NHRP

Natural Hazards Research Platform

Contest 2012

Title: Quantifying Contributions to Seismic Hazard

Project Leaders: Anna Kaiser & Brendon Bradley

Lead organisations: GNS Science/Univ. Canterbury

Total funding (GST ex): $500,000

Quantification and Numerical Modelling of Source, Path, and Site-Specific Effects in the Canterbury Earthquakes: NHRP Contestable Project 2012-GNS-07 Final Report

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GNS Science Consultancy Report 2016/07
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DISCLAIMER

Use of Data:

Date that GNS Science can use associated data: January 2012

BIBLIOGRAPHIC REFERENCE

Kaiser, A.; Bradley, B.; Holden, C.; McGann, C.; Oth, A.; Goded, T.; McVerry, G.; Jeong, S.; Das, S.; Lee, R.; Taylor, M.; Benites, R.; Cubrinovski, M.; Fry, B.; Mueller, C. 2015. Quantification and Numerical Modelling of Source, Path, and Site-Specific Effects in the Canterbury Earthquakes: NHRP Contestable Project 2012-GNS-07 Final Report, *GNS Science Consultancy Report* 2016/07. 18 p.

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PROJECT DETAILS

Natural Hazards Research Platform Contest 2012-GNS-07

Title:
Quantification and numerical modelling of source, path, and site-specific effects in the Canterbury Earthquakes

Programme Leaders: Anna Kaiser[1] & Brendon Bradley[2]

Affiliation: 1. GNS Science, 2. University of Canterbury

Total Budget: $500,000

Final Report Peer-Reviewed by Stephen Bannister (Understanding Earthquakes and Tsunami Programme Leader, GNS Science) and David Burbidge (Head of Department, Tectonophysics, GNS Science).

KEY MESSAGE FOR MEDIA

In this joint project of GNS Science and University of Canterbury, we investigate what contributed to the very strong ground shaking experienced in Christchurch during the Canterbury earthquake sequence. We find that the earthquakes in Canterbury tended to be ‘energetic’, releasing on average more seismic energy for the size of the fault rupture than in other areas studied with our methods. We also find that the local soil conditions in Christchurch strongly contributed to the variable and sometimes highly amplified ground motions observed across the city. By quantifying these phenomena, we have been able to include them into ground shaking prediction models for past and future large earthquakes in Christchurch. These models could also be extended to other sites within Canterbury and our modelling framework could also be applied to other regions of New Zealand.

Abstract / Executive Summary

Ground motions recorded during the Canterbury earthquake sequence were quite variable across the region and reached some of the highest levels documented worldwide. Being able to accurately predict ground motion characteristics for a specific location is necessary to build resilience to earthquake hazards. In this joint project of GNS Science and University of Canterbury, we use several methods to quantify and model regional and local ground motion.

Firstly, we have introduced state of the art spectral inversion techniques applied to the extensive GeoNet dataset to separate and quantify source, path and site contributions to ground motion. Our results suggest that earthquakes in Canterbury tend to release higher than average energy for the size of the fault rupture area, i.e. they have high stress drop. The higher average stress drop is similar to that found globally in “intra-plate” tectonic settings, where rare earthquakes occur on strong faults. We have also produced a database of Canterbury source and site amplification parameters, as well as a frequency-dependent attenuation model to be used for regional ground motion simulations and further research.

Secondly, given that many urban areas of Canterbury are located on deep and/or soft soils, we have used 1-D numerical simulations at selected GeoNet strong motion sites to model the local site response under strong levels of shaking. We also conducted a more detailed 2D soil response study that explains the very large horizontal and vertical ground motions observed at Heathcote Valley. In addition, regional modifications to ground motion prediction equations have been developed and included in the National Seismic Hazard Model to provide more accurate estimates of shaking for structural design and liquefaction assessment.

Finally, using the outcomes of the first two tasks, we have simulated broadband ground motions for the large Christchurch earthquakes at selected GeoNet strong motion sites. Benchmarked against the recorded data from the sequence, the simulations can be used to accurately estimate ground shaking levels and characteristics at new sites within Canterbury, although further work is needed to fully benchmark and incorporate nonlinear effects at soft soil sites. The results can be used to retrospectively assess past performance of structures or landmass under different levels of shaking as well as in simulations of ground motions in possible future earthquake scenarios. In the past, traditional hazard assessment has relied on recorded data from strong-motion sensors or seismometers. We provide a framework to establish cutting edge synthetic approaches and physics-based models of local shaking.

