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Deconvolution of Surface Motions from the Canterbury Earthquake Sequence for use in Nonlinear Effective Stress Site Response Analyses

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ABSTRACT

Records from the 2010-11 Canterbury earthquake sequence as well as the extensive site investigation data that has been collected in the greater Christchurch area provide an exceptional opportunity to evaluate the capabilities of fully nonlinear effective stress site response analyses in capturing the response of liquefiable soils during strong shaking. However, the location of Christchurch in a deep basin structure as well as the absence of “rock” recordings makes the selection of input motions a major source of uncertainty for these types of analyses. The presented research focuses on the process of deconvolving surface motions at select sites to provide input motions for site response analyses at 11 strong motion stations throughout the greater Christchurch area for 6 events from the Canterbury earthquake sequence. Representative seismic site response results using deconvolved motions for the 22FEB11 Christchurch earthquake are also presented.

Introduction

The 2010-11 Canterbury earthquake sequence devastated much of Christchurch, New Zealand. Liquefaction during the 4SEP10 (M_w 7.1) Darfield event affected approximately 10% of the area of Christchurch, while the 22FEB11 (M_w 6.2) Christchurch event affected over 50% of the developed land (see Figure 1). Including these two events, there were a total of seven events with moment magnitude (M_w) greater than or equal to 5.5 between 4SEP10 and 23DEC11 that caused varying degrees of liquefaction in and around Christchurch. Moreover, the M_w 4.7 event that occurred on 26DEC10 and M_w 5.0 event of 16APR11 triggered isolated cases of liquefaction.

Previous studies, such as those by Gingery et al. (2015), Kramer et al. (2011), Youd and Carter (2005), and Zhegal and Elgamal (1994), have examined the effects of soil liquefaction on ground response during strong shaking. The presented research capitalizes on the data obtained from the Canterbury earthquake sequence, specifically data from the GeoNet database of processed strong motion station recordings (geonet.org.nz) and the extensive site investigation data that has been collected by researchers and practitioners throughout Christchurch over the past several years (see Canterbury Geotechnical Database, CGD). The study discussed hereafter focuses on the selection of input motions for evaluating the capabilities of one-dimensional, fully nonlinear effective stress seismic site response analytical procedures to model the seismic response of sites with and without significant shaking-induced pore water pressure generation. Specifically, the deconvolution of surface acceleration time series is performed to provide representative “stiff” soil input motions for seismic site response analyses. Representative results from fully nonlinear effective stress seismic site response analyses using these input motions are also presented.

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Christchurch and the Canterbury Earthquake Sequence

Figure 1 shows maps of liquefaction as observed from aerial photography following the Darfield and Christchurch events (CGD, 2013). Also shown are the locations of strong motion station (SMS) sites operated within the GeoNet network in the greater Christchurch area. The SMS sites are located in areas with varying degrees of liquefaction for these two events, which makes their recordings valuable in the evaluation of seismic site response analyses' ability to capture the response of subsurface soils with and without significant amounts of seismically induced excess pore water pressures. Table 1 provides a summary of the SMS sites studied as well as the peak ground acceleration (PGA) and R_{rup} distances for each event.

