ShakeMapNZ: Informing post-event decision making

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ABSTRACT: Near real-time estimates of ground shaking are important for a range of societal applications, such as post-event damage estimates, prioritizing Building Safety Evaluations, and informing the general public and media. The ShakeMap software, developed by the United States Geological Survey (USGS), integrates instrumental ground motion data with felt intensities to produce near real-time estimates of ground motions and intensity across a region. ShakeMapNZ is an implementation of ShakeMap for New Zealand that generates estimates of PGA, PGV, Sa(0.3s, 1s, 3s) and MMI, for felt earthquakes (M > 3). ShakeMapNZ ground motion maps as well as the spatial data will soon be available on the GeoNet website within 15-30 minutes of an earthquake. ShakeMapNZ is calibrated for New Zealand by incorporating New Zealand specific Ground Motion Prediction Equations, a New Zealand Vs30 model, and is optimised for the GeoNet station network. ShakeMapNZ will be able to be utilized for a number of post-earthquake assessments; from informing infrastructure providers on ground motions to regional earthquake loss assessments.

1 INTRODUCTION

Following a significant earthquake there is a need from a range of sectors for rapid information on the level of ground shaking and estimates of the spatial distribution of damage. Emergency managers seek to know if there was any damage and if so where is it concentrated so they can prioritise the deployment of rapid response teams. Engineers require estimates of ground motion that structures of interest may have experienced. Infrastructure providers are interested in knowing if certain ground motion thresholds were exceeded so that they can mobilise technicians and engineers to assess if damage has occurred and repair if necessary. The general public and media is also increasing its demand for information about the intensity of an earthquake and where the strongest shaking was experienced, often to validate their own personal experiences or to see what friends and families in different locations may have experienced. At present this information is available from disparate sources, for example the epicentral intensity reported by GeoNet, the felt reports displayed on the event map page, or in a text file (via ftp download) that contains the GeoNet strong motion data. Of most interest is the strong motion data which is from a network with an average station spacing of a few kilometers in urban areas such as Wellington and Christchurch, but is tens to hundreds of kilometers in other areas (Fig. 1). To estimate shaking intensity in areas away from strong motion stations, the end user is therefore reduced to either a) assign ground motions of the nearest strong motion station, b) using a fully predictive ground motion prediction model (GMPE) or c) using spatial interpolation methods to develop spatially continuous maps (Wald 1999). All these approaches will introduce significant uncertainty as ground motions can vary by orders of magnitude over the interstation spacing distances due to attenuation and area also be affected by local site effects not considered in the aforementioned approaches. Recently, Bradley (2014) accounted for spatial variations in ground motions and local site effects but only for strong motion data, and not intensity.

ShakeMap was developed by the USGS following the devastating 1994 Northridge Earthquake to rapidly map areas of potentially damaging shaking following an earthquake (Wald, 1999). In the past 16 years many seismic network operators have adopted and callbirated the ShakeMap software for their region, with Italy (Michelini 2008) and Canada (Kaka 2005) some published examples.

The strength of ShakeMap is not in the map itself, but how observed data in the form of strong or weak ground motions and macroseismic intensity data is combined with ground motion prediction equations to produce estimates of ground shaking in a number of ground motion intensity types (Worden 2012). This allows decision makers to move from using magnitude and location as an indicator of an earthquakes severity, to using the spatial distribution of shaking intensity (Wald 1999).

ShakeMap integrates observed instrumental ground motions from seismic recording stations and felt report data from the general public with ground motion prediction models to estimate ground motions and their uncertainties in areas without instrumentation. ShakeMap produces maps of gridded shaking intensity in the form of peak ground acceleration, peak ground velocity, response spectral acceleration (0.3s, 1s, 3s) and macroseismic intensity.

This paper describes how ShakeMapNZ is implemented for New Zealand within GeoNet. With particular focus on how it is customized and calibrated to the New Zealand setting. First the details of the implementation within GeoNet are presented, followed by a ShakeMapNZ example for a recent earthquake, and lastly suggested improvements for future versions of ShakeMapNZ are given.