Keywords: ground motion, Canterbury earthquakes, Christchurch, site effects, attenuation, earthquake stress drop, simulations, ground motion prediction

INTRODUCTION

Ground motions recorded during the Canterbury earthquake sequence reached some of the highest levels documented worldwide, and the ground shaking varied across the region in terms of its amplitude and frequency (e.g. Fry et al. 2011; Kaiser et al. 2012). Being able to accurately predict ground motion characteristics for a specific location is necessary for seismic design and ultimately to build resilience to earthquake hazards.

A number of different factors are thought to explain the high observed ground motions during the Canterbury sequence. These include the earthquake source, the wave propagation path and the local ground conditions ('source, path, and site'). Quantifying these contributions allows us to understand regional shaking characteristics and improve efforts to predict future ground motions for the Canterbury region. Traditionally, key parameters for ground motion prediction have been adopted based on generic or global datasets that may not be applicable to local conditions. The extensive GeoNet strong motion database recorded during the Canterbury sequence provides valuable data with which to quantify region-specific ground motion parameters. Furthermore, the database allows us to benchmark new ground motion prediction models against the observed data, and validate these tools for future use. Thus, we can incorporate the lessons learned from Canterbury into future hazard mitigation efforts for the region.

In this joint project between GNS Science and University of Canterbury (UC), we employ several different techniques to first quantify, and then develop methodology to predict ground motion in the Canterbury region. Under Research Aim 1.1, we derive a database of source, path and site parameters for the Canterbury sequence using a state-of-the-art spectral inversion technique. Under Research Aim 1.2, we simulate local soil response within Christchurch under different levels of shaking using 1-D and 2-D numerical methods. We also incorporate regional modifications to ground motion prediction equations (GMPEs) into the National Seismic Hazard Model (NSHM) for practical use in structural design in Canterbury. Under Research Aim 1.3, we incorporate the results of the first two tasks in physics-based simulations of broadband ground motion for the largest aftershocks of the Canterbury sequence.

RESEARCH AIMS

1.1 SPECTRAL INVERSIONS FOR SOURCE, PATH AND SITE EFFECTS IN CANTERBURY

Description:	We will use the generalized linear inversion method of A. Oth to separate and quantify source, path and site effects using aftershocks of the Canterbury earthquake sequence.
Research Aim Achieved:	Yes
Budget:	$109,200

Discussion

We have successfully quantified source, path and site contributions to Canterbury ground motion using the state-of-the-art generalized spectral inversion method of Oth et al. (2010; 2011a; 2011b). The approach we used is non-parametric, unlike traditional GMPE approaches, which means that we initially made no prior assumptions about the form of the source, path and site terms, allowing us extract insights driven purely by the data itself. The results of initial inversions were presented in Kaiser et al. (2013a) and extended in two subsequent journal papers (Oth & Kaiser 2014; Kaiser et al., in preparation).

Results presented in Oth & Kaiser (2014) suggest that earthquakes in Canterbury tend to release higher than average energy for the size of the rupture area (i.e. they exhibit higher stress drop; see Figure 1). Our median “Brune” stress drop for Canterbury of ~5 MPa, is higher than values from other areas where the same methodology and source model have been applied, i.e. i) ~1 MPa derived for crustal earthquakes in Japan (Oth et al. 2010) and ii) ~3 MPa derived for the shallow crustal L’Aquila sequence in Italy (Ameri et al. 2011). Comparing absolute stress drop values from studies based different methods and/or source models is notoriously problematic. However, we note that Allman & Shearer (2009) use very different methodology to show that globally large intra-plate earthquakes tend to have higher stress drops than inter-plate earthquakes (~6 MPa for intra-plate earthquakes vs. ~3.3 MPa for inter-plate). Hence, our results are compatible with the findings of Fry & Gerstenberger (2011) and Reyners et al. (2014) who associate high stress with the “intra-plate” tectonic setting in Canterbury, where rare events tend to occur on relatively strong faults. Earthquakes in historically more active regions of New Zealand are less likely to exhibit this characteristic. This hypothesis is currently being verified by applying techniques established in this project to the recent Cook Strait earthquake sequence (e.g. Kaiser et al. 2013b) in the very different tectonic environment of central New Zealand. We also find a tendency for higher stress drops to cluster near the tip of faults that ruptured previously during the sequence. This is assumed to be related to loading of the surrounding crust following an earthquake rupture.

