion data as inputs. They are triggered when a GeoNet earthquake solution (magnitude, location, depth) changes, or at certain time intervals after an earthquake when new strong motion data may be available. There is no human review involved in these runs.

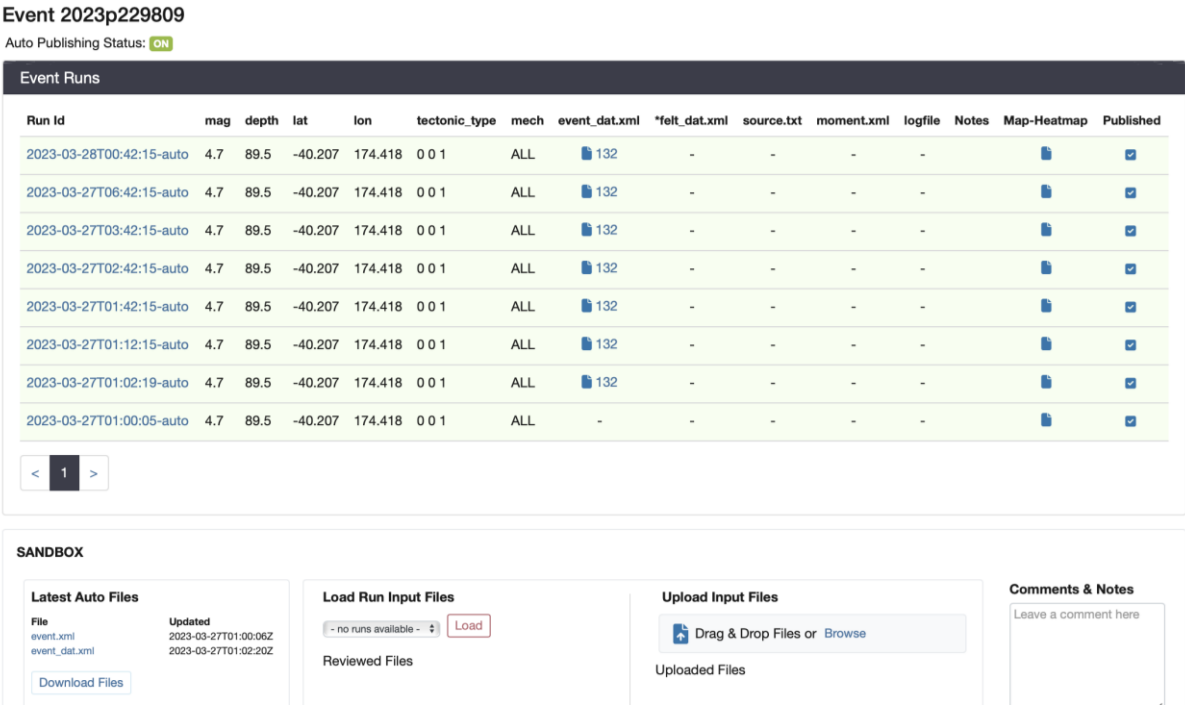


Figure 2: Snapshot of the Shaking Layers Earthquake Experts Panel App.

Manual Updates

The tool also allows reviewed versions of Shaking Layers to be generated by response seismologists within the GNS Earthquake Expert Panel (EEP) via an application known as the EEP App). Through the EEP App (Figure 2), a seismologist has the ability to manually review runs or events, add or alter inputs, and publish an updated version. A reviewed run is carried out by a seismologist based on any new/updated available science. A reviewed run may include new scientific input data such as an earthquake fault rupture geometry, felt reports, additional strong motion data, earthquake tectonic type information, moment tensor solutions and other information. More details on the different types of runs can be found in [10].

The EEP app shows all runs for each event in the Shaking Layers tool. Through the app, seismologists can do the following:

- Upload an updated input file, create a new reviewed run, compare outputs and publish runs to the Shaking Layers website. In this step, for example, moment magnitudes (Mw), depth or focal mechanism information may be incorporated from Regional Moment Tensor inversion [28] or w-phase solutions [e.g. 3].
- Upload a new configuration file that modifies the default configuration. For example, if the tectonic regime of the event is known, then the default probabilistic configuration based on the event location will be modified with the specific tectonic regime for that event (see more details in [10]).
- Upload an additional input file e.g. fault rupture file or intensity data derived from felt reports when available. Rupture files could be first rapid estimates of fault extent [e.g. 3,12] and/or more detailed models based on surface rupture geometry, seismic and/or geodetic analysis. In New Zealand, MMI data in SL tool are currently derived from GeoNet's "Felt Detailed" felt reports [15].
- Retract an event: this occurs only in rare occasions, e.g. the event does not correspond to an earthquake, or if it's outside the area of New Zealand influence.
- Stop publication of runs. This can be done when one run or a whole set of runs have wrong/suspicious results. Seismologists can correct/amend input/configuration data and create a new reviewed run and then publish that run to the SL website.