2 SHAKEMAP CONFIGURATION IN GEONET

2.1 GeoNet Network

At present GeoNet has a network of around 270 strong motion stations that are used to provide near real-time instrumental ground motions (Fig. 1). This includes a number of older CUSP sensors, as well as newer Basalt sensors. Newer stations provide continuous data feeds, while older stations are triggered then dial up to send the data back to GeoNet. In most cases all data is received within 10-15 minutes. The GeoNet strong motion network is growing at present by around ~10 sensors a year. Strong motion stations are often located in buildings (fire station’s, schools etc), mostly in populated areas, but some are also co-located with broadband stations. New strong motion sensors record continuously at 50 Hz where as older triggered sensors record at 200 Hz.

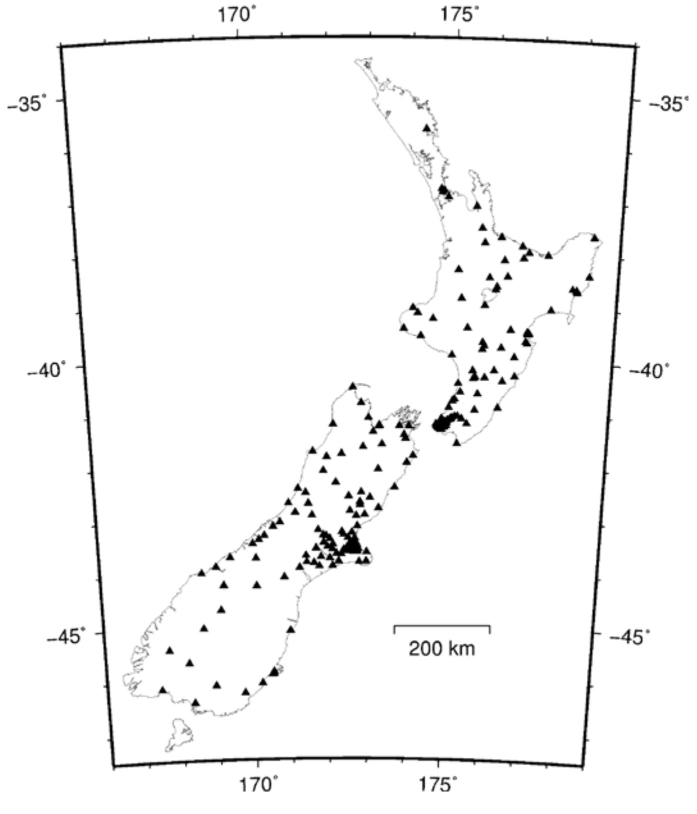

Figure 1. GeoNet Strong Motion Station network as of December 2014. Note that station spacing is higher in urban areas with high seismic hazard (e.g. Wellington and Christchurch).

2.2 **GeoNet Triggering of ShakeMapNZ**

The following process is used to generate a ShakeMap within 15-30 minutes of an earthquake:

1. SeisComP3 (GeoNet seismic operating system) detects and locates an earthquake from live data streams. ShakeMap is triggered if M > 3.0;
2. SeisComP3 waits for all strong motion data streams to arrive then generates a ShakeMap event data file which contains the earthquake location and magnitude, and the peak strong (and weak) motion data. Note this is step is the main time delay in the process. ;
3. FeltReport data is used to generate estimates of MMI and an intensity input data file is generated (this step is in development and not yet included in the production version);
4. ShakeMap is then triggered to model PGA/PGV/Sa and intensity over a large region;
5. ShakeMap mapping tiles are generated as well as data outputs (ASCII files, shapefiles etc), these are then pushed to the web server for download by end-users;
6. If the earthquake solution is updated, Steps 4-5 are repeated.