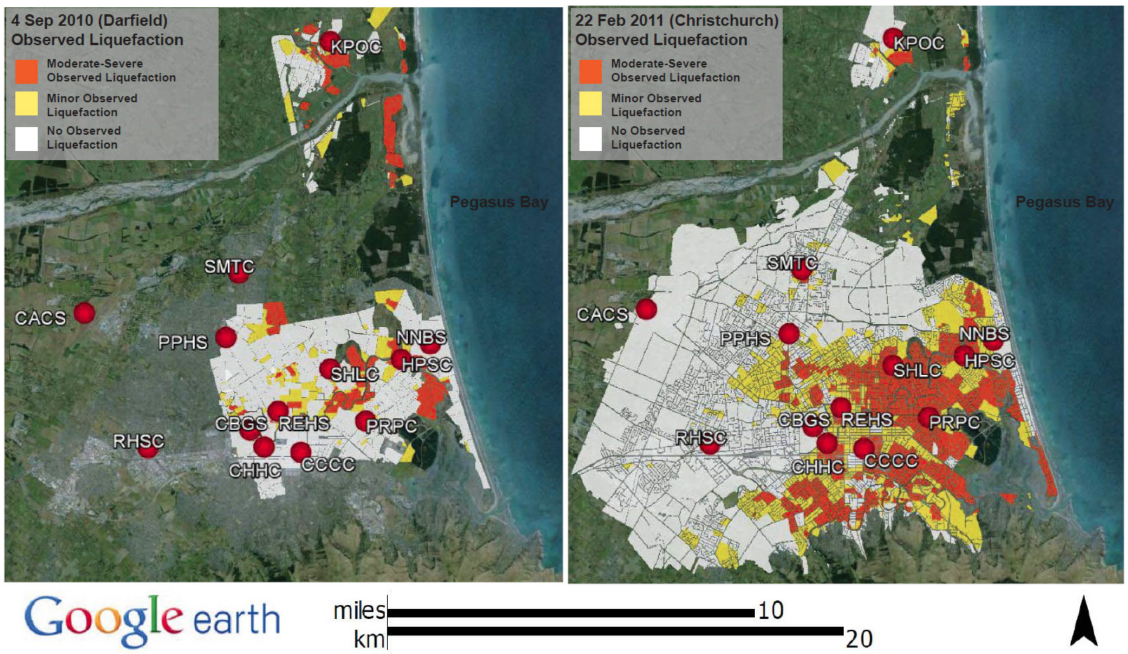

Figure 1: Observed liquefaction maps for the Darfield and Christchurch events (CGD, 2013)

All of the strong motion station sites of interest are situated within the Canterbury Plains. The general geology of this area comprises of distinct layers of gravels interbedded with layers of finer sediments (i.e., silts, sands, and some peats and clays) to a depth of over 500 m below the ground surface (Brown and Weeber, 1992). Moreover, depth to "basement" rock for soils underlying the Canterbury Plains can be over 2 km below ground surface (Brown et al., 1995). These deep sediment deposits coupled with the presence of the volcanic rock that makes up the Port Hills and Banks Peninsula to the southeast of central Christchurch create a basin structure.

The deep basin structure that underlies the studied sites makes the selection of representative "rock" input motions difficult due to the absence of outcropping "rock" recordings on the north side of the Port Hills (i.e., Canterbury Plains side of the Port Hills). The Lyttelton Port strong motion station (LPCC) has a V_{s30} of about 792 m/s (Wood et al., 2011), placing it in the category of engineering bedrock (i.e., B/C rock boundary for $V_s \approx 760$ m/s); however, the location of LPCC with respect to the locations of the events of interest and seismic energy propagation from these events make it a non-ideal input motion for seismic site response analyses in the Christchurch area (i.e., LPCC is located on the southern side of the Port Hills as opposed to the northern side as well as the hanging wall of the 22FEB11 Christchurch event as opposed to the footwall).

Table 1: Characteristics of event parameters at strong motion stations

Station	**4SEP11 M_w 7.1**		**26DEC10 M_w 4.7**		**22FEB11 M_w 6.2**		**13JUN11[1] M_w 6.0**		**23DEC11 M_w 5.8**		**23DEC11 M_w 5.9**	
	PGA (g)	**R_{rup} (km)**	**PGA (g)**	**R_{rup} (km)**	**PGA (g)**	**R_{rup} (km)**	**PGA (g)**	**R_{rup} (km)**	**PGA (g)**	**R_{rup} (km)**	**PGA (g)**	**R_{rup} (km)**
CACS	0.2	11.7	0.02	13.1	0.21	12.8	0.14	16.2	0.07	19.4	0.08	16.7
CBGS	0.16	14.4	0.27	4.4	0.5	4.7	0.16	7.6	0.16	12.9	0.21	10.2
CCCC	0.22	16.2	0.23	2.6	0.43	2.8	-	-	0.13	11.1	0.18	8.7
CHHC	0.17	14.7	0.16	3.5	0.37	3.8	0.22	6.8	0.17	12.5	0.22	10.0
HPSC	0.15	21.7	0.05	6.6	0.22	3.9	0.26	5.5	0.2	6.12	0.26	3.2
KPOC	0.34	27.6	0.01	19.8	0.2	17.4	0.1	19.4	-	-	-	-
NNBS	0.21	23.1	0.04	7.8	0.67	3.8	0.2	5.6	-	-	-	-
PPHS	0.22	15.3	0.09	8.2	0.21	8.6	0.12	10.4	0.12	13.4	0.14	10.5
PRPC	0.21	19.3	0.09	3.7	0.63	2.5	0.34	3.7	0.29	8.1	-	-
REHS	0.25	15.8	0.25	4.4	0.52	4.7	0.26	6.8	0.2	11.5	0.25	8.8
RHSC	0.21	10.0	-	-	0.28	6.5	0.19	11.8	0.16	17.2	0.16	14.6
SHLC	0.18	18.6	0.16	5.6	0.33	5.1	0.18	6.3	0.26	9.1	0.28	6.1
SMTC	0.18	17.5	0.03	10.5	0.16	10.8	0.09	12.0	0.07	13.2	0.15	10.4