In Kaiser et al. (2013a; 2016 in preparation) we present our analysis of the wave attenuation and site amplification characteristics for the Canterbury region. We see strong frequency-dependence of the attenuation, with particularly pronounced attenuation at high frequencies. We attribute this to the effect of the soil conditions and shallow water-table found throughout the region. Our new attenuation or ‘Q’ model for Canterbury can be used in ground motion simulations, replacing standard overseas-based models.

We have also quantified the site amplification at each GeoNet strong motion station in the 0.5–20 Hz frequency range. Results show that site response is variable across Christchurch city, and interestingly also varies strongly at locations on rock (see Figure 2), traditionally assumed to have negligible site response. Rock site amplification can be due to topographic effects and/or deposits of local weaker material, and can influence local slope stability; this has been investigated in more detail in a parallel 2012 NHRP-funded project (led by C. Massey).

Key regional source, attenuation and site parameters discussed above have been used to improve ground motion simulations of the largest Canterbury earthquakes (Research Aim 1.3 of this project; Holden et al. 2014a; Holden & Kaiser 2016) as well as simulations of ground motion during a hypothetical Alpine Fault rupture (e.g. Holden et al. 2013; Holden 2014).

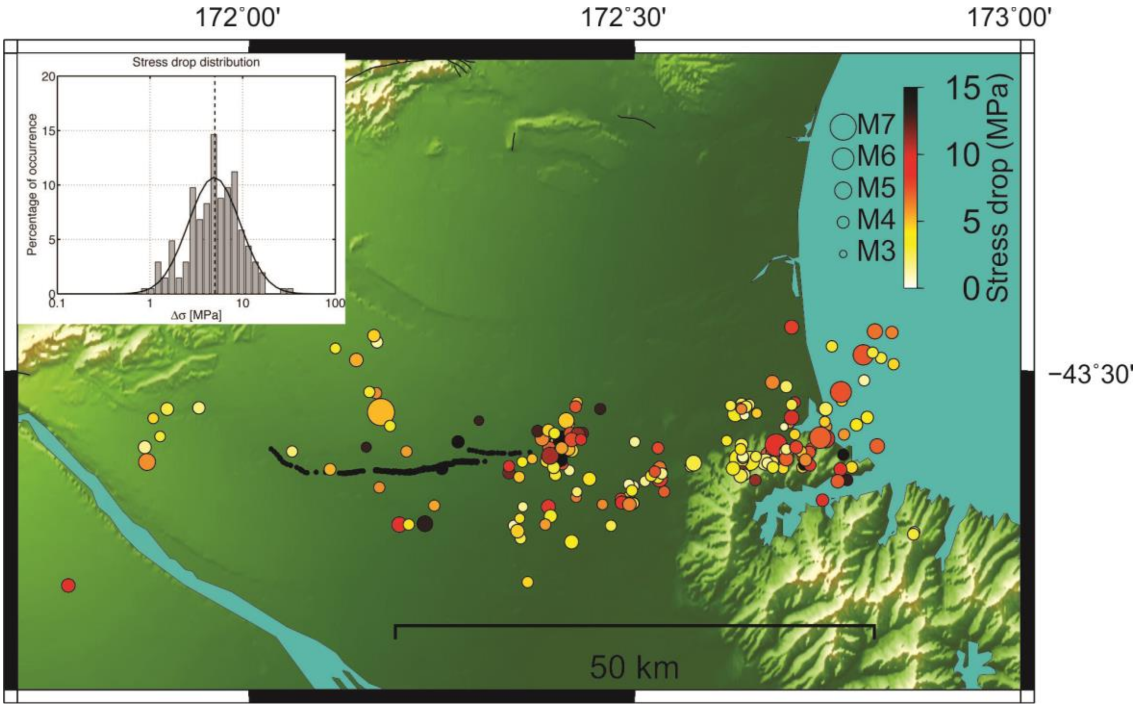

Figure 1 Stress drop distribution for a subset of earthquakes of the 2010–2012 Canterbury sequence from Oth & Kaiser (2014).