3 **GROUND MOTION AND INTENSITY PREDICTION MODELS**

To customize ShakeMap to New Zealand, one of the major changes was the addition of a New Zealand specific Ground Motion Prediction Equation (GMPE) to the GMPE library of ShakeMap. GMPE are the largest source of uncertainty for any seismic hazard assessment, so selection of a suitable GMPE is critical in reducing uncertainty in the ground motion estimates in ShakeMap. For ShakeMapNZ, the selection of the GMPE is magnitude and location dependent. For shallow crustal earthquakes, the NZ specific GMPE of Bradley (2013) is adopted. This model is based on Chiou and Youngs (2008), but new terms are added for distance through the high attenuation region in the Taupo Volcanic Zone as well as to account for presense of site class A in New Zealand. Bradley (2013) derived new coefficients for the model using New Zealand strong motion data collected prior to 2010. It was recently adopted in the seismic hazard model for Canterbury, which underpins an update of the Seismic Hazard Zoning Factor for the region (Gerstenberger 2014). For instraslab and interface earthquakes ShakeMapNZ uses the GMPE of Zhao (2006), which was derived using international subduction zone events.

For Intensity Prediction Equations, the model of Allen (2012) is adopted which includes macroseismic intensity data from around the globe as well as over 100 New Zealand events from the Dowrick and Rhoades (2005) database. 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 faster than what is observed from the Felt Report data, which appears to ‘flatten out’ at larger distances. At present including Felt Report data in the bias correction for ShakeMap is in development. This will be included in a future update of the New Zealand implementation. However, to bias correct for the inter-event uncertainty in the IPE, all observed instrumental ground motions are converted to macroseismic intensity using the Ground Motion to Intensity Conversion Equation (GMICE) of Worden et al (2012). This model allows bi-directional conversion between instrumental ground motions and intensity and is based on data primarily from California.

3.1 **Bias Correction of Ground Motion Prediction Models**

Ground motion prediction equations, or attenuation equations, model ground motion parameters such as PGA, PGV and Sa as a log normal variable typically have the functional form of:

$$Y = f(M, R, \vartheta) + \eta + \varepsilon \qquad (1)$$

Where *Y* is the ground motion parameter at the site as a function of earthquake magnitude (*M*), distance (*R*), and other explanatory variables (ϑ) such as site class, directivity or hanging-wall effect. η is the interevent variability which has zero mean and standard deviation of σ, and ε is the intraevent variability with zero mean and standard deviation of σ. ShakeMap uses observed strong motion data and felt intensities (in development) to remove the interevent variability in the GMPE through bias correction. ShakeMap uses a least squares approach to minimizes the L1 norm (absolute deviation) between the observations and GMPE by using a magnitude shift. Figure 2 shows the bias correction for the 6 January 2015 M6.0 Wilberforce event. For this step, all data sets (strong ground motion and felt intensities) are converted into the ground motion parameter of interest (e.g. PGA) through Ground Motion Intensity Conversion Equations (GMICE) and used in the bias correction. Although this introduces added uncertainty through the GMICE, it allows a more robust bias correction as the felt intensities have more uniform distance ranges than strong motion stations alone. However one of the strengths of the ShakeMap method is that it carries this conversion uncertainty through to the final ground motions and uncertainty maps.