Publishing

Automatic updates are published to the Shaking Layers website until a manual run is in progress. Once the manual run has been published, auto-publishing is re-established. Further details around the priority rules for the different types of runs are summarised below:

- When an earthquake occurs, runs are created and published automatically until the EEP intervenes.
- Auto publishing will stop if a manual run is initiated, to allow the responder to assess, and adjust the results as needed.
- If the latest run is unpublished, automatic updates can still be generated, but will be unpublished by default.
- Once an EEP member publishes the latest run, automatic publishing will resume for any automatic updates that are generated. These runs are called revised runs.

SHAKING LAYERS TEAM STRUCTURE

The project has been developed by a team (Figure 3) composed of scientists, software architects, and developers, ensuring needs for scientific and technical inputs were both fulfilled. The

roles and responsibilities are summarised below, though in many cases, one person covered more than one role:

- Leadership team: group led by the Project leader, responsible for decision-making and overall direction of the project.
- Project sponsor: ultimate person responsible for the success of the project.
- Business owner: responsible for all high-level issues, ensuring the project was going ahead on time and budget.
- Project manager: responsible for the management of the project, including monthly reports and budget administration.
- Project leader: responsible for the everyday work for the project, ensuring the workflow was going smoothly and as planned.
- Product owner: responsible for the scientific and technical input for the project, including making sure that the decisions made by the Scientific Advisory Panel (SAP) and End User Advisory Panel (EUAP) were being included in the tool and reconciled with the software development team's decisions and requirements.
- End-user liaison manager: responsible for all interactions with the EUAP and the public, including the design of several surveys and the organisation of the EUAP regular meetings.
- EUAP: panel in charge of co-creating the tool with the team, ensuring it was fit for purpose.
- Science liaison person: in charge of organising the regular meetings with the SAP and any interaction with it.
- SAP: panel in charge of co-creating the tool with the team, ensuring it was scientifically robust.
- Subject matter experts: technicians in charge of different parts of the project, including the tool development, the strong-motion data and a testing technician who was carrying out any tests needed to make decisions, e.g. setting up different tectonic regimes based on the region.
- Architect: responsible for the architecture of the tool, making sure all inputs and pathways were included, and ensuring the feedback from the SAP and EUAP were part of the architecture.
- Software development team: in charge of the development of the two different websites, EEP app, GIS layers, the API and the inclusion of the SL tool on the GeoNet app.

Details of the SAP and EUAP panels are provided below.

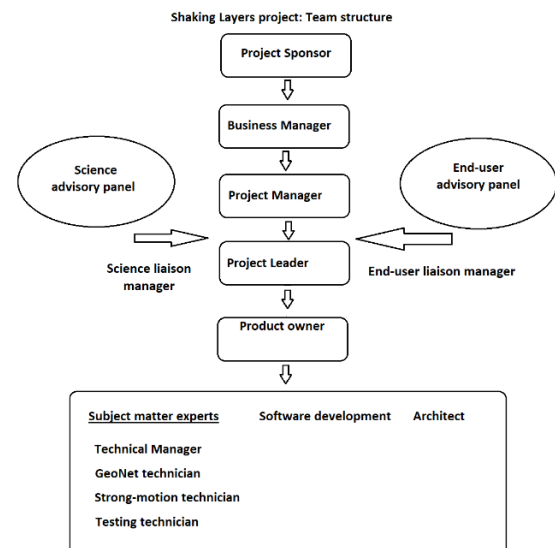


Figure 3: Shaking layers team structure.

THE ROLE OF THE SCIENCE AND END-USER ADVISORY PANELS AND THE PUBLIC

As mentioned above, the Shaking Layers tool has been developed with the SAP and EUAP, as well as feedback from a sample of the New Zealand public through a survey. User information obtained from the EUAP and the survey helped us create user personas.

The SAP was responsible for ensuring scientific robustness. The SAP is composed of six members specialised in natural hazards, including seismologists and geologists. Their role consisted of approving all scientific decisions related to the tool. Some examples are the tectonic regime set up for New Zealand, the GMPE logic tree, what Vs30 layer to use, and scientific improvements needed in future versions of the tool. Interactions with the SAP mainly consisted of monthly meetings where different scientific topics from the project were discussed and approved.

The EUAP was in charge of co-creating the tool with the team, ensuring it was fit for purpose. The EUAP is composed of 17 members representing the end-users in most need of SL following a damaging event, including: National Emergency Management Agency (NEMA), Toka Tū ake NHC, City and Regional Councils, Civil Defence, Fire Emergency New Zealand (FENZ), KiwiRail, response engineers, QuakeCore, GNS Science Seismic Duty Officers, geohazards analysts from the National Geohazards Monitoring Center (NGMC), and the scientific community. Interactions with the EUAP included: 1) monthly meetings where different aspects of the project were discussed, mostly technical and around output needs and formats; 2) survey on needs for technical inputs; 3) testing of Shaking Layers technical and public-faced website and feedback; 4) review and approval of the project user personas.