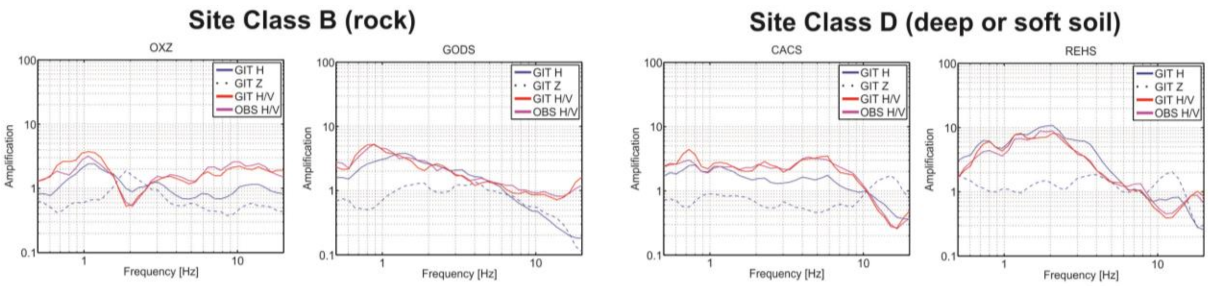

Figure 2 Examples of site amplification functions derived at four GeoNet strong motion sites (two on rock and two on deep soil). Amplification ratios are relative to the horizontal motion at an average rock reference station. Blue solid line shows amplification of the horizontal component derived from the spectral inversions (GIT) and blue dashed line shows amplification of the vertical component. Comparisons of the H/V ratio inferred from the spectral inversion results and the H/V ratio observed directly from the records (red and pink lines) show a good match. However, it is important to note, that at some sites (e.g. GODS), our spectral inversion results show that the observed H/V ratio may be biased by amplification on the vertical component, leading to a shift in the amplification peak relative to the spectral inversion results.

Outputs

Publications

Kaiser, A.E.; Oth, A.; Benites, R.A. 2013. Source, path and site effects influencing ground motions during the Canterbury earthquake sequence, determined from spectral inversions. Paper 18: Proceedings of the New Zealand Society for Earthquake Engineering Annual Meeting, 26–28 April, Wellington, 8p.

Oth, A. & Kaiser, A. 2014. Stress release and source scaling of the 2010–2011 Canterbury, New Zealand earthquake sequence from spectral inversions of ground motion data. Pure and Applied Geophysics 171(10): 2767–2782.

Kaiser, A.; Oth, A.; Benites, R. in preparation. Frequency-dependent attenuation and site amplification during the Canterbury earthquake sequence, New Zealand, from spectral inversion of ground motion. To be submitted to Geophysical Journal International.

Conference Presentations

Kaiser, A.E.; Oth, A. 2012. Spectral inversions of data from the Canterbury earthquake sequence, New Zealand, for source, path and site parameters. Poster presentation at ECGS Workshop 2012: earthquake source physics on various scales, October 3–5, 2012, Luxembourg (poster).

Kaiser, A.E.; Oth, A.; Benites, R.A. 2013. Source, path and site effects influencing ground motions during the Canterbury earthquake sequence, determined from spectral inversions. Oral presentation at the New Zealand Society for Earthquake Engineering Annual Meeting, 26–28 April, Wellington, 8p (oral).

Kaiser, A.E.; Oth, A. 2013. Separating source, path and site influences on ground motion during the Canterbury earthquake sequence, New Zealand. SSA Annual Meeting, April, 2013, Salt Lake City (oral).

Kaiser, A.; Oth, A. 2013. Source characteristics, regional attenuation and site influences on ground motion during the Canterbury earthquake sequence, New Zealand. AGU Fall Meeting, 9–13 December 2013, San Francisco (poster).