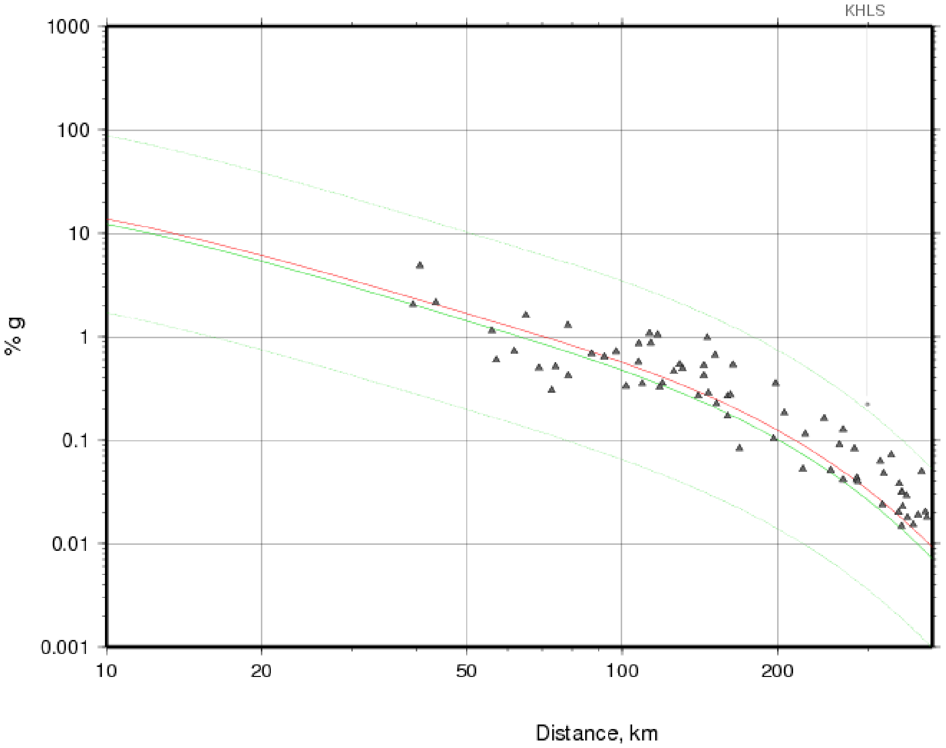

Figure 2. Bias correction of Ground Motion Prediction Equation for the 6 January 2015 M6.0 Wilberforce Earthquake. The triangles are the stations from GeoNet. The red line is the unbiased GMPE model (Bradley 2013) and the green solid line is the bias corrected model using the station data within 100 km, the dashed green lines are the one-sigma bounds (intra-event uncertainty). The station data has been normalised to rock.

For the bias correction of ShakeMap, there are two key parameters than control this step. First, the maximum distance of stations ($\mathrm{Max}_{\mathrm{DIST}}$) to include in the bias correction, and second the minimum number of stations ($\mathrm{Min}_{\mathrm{STNS}}$) available before bias correction is applied. The former parameter, $\mathrm{Max}_{\mathrm{DIST}}$, is important because it determines the stations that will be used to bias correct the GMPE to remove the inter-event uncertainty. The latter parameter, $\mathrm{Min}_{\mathrm{STNS}}$, determines if the bias correction is applied. For most near real-time earthquake alerts, the interest is shaking intensity or damage and loss. For these applications the focus is on constraining the near-source ground motions where shaking and damage will most likely be most severe. When the bias correction is performed, if there is a large amount of data at larger source to site distances (> 200 km), which is often the case, then this will weight more heavily on the bias correction than the often few near source (<20 km) or intermediate (20-100 km) distances. Therefore there is a trade-off between including a sufficient amount of stations to remove the inter-event uncertainty through bias correction, and making sure the near-source part of the GMPE is well fitted to the observed data. The optimum combination of $\mathrm{Max}_{\mathrm{DIST}}$ and $\mathrm{Min}_{\mathrm{STNS}}$ will be controlled by the network configuration and regional seismicity.

Figure 3 shows a plot of the cumulative number of earthquakes (M > 4.5 since 1990) that would be recorded by a given number of stations (3, 6, 9, 12 or 15) as a function of hypocentral distance for the current GeoNet network configuration. This plot can be used to identify the best configuration for

$\mathrm{Max}_{\mathrm{DIST}}$ and $\mathrm{Min}_{\mathrm{STNS}}$. For example, if $\mathrm{Min}_{\mathrm{STNS}}$ was set to 3, then we would need a $\mathrm{Max}_{\mathrm{DIST}}$ of 170km to ensure bias correction was applied 100 % of the time (assuming the seismicity is similar to that of 1990-present). If we set $\mathrm{Min}_{\mathrm{STNS}}$ to 6 then we need $\mathrm{Max}_{\mathrm{DIST}}$ to be set to 230 km for 100% bias correction. Therefore we set $\mathrm{Min}_{\mathrm{STNS}}$ to 3 and $\mathrm{Max}_{\mathrm{DIST}}$ to 120 km. Future development will add zones where different $\mathrm{Max}_{\mathrm{DIST}}$ and $\mathrm{Min}_{\mathrm{STNS}}$ can be set based on the network density and population centres as well as exploring the use of magnitude dependent parameterisation of $\mathrm{Min}_{\mathrm{STNS}}$ and $\mathrm{Max}_{\mathrm{DIST}}$.