In addition, a public survey was open from December 2021 to February 2022 gathering information on the New Zealand public's preferences for earthquake information, Shaking Layers and maps. We had over 1100 respondents and found that they valued a wide range of information after a large earthquake. Information on earthquake size, location, fault rupture and shaking intensity (MMI) as well as cascading hazards (liquefaction and landslides) and their potential impacts allowed participants to 1) validate their experience, 2) estimate the threat level and 3) decide if they needed to take protective actions (for themselves or others).

Participants in this survey preferred interactive maps to static maps. Official websites and apps are the preferred sources of information about earthquakes followed by social media, TV, and Radio (News agencies). We made the following changes to SL as a result of feedback from this survey:

- Providing shaking information (MMI) as both contour and graduated colour data on one map
- Using colour vision deficient friendly colours on Shaking Layers maps
- Making the interactive maps the key focus for Shaking Layers for the public
- Developing plans to add information on cascading hazards to earthquake web pages and app (feature under development)

More generalised feedback from the public survey and targeted questions answered by the EUAP enabled us to develop some user personas that were used to test the tool and make sure their user needs were being met.

ACCESS TO SHAKING LAYERS OUTPUTS

There are five ways of accessing the outputs from the Shaking Layers tool:

- Via the Application Programming Interface (API) that provides a way for external applications to access Shaking Layer data through URL based queries. The Shaking Layer Data API guide is located at <https://shakinglayers.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. This feature has been available since May 2022.
- Via the shakinglayers.geonet.org.nz website (or “SL website”; Figure 5), designed for technical users to easily access and download outputs. This feature has been available since May 2022.
- Via geonet.org.nz earthquake event pages, where interactive map layers are available, along with linkages to the SL technical website for users to download data. Access via GeoNet website has been available since September 2023. It should be noted that only the latest run is available through this channel.
- Via the GeoNet mobile app where a limited feature set of the interactive map layers can be displayed for earthquake events. This feature has been available since November 2023. It should be noted that only the latest run is available through this channel.
- Via GIS layers in ArcGIS Online, where all available layers (latest runs only) are displayed for 30 days from the earthquake origin date. These layers can be overlaid with other key data to assess regional impacts and aid recovery efforts. This feature has been available since May 2024.

Each of these access mechanisms is explained in the following sections.

Shaking Layers API

An API has been created so users can fetch a set of standardized files from each Shaking Layers run. This capability allows users and systems to automate the retrieval of SL data. The API provides a consistent interface and data format over time, independent of changes to the underlying ShakeMap software.

The raw file set consists of default files generated by the ShakeMap software (https://usgs.github.io/shakemap/manual4_0/index.html). For information on the raw files please refer to the USGS ShakeMap website (https://usgs.github.io/shakemap/manual4_0/ug_products.html#output-files-and-products).

The standard set of files uses different units, file names, and data field names that follow the conventions of GNS and the New Zealand community's use. For example, all acceleration values (PGA, SA) in the standard files are in units of “g” compatible with other GeoNet tools, as opposed to the raw files, where they use %g units. Any changes to the standard file set will be notified and the API versioned to allow a user driven migration to the new version. More details on the difference in both types of files can be found in the website disclaimer (Figure 4) and in [10].

Technical Website for the Shaking Layers tool

The SL website (shakinglayers.geonet.org.nz) is the main access for technical end-users to download various outputs. The main features of the SL website are:

Find recent earthquakes – The home page (Figure 5) contains a list of earthquakes from the last 30 days that can be ordered by time, magnitude, depth or region. It can also be accessed via the tab “Recent Quakes” on the main menu. In addition, a list of events per year can be accessed via the “Years List” tab on the top of the website (Figure 5). Events corresponding to years before 2021 are derived from the ShakeMapNZ atlas [16].

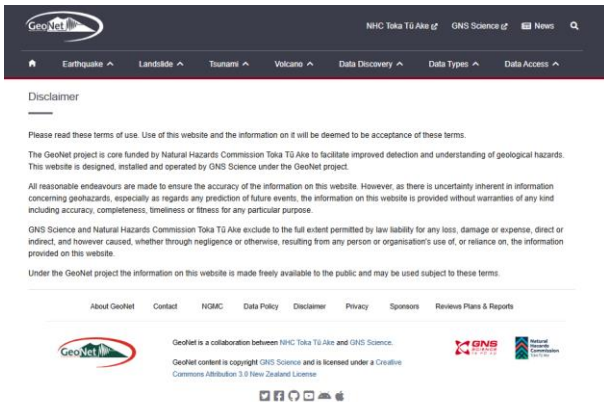


Figure 4: Shaking Layers website: disclaimer.