Databases and Models

1. Database of source stress drop, corner frequency and moment magnitude for the Canterbury sequence
2. Frequency-dependent regional attenuation model (Q model)
3. Database of site amplification functions at 60+ GeoNet stations

End-users

1. Key regional source, path and site parameters quantified in this task have been used to improve and benchmark ground motion simulations in Canterbury under Research Aim 1.3 of this project and also for other earthquake scenarios (e.g. Alpine Fault/Hope Fault (Holden et al. 2013; Holden 2014).
2. The database of Canterbury stress-drops has been made publically available (Appendix of Oth & Kaiser 2014) and also provided on request to the following researchers: P. Somerville, AECOM; R. Abercrombie, Boston University.
3. The database of site amplification functions is being prepared for publication and has been provided on request to the following researchers: C. Neighbors, UC Riverside; J. Gomberg, USGS. It has also contributed to the concurrent NHRP project “Rethinking PSHA” through expanding the GeoNet station site-meta-database for new GMPE development in New Zealand (e.g. Van Houtte et al. 2015; conference paper in preparation). This database will be maintained on an ongoing basis and is in the process of being made publically available through the GeoNet website.
4. The success of the spectral inversion framework established in this project has led to further research using a simplified inversion approach applied to the extensive temporary QCN aftershock deployment in Christchurch (e.g. Neighbors et al. 2013). This work aims to utilize low-cost sensor networks to extract useful ground motion parameters (e.g. stress drop, local site kappa), with a journal paper currently in preparation.

1.2 NUMERICAL MODELLING OF SITE EFFECTS IN CANTERBURY AND DEVELOPMENT OF CANTERBURY-SPECIFIC GMPES

Description:	We will use equivalent linear and nonlinear modelling methods to investigate and quantify site-specific response during the largest Canterbury earthquakes. Knowledge gained from Research Aims 1.1 and 1.2 will be used to develop modifications to standard national GMPE models to account for specific physical factors that influence ground motions in the Canterbury region.
Research Aim Achieved:	Yes
Budget:	$237,836

Discussion

UC-led site characterization of the Canterbury region involved developing a Christchurch-specific correlation between Cone Penetrometer Testing (CPT) values and shear-wave velocity (Vs) (McGann et al. 2015b, McGann et al. 2015c), which was then applied to the high-density CPT dataset in the Canterbury region to enable the development of city-wide surficial site response parameters (McGann et al. 2015a; with two companion journal papers in submission).

1D site response analyses were performed at both UC and GNS using detailed soil profiles at the strong motion stations in the Christchurch CBD to obtain basic insights into the role of near-surface site effects. These simulations are designed to capture the nonlinear soil response that occurs under very strong shaking, such as experienced in the largest Canterbury earthquakes.

The UC analyses utilized equivalent linear, nonlinear total and nonlinear effective stress approaches for representing the stress-strain constitutive behaviour of the soil, and deconvolved motions from nearby stiff soil sites (Riccarton, Lyttelton, Canterbury Aeroclub) as input ground motion time series. Such analyses are published in UC theses (Arefi 2014, Taylor 2016), with journal publications in preparation. Research under this task also resulted in the development of a 3D soil constitutive model (Das 2014, Das et al. 2013).

The GNS analyses used the nonlinear total stress approach within the DEEPSOIL software (Hashash et al. 2012) to assess the 1-D site response. Both observed motions (from rock station LPCC) and synthetic motions (from Research Aim 1.3 of this project; Holden & Kaiser 2016), as well as simulated motions for a hypothetical Alpine Fault rupture (e.g. Holden 2014) were used as input. Simulations were able to reproduce the general characteristics of key amplification peaks in the observed data (e.g. long-period peak at ~3s), but with some variability in peak amplitude and period depending on the input motion. A journal article (Goded et al.) is currently in preparation illustrating the results.

The key outcomes from the 1-D site analyses are that: (i) the importance of shallow site response is pronounced for all levels of ground motion, but particularly at high levels in which strain localization occurs in critical soil layers; (ii) while differences exist between the various modelling options, there is greater uncertainty associated with the input motion (because of a

lack of nearby rock records) when trying to reproduce the observed surface motions. This highlights the importance of accurate physics-based simulations, which can produce input motions that are seen as a viable alternative to the use of less-than-ideal rock records (i.e. ones affected by site effects or located too far from the site of investigation) or deconvolved surface records..Furthermore, the 1-D site modelling framework developed here can be used to simulate future earthquake scenarios at the sites investigated here (requiring only the addition of an appropriate earthquake input motion). The framework can also be extended to the wider Canterbury region in future as additional subsurface data become available.