Notes:

1) The M_w 6.0 event on 13JUN11 was preceded by a M_w 5.3 event that occurred approximately 80 minutes earlier.
2) PGA values from Bradley et al. (2014) for Darfield, Christchurch, 13Jun11, and 23Dec11 (M_w5.9) events; values for 23Dec11 (M_w5.8) and 26Dec10 events are from metadata provided by Bradley (2013) pers. comm.
3) R_{rup} values from Bradley et al. (2014) for Darfield, Christchurch, 13Jun11, and 23Dec11 (M_w5.9) events; values for 23Dec11 (M_w5.8) and 26Dec10 events are from metadata provided by Bradley (2013) pers. comm.

Deconvolution of Surface Motions

With the lack of representative "rock" input motions, as well as the difficulty in accurately characterizing the stratigraphy beneath the studied sites to a depth of engineering bedrock, deconvolving recorded surface motions is a viable alternative. Deconvolution consists of inputting an outcropping motion at the surface of a 1D soil column and using an equivalent-linear analysis to calculate the acceleration-time history at a point beneath the ground surface (Idriss and Akky, 1979). This "within" base motion can be converted to an outcropping motion and used as an input motion for subsequent convolution analyses.

Silva (1988) outlines a procedure to help avoid the situation of unrealistic motions being calculated at depth due to the propagation of the total surface motion via an equivalent-linear analysis during the deconvolution process. These steps were adhered to and are as follows:

1. A low pass (LP) filter was applied to the recorded surface motion to be used for the deconvolution analysis at 15 Hz and scaled by 0.87; SeismoSignal™ was used to perform a 4th order, LP Butterworth filter.
2. The filtered and scaled motion from step 1 was input at the surface of a 1D soil column.
3. The motion from a layer of interest at some depth below the surface is obtained via an equivalent linear solution.
4. The final iteration values of shear modulus reduction (G/G_{max}) and material damping (λ)

for each layer during the deconvolution process is obtained.

5. The deconvolution process was performed again by using a linear analysis with the final values of G/G_{max} and λ from step 4 for each layer of the 1D soil column and inputting the LP filtered (15 Hz) full surface motion (i.e., not scaled by 0.87) at the top of the column to obtain the "final", outcropping, deconvolved motion.

SHAKE2000 was utilized to perform all deconvolution analyses. The empirically based normalized shear modulus reduction and material damping relationships proposed by Darendeli (2001) were used for all material above the Riccarton Gravel.

Half-Space and Sites for Deconvolution

Figure 2 provides a simplified subsurface profile for Christchurch. The Riccarton Gravel layer was used as the half-space for deconvolution analyses and subsequent seismic site response analyses. The impedance contrast between the stiffer Riccarton Gravel and the softer overlying surficial deposits (on average the Riccarton Gravel impedance was approximately twice that of the overlying soil for the sites studied) as well as the presence of this layer throughout the Christchurch region substantiated this material as a reasonable half-space for deconvolution.