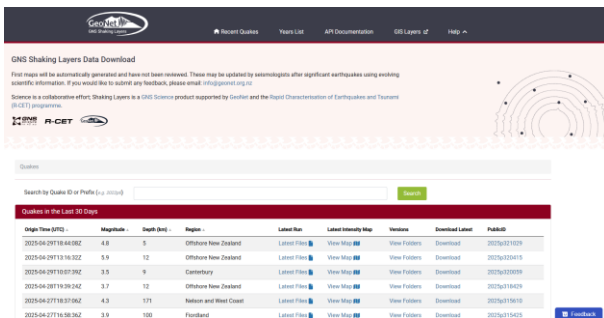


Figure 5: Shaking Layers website, list of latest earthquakes in the last 30 days.

Access all latest run files - For each event, there is a direct link to the latest run (Figure 5). Once inside the latest run page, there are two types of outputs that can be downloaded: standard files (Figure 6) or raw files (Figure 7). All files can be downloaded either individually or collectively as a ZIP file.

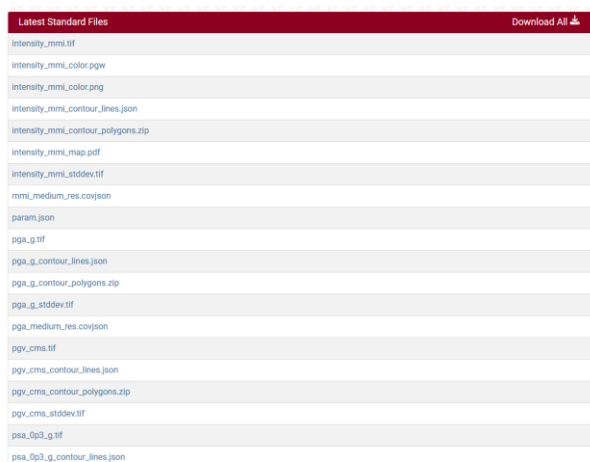


Figure 6: Shaking Layers website: example of access to standard files for the latest run.

View a static intensity map - The latest MMI map (e.g. Figure 8) can be accessed by clicking on the relevant “View Map” icon (Figure 5). Other static maps are accessed via download. The MMI map fast view is provided so the user can quickly check

they are accessing the correct event and confirm the main SL features.

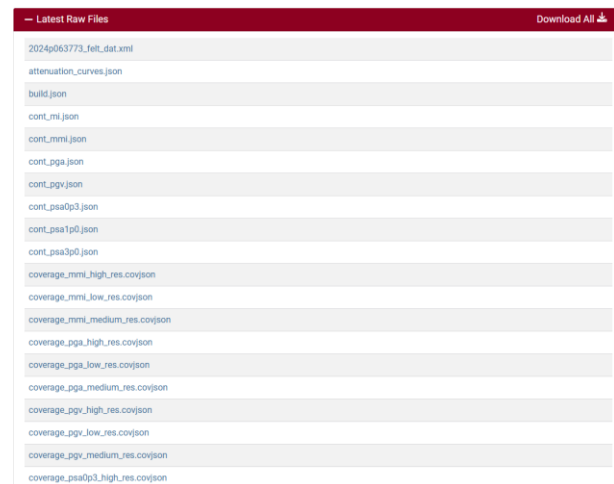


Figure 7: Shaking Layers website: example of access to raw files for the latest run.

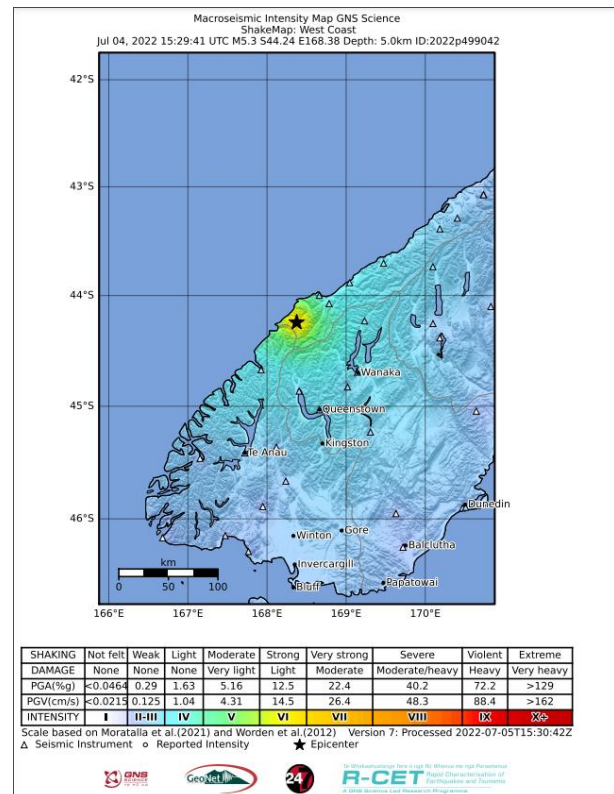


Figure 8: Shaking Layers website: example of an MMI intensity map, corresponding to a magnitude 5.3 event in New Zealand's West Coast on 4/7/22.