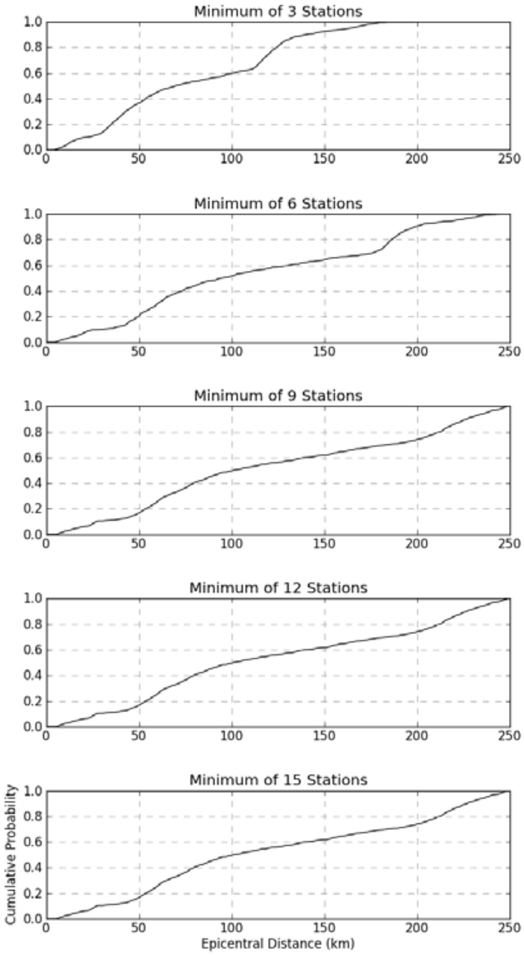

Figure 3. Cumulative number of earthquakes (M > 4.5 since 1990) that would be recorded by a given number of stations as a function of hypocentral distance. For a minimum of three stations in the bias correction, a maximum distance of 170 km would be needed to bias correct 100 % of the time (based on previous seismicity patterns). For 6 stations, the distance increases to 230 km for 100 % bias correction.

4 SITE CLASSIFICATION

Site effects are an important contributor to the spatial variation in strong ground motions. Local site conditions can cause significant amplification or deamplification of ground motions. To account for local site amplification in the peak ground motion estimates, ShakeMap adopts an amplification factor approach (Borchedt 1994). In this approach, period dependent ground motions are amplified according to amplification factors based on the shear wave velocity in the upper 30m (V_{S30}).

ShakeMap requires V_{S30} values for two processing steps. Firstly, observed ground motions are corrected to a reference “Rock Site Class” prior to the bias correction and removal of the inter-event residual term in the GMPE. Secondly, during the prediction stage where ground motions are estimated for all grid nodes, ShakeMap estimates the rock ground motion at all unknown sites (grid nodes) then corrects for site class using the amplification factors.

Table 1. Site Classification and V_{S30} Mapping.

Site Class	Site Class Description	V_{S30} Assignment for ShakeMap
A	Unconfined Compressive Strength (UCS) > 50 MPa & V_{S30} > 1500 m/s & not underlain by < 18 MPa or V_{S30} 600 m/s materials.	1500 m/s
B	1 < UCS < 50 MPa & V_{S30} > 360 m/s & not underlain by < 0.8 MPa or V_{S30} 300 m/s materials, a surface layer no more than 3 m depth (HW-CW rock/soil).	760 m/s
C	Not class A, B or E, low amplitude natural period ≤ 0.6s, or depths of soils not exceeding those in Table 2.	560 m/s
D	Not class A, B or E, low amplitude natural period > 0.6s, or depths of soils exceeding those in Table 2, or underlain by < 10 m soils with undrained shear strength < 12.5 KPa, or < 10 m soils SPT N < 6.	270 m/s
E	> 10m soils with undrained shear strength < 12.5 KPa, or > 10m soils with Standard Penetration Test (SPT) N < 6, or > 10m soils with V_{S30} ≤ 150m/s, or > 10m combined depth of previous properties.	180 m/s