A detailed case study of the Heathcote Valley area involving site characterisation (Jeong et al. 2014) and 1D and 2D site response analyses (Jeong and Bradley 2015) was also undertaken by UC. The 2D linear and nonlinear total stress analysis simulations, which are for orthogonal directions corresponding to both along- and across-the-valley, have been validated with the recorded ground motions at the HVSC station. Simulation results illustrate the importance of the inclined subsurface volcanic rock interface in the development of basin-diffracted surface waves, as well as the importance of the large impedance contrast for the development of large amplitude direct body waves. 3D analyses are being undertaken as part of subsequent work. Two journal papers are currently in preparation on this task.

In order to incorporate local ground motion characteristics into current design practice, Christchurch-specific modifications to Ground Motion Prediction Equations (GMPEs) have been developed at UC. These GMPE modification factors have been developed for four subregions of Canterbury based on the examination of observed and empirically predicted ground motion amplitudes. The modification factors include: (i) spectral acceleration amplitudes that are regionally variable (Bradley 2015b); and (ii) damping ratios other than 5% (Bradley 2015a). These modifications have been implemented by GNS into the National Seismic Hazard Model (NSHM) for use in the Christchurch area. This has been facilitated by development of new python code that efficiently incorporates the recommendations of the Expert Elicitation Panel (EE) for ground motion prediction and structural design in Canterbury into practical use. This framework has been used to generate site-specific design spectra and key parameters for liquefaction assessment in consultancy studies for the major Northern Arterial roading project (McVerry et al., 2014) and Bromley substation (Abbott & McVerry, 2015). In addition, hazards results for the four sub-regions have been re-evaluated, and detailed results of the revised modelling will be presented in a Science Report that is nearing completion (McVerry et al. in preparation).

Previously. the presence of long-period peaks (~3 seconds period) in the recorded motions of the 2010 Darfield and Feb 2011 Christchurch earthquakes led to the limitation that the current Z=0.3 spectra for Christchurch may be used only for periods up to 1.5s, with special studies required for longer periods. The modified hazard spectra that result from incorporating factors for sub-regions of Christchurch, have shown that changes to the design spectra for periods longer than 1.5s that were initially anticipated after the February 2011 Christchurch earthquake have not been found necessary. On the basis of this work, MBIE issued Building Controls Update No 172 (28 September 2015) stating:

"The limitation on using the site hazard spectra using Z=0.3 minimum factor in Canterbury only for structures of 1.5 seconds and less has now been removed … In addition, the return period factor R_s for serviceability limit state in Canterbury shall now revert to 0.25, i.e. the same as that provided in …NZS 1170.5."

Outputs

Publications

Bradley BA. 2015. Systematic Ground Motion Observations in the Canterbury Earthquakes And Region-Specific Non-Ergodic Empirical Ground Motion Modeling. *Earthquake Spectra*; 31(3): 1735–1761.

Bradley BA. 2015. Period Dependence of Response Spectrum Damping Modification Factors due to Source- and Site-Specific Effects. *Earthquake Spectra*; 31(2): 745–759.

Goded, T.; McVerry, G.; Holden, C.; Kaiser, A. Numerical analysis of the amplification characteristics of central Christchurch soils during the 2010–2012 Canterbury earthquake sequence New Zealand. In preparation for *Seismological Research Letters.*

McGann CR, Bradley BA and Cubrinovski M. 2015a. High-Density Shallow Shear Wave Velocity Characterization of the Urban Christchurch, New Zealand Region University of Canterbury Research Report No. 2015–02, University of Canterbury. 67pp.

McGann CR, Bradley BA, Taylor ML, Wotherspoon LM and Cubrinovski M. 2015b. Applicability of existing empirical shear wave velocity correlations to seismic cone penetration test data in Christchurch New Zealand. *Soil Dynamics and Earthquake Engineering*; 75(0): 76–86.