Download all latest run files - A quick link “Download latest” can be accessed from the earthquake list (Figure 5). This will download the complete set of standard files for the latest run for that event.

Access all run versions for an earthquake event - For each earthquake, the link to “Versions” (Figure 5) contains all the run versions for that event (Figure 9), named with their date and time, using the Coordinated Universal Time (UTC). For each run, the intensity map can be viewed through the corresponding “View Map” icon (Figure 5), similarly to the homepage. Clicking on each run will take the user to a site where the standard and raw files can be downloaded.

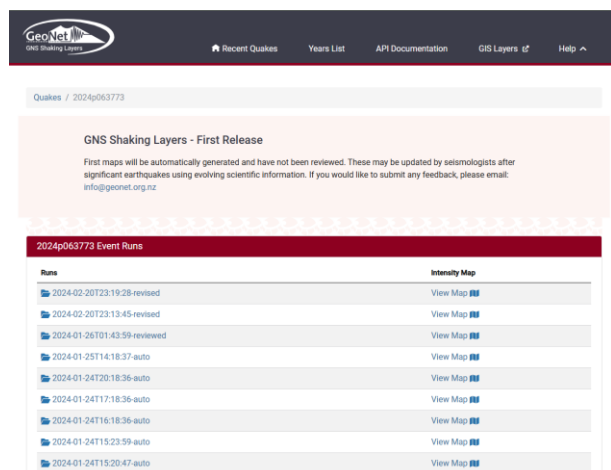


Figure 9: Shaking Layers website: example of access to the run versions for a specific earthquake.

Access to Shaking Layers guidelines – On the website menu, there is a link to “Guidelines” where users can read about how SL works and the configuration settings used to create SL runs and files. There is a download link for the full guidelines document [10] as a pdf.

Access to API documentation - On the top of the website, there is a link to the “API Documentation” with relevant information on how to query the dataset via API (Figure 10).

Link to the GeoNet website - For each event, clicking on the earthquake ID will take the user to the technical information site for that event on the [geonet.org.nz](https://www.geonet.org.nz) website.

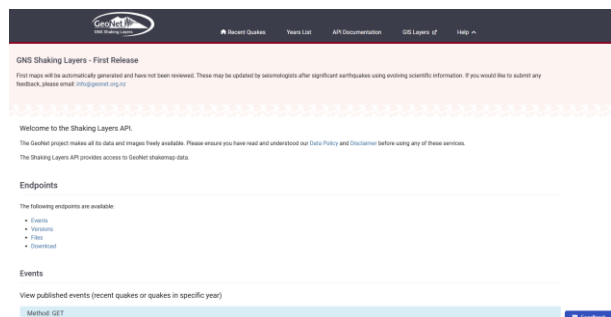


Figure 10: Shaking Layers website: access to the API description.

Interactive Web Maps on the GeoNet Website

The Shaking Layers tool displayed on the GeoNet website gets the latest data from the SL API and has a different purpose to the display on the SL technical website: whereas the latter is designed for technical end-users, the SL design on the GeoNet website prioritises features for the public’s use. This tool has been available since September 2023, allowing users to view a dynamic map (Figure 11) displaying the shaking intensity for a particular earthquake. The display can be zoomed in and out and is shown in a “SL Map” tab, alongside a map of felt report data, which is a dynamic map of felt shaking (“Felt RAPID” tab). Other SL output layers can be turned on or off by a user, including strong-motion stations, MMI as contours or as a heatmap, PGA, PGV, and spectral acceleration at different periods, as well as the epicentre of the earthquake.

It should be noted that the colour palette used in SL has been modified from the original USGS ShakeMap [5]. The new colour palette has been designed to be accessible to those users who experience colour vision deficiencies, and compatible with other colour palettes used on GeoNet website such as the Felt RAPID felt reports [13]. Currently, the SL tool uses MMI data

only from curated Felt Detailed felt reports [14], and not from Felt RAPID reports [13], which are the displayed felt reports on GeoNet website. Research towards the inclusion of Felt RAPID reports in addition to Felt Detailed is under way [25]. In addition, we included a value label above each of the contours, as well as having the feature for users to click on the contour line or anywhere in a shaded area that shows a pop up of that value for that pixel on the screen.