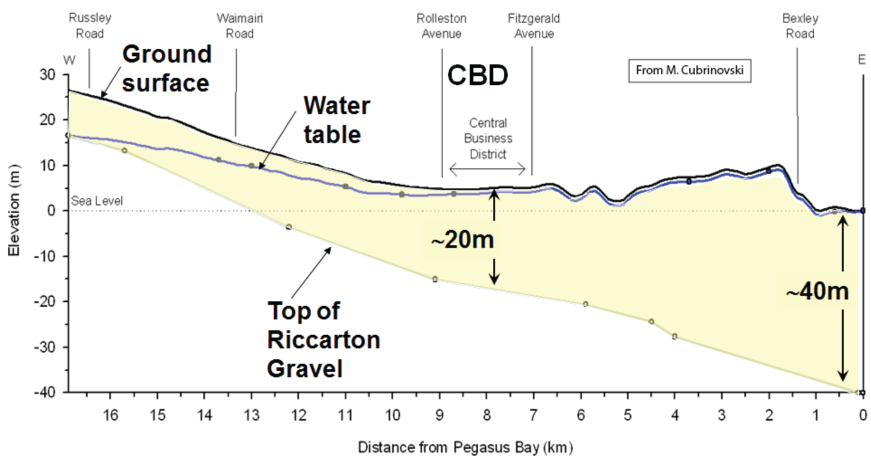

Figure 2: Simplified subsurface profile for Christchurch (from Cubrinovski et al. 2012)

The SMS sites used for the deconvolution procedure were the Canterbury Aero Club station (CACS) and the Riccarton High School station (RHSC) sites; the locations of these stations are shown in Figure 1. These sites are located on soil that did not show surface manifestations of liquefaction during any of the events of interest and are believed to have shown minimal nonlinear response during shaking; these points are important to note as an equivalent-linear solution to the seismic site response cannot fully capture the nonlinear response of soils, but is necessary for deconvolution. Furthermore the assumed depth to the Riccarton Gravel layer for these sites (i.e., 6 and 16 m, respectively) is the lowest among the 13 strong motion station sites listed, which requires the surface motion to be deconvolved over a relatively shallow profile. Representative time histories of the deconvolved "outcropping" motions at the CACS site will be shown later.

Deconvolved ground motions were scaled to account for differences in the site-to-source distance and V_s of the Riccarton Gravel between the deconvolution sites and the convolution site response sites. This scaling was completed using the New Zealand specific ground motion prediction equation outlined in Bradley (2013). By using the same source parameters for a given event (i.e., M_w, Z_{tor}, dip, etc.) and changing the distance parameter (R_{rup}) and the V_{s30} between the sites where the deconvolution was performed and the sites where convolution analyses were carried out allows for an average scale factor across all periods to be calculated. The parameter V_{s30} was used as a proxy to scale between the different assumed values of V_s of the Riccarton Gravel. Shear wave velocity values for the Riccarton Gravel were assumed based on the work of Wotherspoon et al. (2013) and ranged from 300 to 460 m/s for the sites studied.

Overview and Sample Results of Seismic Site Response Analyses

Nonlinear effective stress, nonlinear total stress, and equivalent linear one-dimensional, seismic site response analyses were performed for each station listed in Table 1 for each event of interest that was recorded (i.e., if a particular event was not recorded for a particular station, no analysis was carried out for that combination of station and event). The seismic site response program *DeepSoil* (V5.1, Hashash, 2012) was used to conduct all convolution seismic site response analyses. This program utilizes a discretized multi-degree-of-freedom lumped parameter model of the 1D soil column and captures the hysteretic soil response through a pressure-dependent hyperbolic model to represent the soil's backbone curve and the modified extended unload-reload Masing rules for nonlinear analyses. Effective stress nonlinear analyses differ from total stress nonlinear analyses in that the generation of excess pore water pressure during seismic loading and subsequent degradation of both the strength and stiffness of a softening soil is accounted for using the models presented by Matasovic (1993). DeepSoil also accounts for the dissipation and redistribution of excess pore water pressure during seismic loading.

The correlations proposed by Darendeli (2001) were used to obtain initial estimates of G/G_{max} and λ curves for the soils above the Riccarton Gravel layer at each site where seismic site response analyses were completed. The procedure proposed by Yee et al. (2013) was used to correct the G/G_{max} curves to better capture the large strain response of soils, as the Darendeli (2001) correlation tended to underestimate the estimated shear strength of the soils studied. Due to a lack of published guidance in correcting the material damping curve to capture large strain behavior, a hybrid damping curve was calculated that transitioned from the damping curve calculated from the Darendeli (2001) relationship to a strength based material damping curve via a linear (in semi-log space) approximation. These "strength corrected" curves were used as target curves for the fitting procedures employed in DeepSoil to represent the strain dependent soil properties for nonlinear analyses. When available, CPT data from both the CGD (2014) and Wotherspoon et al. (2013) were used to estimate soil properties and V_s profiles (via the McGann et al. (2014) CPT-V_s correlation). V_s profiles that resulted from interpretations of surface wave testing by Wotherspoon et al. (2013) and Wood et al. (2011) were used when CPT data were not available at a given site (e.g., gravel/stiff soil sites).