To derive the V_{S30} map for New Zealand (Fig. 4), the Site Class Map of Destegul (2008) was converted to V_{S30} by assigning the mean V_{S30} value for each Site Class. This was generated with a grid resolution of 100 m. Table 1 outlines the mapping between the NZ1170 site class and Vs30.

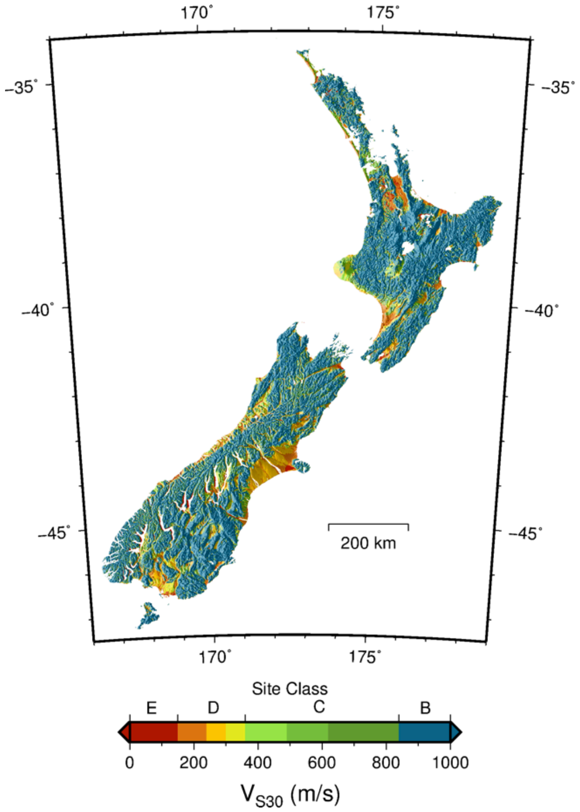

Figure 4. V_{S30} Map of New Zealand. As can be seen the most common site class for New Zealand is B, corresponding to V_{S30} values of >760 m/s. Although most cities and large towns are located on site class C or D (V_{S30} 180 – 760 m/s).

5 EXAMPLE SHAKEMAP

5.1 6 January 2015 M6.0 Wilberforce Earthquake

The Wilberforce Earthquake was the first significant event since the ShakeMapNZ system was running in beta version on the GeoNet production server. A ShakeMap was generated within 15 minutes of the event following the first reviewed solution from the Duty Seismologist. Upon revision of the magnitude and location (a few hours later), the ShakeMap was automatically re-generated. It can be seen from the bias correction plot in Figure 2 that there was a number of recordings in the intermediate distance ranges for this event, with over 20 stations within 120 km. Using the recorded motions, there was a slight downward bias correction for the PGA of this event. The nearest station was ~38 km from the hypocentre, so in this case the estimates of shaking intensity from ShakeMap in the epicentral region were of great value to inform the potential of damage. The estimated intensities were strong to damaging on the GeoNet reporting scale, which equates to MMI7 with a few pockets of MMI8 in the valleys. Luckily in this instance, the epicentral region was sparsely populated