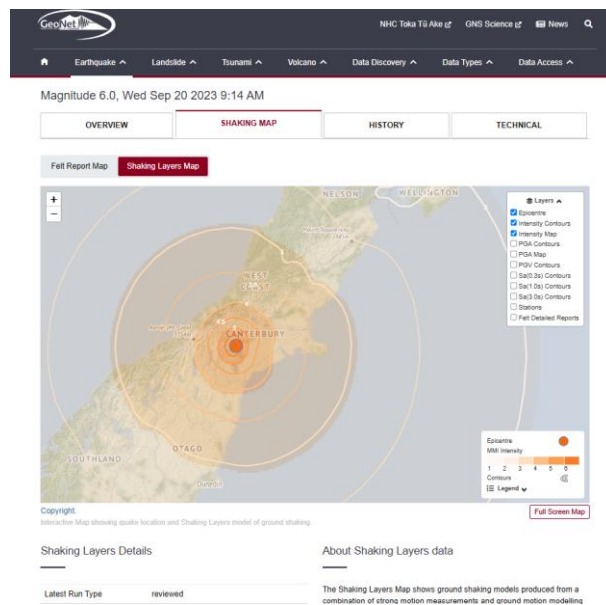


Figure 11: Shaking Layers tool on GeoNet website: example of a dynamic intensity map showing MM intensity contours and heatmap, corresponding to the M6.0 Geraldine earthquake on 20/9/2023.

Both the Shaking Layers and GeoNet websites are linked, with end-users being able to switch from one to the other, clicking on the “Shaking Layers” button from the technical tab on GeoNet (Figure 12). The maps on GeoNet website always correspond to the latest run, whereas on the SL website, all previous runs can be viewed and downloaded, allowing for a documentation process for the end-user if needed.

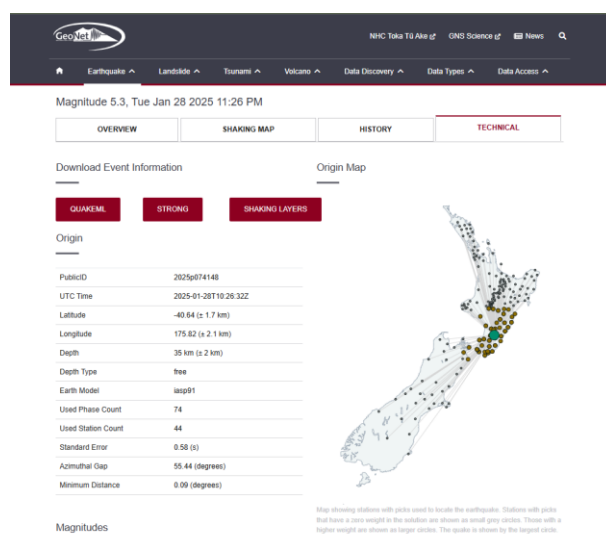


Figure 12: Shaking Layers tool on GeoNet website: technical tab where end-users can access the technical Shaking Layer website by clicking on the “Shaking Layer” button (please note only the first half of the page is shown due to space constraints).

The Shaking Layer tool is now also accessible from the GeoNet app on mobile devices (Figure 13), with similar features to the website. This feature has been available since November 2023. The layers available on the GeoNet app are reduced compared to what is displayed on the GeoNet and SL websites (MMI intensity heatmap and contours only). This was a conscious decision because the app is used predominately by non-technical users who are more interested in the MMI layers, or moderately and highly technical users who may take a first look at an earthquake before accessing the detailed information on their computer via one of the aforementioned websites.



Figure 13: Shaking Layers tool on GeoNet mobile app showing Shaking Layers for the magnitude 4.2 Pongaroa earthquake on 13/11/2023.

SHAKING LAYERS RELEASE

The Shaking Layers tool is currently business hours technical support, should there be an issue with the system. This milestone was crucial to allow the release of the tool publicly. To ensure awareness, understanding, and uptake, a release plan was created for SL, driven by GNS communications experts and the Shaking Layers Leadership group.

Shaking Layers has applications for multiple audiences. As such, the communications for the release of SL needed to

consider the individual needs and motivations of each audience to engage their interest and support their use of the SL maps.

Based on consultation with the EUAP and a public survey, it was determined the audiences could be divided into three main groups: general public, moderately technical users and highly technical users (Figures 2 and 3). These groups match the high-level groupings of the personas.

The communications approach for reaching and engaging these audiences was to:

1. Develop an engaging narrative on how Shaking Layers can be used as a tool that benefits both the public and technical end-users.
2. Develop communications products tailored to the three groups of end-users identified for SL.
3. Use audience-appropriate channels to promote the release of SL and disseminate the tailored communications products.