Figure 3 shows a comparison of the pseudo-acceleration response spectra (5% damping) from calculated surface motions resulting from nonlinear site response analyses (effective stress and total stress) and equivalent linear analyses at the PPHS strong motion station site using deconvolved motions from both the CACS and RHSC sites as input motions in the fault normal (FN) direction. The input motions are labeled based on the V_s profiles used in the deconvolution process, and the results are labelled based on the input motions (i.e., results labelled as *CACS Woth1* were calculated using the input motion that resulted from deconvolution at the CACS site using the V_s profile from Wotherspoon et al., 2013). The response spectrum calculated from the recorded surface motion at the PPHS site is shown for comparison as well. The residuals of the spectral acceleration values from the recorded surface motion and those from the surface motions calculated via site response analyses can be calculated to compare the results on a quantitative basis across all periods. The residual is calculated as follows:

$$\delta = \ln\left(S_{a_{recorded}}\right)_{T_i} - \ln\left(S_{a_{predicted}}\right)_{T_i} \quad (1)$$

where T_i is the period of interest for calculating the residual. Shown in Figure 3 are plots of the residuals for periods ranging from 0.01 to 10 s for all analyses completed using the *CACS Woth1* and *RHSC Woth1* input motions. Also provided are the averages of the residuals (arithmetic mean) across all periods for each analysis.