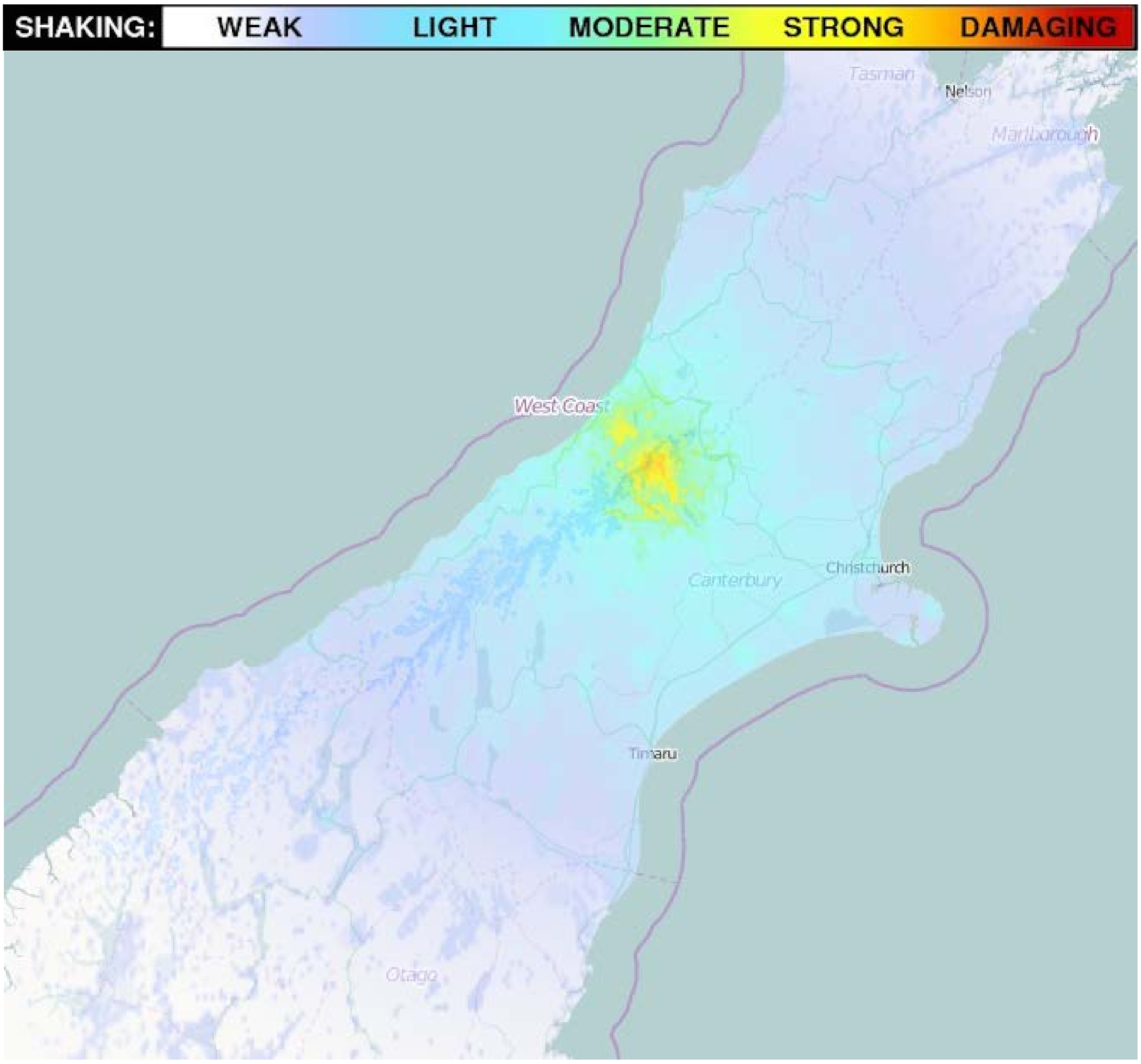

Figure 5. ShakeMap of the 6 January 2015 M6.0 Wilberforce Earthquake.

6 FUTURE IMPROVEMENTS

ShakeMapNZ will continue to evolve over the next few years as new features are added. Examples of ongoing work include:

- Implement the use of Felt Report data for MMI estimation and bias correction of IPE;
- Update Dowrick and Rhoades (2006) IPE with Felt Report data;
- Develop NZ-specific GMICE;
- Develop process for automated inclusion of CMT solutions to define a finite fault;
- Continued refinement of the mapping interface (e.g. to show station data).

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