In crafting a compelling narrative for promoting Shaking Layers for these end-users, key messages (Table 2) were developed underpinned by each users' motivations for using SL. The motivations were based on user personas developed in the project (see more details above). The messages canvass both the individual benefits of using SL as well as the wider benefits for New Zealand, and are summarised below:

1. People may like to use SL out of curiosity or to check on the shaking felt by friends and family/whānau.
2. SL presents New Zealanders with information that helps them make sense of the way our environment responds to earthquakes.
3. SL can close the time gap to support those who need this critical information following an earthquake fast.
4. The purpose of the maps is to provide better and accessible information on earthquakes to all New Zealanders including the public, emergency responders, planners, engineers, researchers and others, within a few minutes of the earthquake.
5. SL maps can be used by a variety of agencies for informed decision making and planning to improve preparedness for and resilience to earthquake events.

Products and Channels

The next step was to weave these messages and supporting information into products and channels appropriate for each end-user (See Table 2).

Table 2: Communications products and channels by audience type.

Audience	Product	Channel
General public	Media release, web story, introductory video, social media posts, GeoNet app story	Mainstream media, GeoNet website, GeoNet app, social media, YouTube
Moderately technical	End-user Advisory Panel (EUAP) memo, Steering Committee memo, recorded PowerPoint presentation (in dev.)	Stakeholder email, YouTube, GeoNet website
Highly technical	Technical webinar presentation, user guidelines, EUAP memo, Steering Committee memo	Online webinar platform, GeoNet website, email

Each audience has at least one key communications product to support them to use Shaking Layers.

Key communications products developed as part of the release are:

- An introductory video for the public (<https://www.youtube.com/watch?v=65p78bs-Abk>). The video introduces what SL is, how it can be used, and why people may be interested in the information it offers.
- A recorded PowerPoint presentation (in development) for the moderately technical audience, that explains how and why the maps may change over time (particularly for the largest earthquakes) to support them to assess and scrutinise the data as it is delivered, particularly in a response scenario where the SL information may be critical for emergency services.
- A webinar and guidelines for the highly technical audience, that provide in depth instructions on how to access and use the data that inform the maps, so that it can be used to support other technical applications. The webinar took place following the release of SL on the GeoNet website on 7 September 2023. The aim of the webinar was to introduce the SL tool to users, show them different ways to access it, and the various features described above, and leave time for questions. The webinar lasted 60 minutes, and only registered users could attend. The users' roles and organisations were requested in the registration process. There was a total of 32 attendees, from New Zealand and overseas. Attendees included emergency managers, risk modellers, engineers, researchers, Civil Defence and councils, amongst others. The webinar was recorded and the video distributed to all registered people. The webinar can be accessed from <https://www.youtube.com/watch?v=4hS8wndgb8w&feature=youtu.be>

SL products for the public were promoted on the website and more recently on the app, mainly via media release sent to mainstream media and posts on the GeoNet and GNS social media platforms.

During the period 4 September – 21 November 2023, social media posts promoting Shaking Layers have had 202.5k impressions (i.e., times a post was seen) and 10.4k interactions (i.e., total number of times a user has interacted with a post, which includes all clicks anywhere on the post (including hashtags, links, avatar, username, and post expansion), reposts, replies, follows, and likes). Sentiments shared by the public on social media have been overwhelmingly positive with users sharing their gratitude and enthusiasm for using the SL maps following earthquake events.

Communications about Shaking Layers have been integrated into daily operations such as posting SL maps on GeoNet social media platforms following an earthquake event and communicating key updates to SL products as they occur.

PROJECT CHALLENGES AND LESSONS LEARNED

The development and implementation of the Shaking Layers tool has had its challenges and lessons learned. A few of those are summarised below:

Challenges

Working across several disciplines and with team members from across GNS Science, required learning the different ways of working. Respect and effective communication have been key to overcoming this challenge, including early development of a shared vocabulary of terms to reduce ambiguity for team

members coming from different technical backgrounds (e.g. science, software)

Adapting an external tool to a new environment is complicated. Understanding the ins and outs of an externally developed piece of software to enable seamless integration with a separate system is challenging. In this case, the ShakeMap software, developed by the USGS was an external tool that needed to be integrated with GeoNet's architecture, internal systems, and resilience requirements. The SL team has the utmost appreciation to the USGS ShakeMap team for the support to ensure this undertaking was a success.

The development of the EEP App for manual runs had never been done before by the development team. It has been particularly challenging, needing several reviews throughout its development. The best way to validate the EEP app has been through real (but less common) large events, which is not ideal for the tool, the developers, or the scientists. The requirements for the EEP App vary significantly from the public access needs. For example, the App needs the different scientific inputs used in each run to be very clear, so that seismologists can easily assess which aspects need to be updated with the latest information. In addition, being able to see the number of strong motion stations or felt reports used in each Shaking Layer run has been useful, and was a feature only added following trials of the EEP App in real-world events.