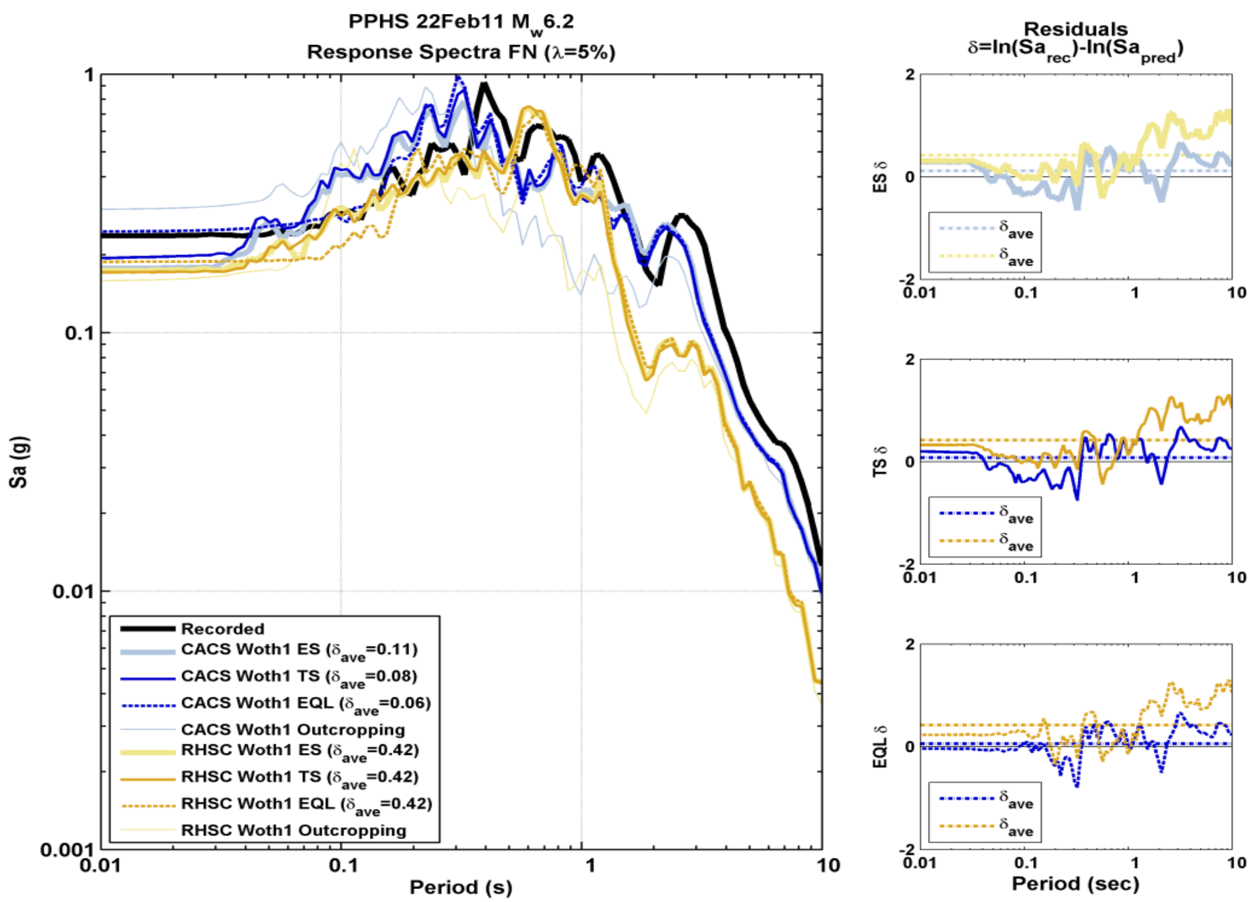

Figure 3: Response spectra comparisons for PPHS (FN) for the Christchurch earthquake

Based on the results shown in Figure 3, analyses that utilized the *CACS Woth1* input motion resulted in a lower average residual compared to those that used the *RHSC Woth1* input motion.

Interestingly, the equivalent-linear analysis that used the *CACS Woth1 FN* input motion resulted in a lower average residual compared to the nonlinear effective stress and total stress anlayses. Furthermore, all analyses (except for the equivalent-linear analysis using the *CACS Woth1 FN* input motion) underestimate the peak ground acceleration at the PPHS station for the Christchurch event. Representative deconvolved Riccarton Gravel acceleration-time histories are shown in Figure 4. The characteristics of the ground motions are judged to be reasonable.

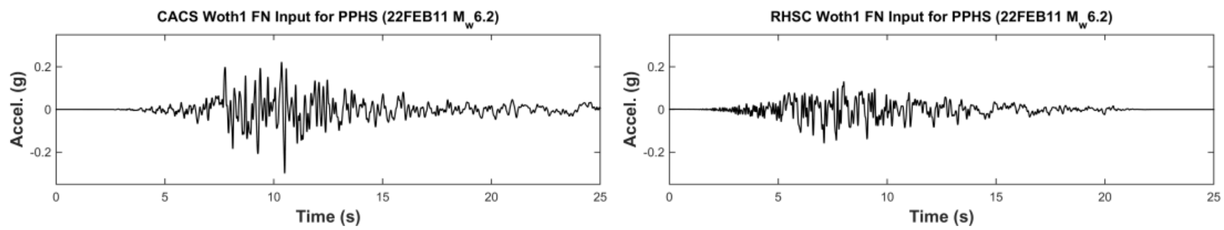

Figure 4: Input motions for analyses summarized in Figure 3

Conclusions

The deep basin structure that underlies much of Christchurch and the lack of representative, recorded “rock” motions in the areas of interest makes the selection of input motions for seismic site response analyses in Christchurch a major source of uncertainty. The deconvolution of surface motions at select sites provides a means for generating input motions for conventional site response analyses. The presence of the Riccarton Gravel layer throughout much of Christchurch, as well as its relative stiffness compared with the overlying, softer soils of both the Christchurch and Springston Formations make it a suitable half-space for deconvolution and subsequent convolution analyses. Representative results for seismic site response analyses completed at the PPHS strong motion station site for the Christchurch event support the use of deconvolved motions as input motions for such analyses. Reasonable trends with regards to the comparison of calculated surface motions and recorded surface motions (via a comparison of response spectra of these motions) at this site are observed.

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Figure 1 was created from maps or data extracted from the Canterbury Geotechnical Database (https://canterburygeotechnicaldatabase.projectorbit.com), which were prepared or compiled for the Earthquake Commission (EQC) to assist in assessing insurance claims made under the Earthquake Commission Act 1993. The source maps and data were not intended for any other purpose. EQC and its engineers, Tonkin & Taylor, have no liability for any use of the maps and data or for the consequences of any person relying on them in any way.

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