Balancing the demands of the project with the time constraints of our end-users required attention to detail and time. Not only were members of the project teams working on multiple other projects at the same time, but so were end-users. Managing expectations across the project – within the team and with end-users required proactive and consistent effort to maintain momentum and engagement.

Maintaining meaningful engagement with end-users meant a lot of effort went into ensuring we had useful content to share or feedback to seek with each session. Meetings couldn't be too close together as to be overwhelming or too far apart which could cause people to lose interest. Along with project demands, we had to strike the right balance between consultation, updates, and the amount of time we were asking of others.

Successes

Collaboration and communication have been highlights of this project. The project structure and willingness of individuals were able to bring programmes and expertise together to create a tool in a way we had never done before at GNS Science. To support these things, smaller artefacts, like a glossary of terms, helped keep participants on the same page and manage different ways of working.

Developing the tool with a multi-disciplinary team has been key to its success. The team consisted of seismologists, risk modellers, social scientists, seismic duty officers, the NGMC and developers, amongst others. This diversity has been critical to creating a product that all parties feel confident standing by – it is technically sound, scientifically up-to-date, and users feel invested and informed.

Advisory panels to help make decisions. The SAP meant that we could get the right people in the room to vet and endorse scientific decisions that impacted the code. This meant that updates and requirements could be discovered throughout, rather than being relayed urgently or with criticism at the end. Developing the tool with an EUAP from the very start has also been key. Identifying the user's needs early on, checking in with them throughout the project, and facilitating testing of the tool at different stages have helped avoid last minute changes, saving many hours of amendments, and the costs of reactive and impactful adjustments.

A well organised and seamless public release of the product, due to both the project teams hard work and the communications plan. We had materials prepared, tailored to the right audiences and experts on hand to answer questions as they arose, which helped build confidence in the tool as it was released into the public sphere.

Lessons Learned

Shared language is fundamental. We were working with a range of different experts with different ways of working, so creating a glossary that we could all depend on to help us avoid misunderstanding was enormously helpful.

Collaboration is key – a project like this needs all functions to be strong to be successful, functions in this project included scientists, technologists, users, project leaders and owners, and architects. If we had neglected any one of these things, we would not have been able to achieve this outcome in the timeframe it has taken. Exposure of the different functions to each other through the Leadership group was also really helpful in being able to build understanding and devise solutions. A similar model is being considered for development of other tools.

Collaborating with the GNS IT team was important to the successful development of the EEP App. This model will be reused for other internal secure portals that might be needed in the future.

Conducting social science research and including results before product development was a new and exciting opportunity for us. This allows us to have some informed quantitative data behind design decisions and we plan to integrate this type of discovery as much as possible.

CONCLUSIONS AND FUTURE WORK

Since May 2022, there is a New Zealand based Shaking Layers tool available for decision-makers, emergency managers, scientists and the public. Maps are produced for every magnitude > 3.5 earthquake within New Zealand and magnitude > 5.0 earthquake in the outer New Zealand region, once the event has been confirmed by the NGMC as part of GeoNet's earthquake location system. SL include PGA, PGV, MMI and spectral acceleration maps at different periods.

Currently, SL are being automatically generated using GeoNet earthquake solutions (magnitude and hypocentre) and strong-motion data. When large earthquakes occur, maps will be improved and updated by science responders with the latest scientific information, when available, e.g. extended rupture models or intensity data derived from felt reports.

At the present, the tool has produced near real-time SL for a total of 1,490 events of magnitudes 3.5 to 6.4 since March 2022 (last updated 8/4/24).

End-users can visualize the intensity maps, check the different runs for the same event, and download the outputs for their own use. Access to outputs is available via an API, ArcGIS Online, the GeoNet mobile app, and two different websites: 1) via shakinglayers.geonet.org.nz, for technical end-users, where data can be visualized and downloaded; and 2) via geonet.org.nz, that provides a dynamic map with different layers, especially designed for the public. Both websites are linked, so that users can easily move from one to the other.

- Now that the Shaking Layers version 1 tool has been developed, work on future improvements may include:
- Scientific improvements and further streamlining of rapid rupture models from the R-CET programme into Shaking Layers, enhancing its robustness for our largest earthquakes.

- Automation of MMI data feed from GeoNet "Felt Detailed" felt reports.
- SL testing using data from GeoNet's "Felt RAPID" felt reports, a crowdsourced database that receives up to tens of thousands of reports within 15 minutes of a felt earthquake.
- Improvements to site response models (e.g. underpinning Vs30-based models or more advanced models)
- Linking SL with other hazard tools, such as the Earthquake-induced Landslide forecasting tool [29].
- The use of SL for a prolonged period of time will help identify the areas where new strong-motion sensors could be deployed, improving the strong-motion network in New Zealand.

More information on the science background and future improvements for the SL tools will be provided in future publications.

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