McGann CR, Bradley BA, Taylor ML, Wotherspoon LM and Cubrinovski M. 2015c. Development of an empirical correlation for predicting shear wave velocity of Christchurch soils from cone penetration test data. *Soil Dynamics and Earthquake Engineering*; 75(0): 66–75.

McVerry, G.H.; King, A.B.; Mueller, C. (in preparation.) Design spectra for the Christchurch region, GNS Science report.

Student Theses

Arefi MJ. 2014. Dynamic characteristics and evaluation of ground response for sands with non-plastic fines, PhD Thesis, in *Civil and Natural Resources Engineering*. University of Canterbury, 385pp.

Das S. 2014. Three dimensional formulation for the stress-strain-dilatency elasto-plastic constitutive model for sand under cyclic behaviour, ME Thesis, in *Civil and Natural Resources Engineering*. University of Canterbury, 230pp.

Taylor ML. 2016. The geotechnical characterisation of Christchurch sands for advanced soil modelling, PhD thesis, in *Civil and Natural Resources Engineering*. University of Canterbury, (submitted; under review).

Lee, Robin (PhD ongoing; expected March 2017)

Conference presentations

Das S, Bradley BA and Cubrinovski M. 2013. A three dimensional plasticity model for sands based on state concept, in *1st Australian Conference on Computational Mechanics (ACCM13)*: Sydney, Australia, 8pp. (oral)

Jeong S, Bradley BA, McGann CR and DePascale G. 2014. Characterization of dynamic soil properties and stratigraphy at Heathcote Valley, New Zealand, for simulation of 3D valley effects, in *Southern California Earthquake Centre (SCEC) Annual Meeting*: Palm Springs, California. (poster)

Jeong S and Bradley BA. 2015. Simulation of 2D site response at Heathcote Valley during the 2010–2011 Canterbury earthquake sequence, in *10th Pacific Conference on Earthquake Engineering*: Sydney, Australia, 8pp. (oral)

McGann CR, Bradley BA, Cubrinovski M, Taylor M and Wotherspoon LM. 2014. Comparison of existing CPT-Vs correlations with Canterbury-specific seismic CPT data, in *New Zealand Society for Earthquake Engineering Conference*: Auckland, New Zealand, 8pp. (oral)

McGann CR, Bradley BA and Cubrinovski M. 2014. Shallow shear wave velocity characterization of the urban Christchurch, New Zealand region, in *Southern California Earthquake Centre (SCEC) Annual Meeting*: Palm Springs, California. (poster)

McGann C, Bradley BA, Taylor ML, Cubrinovski M and Wotherspoon L. 2014. Comparison of existing CPT-Vs correlations with Canterbury-specific seismic CPT data, in *2014 NZSEE Annual Conference*: Auckland, New Zealand, 8pp. (oral)

End-users

1. The 3D soil liquefaction model (Das et al. 2014) has been implemented in the open-source platform, OpenSees for current 3D surficial soil modelling that is on-going.
2. The CPT-Vs correlation and Vs30 maps of Christchurch have been extensively utilized by geotechnical engineers in site characterization of the region. The Vs30 map is available on the Canterbury Geotech database.
3. The Canterbury-specific GMPE modification factors are routinely adopted for region-specific seismic hazard analysis
4. The Canterbury region NSHM framework (incorporating modification factors above and recommendations of the Expert Elicitation Panel) has been used in consultancy studies to provide site-specific design spectra and key parameters for liquefaction assessment, e.g. for the major Northern Arterial roading project (McVerry et al., 2014) and Bromley substation (Abbott & McVerry, 2015).

1.3 STOCHASTIC SIMULATION OF GROUND MOTIONS FROM THE CANTERBURY EARTHQUAKES

Description:	Use the stochastic simulation method, calibrated for NZ, to simulate ground motions at the locations of strong motion stations from the Canterbury earthquakes.
Research Aim Achieved:	Yes
Budget:	$152,962

Discussion

GNS-led research under this task employed the stochastic EXSIM method (Motazedian and Atkinson 2005) to simulate broadband synthetic seismograms for the largest aftershocks of the Canterbury sequence. Results are summarized in a journal article currently in press (Holden & Kaiser 2016). The simulations incorporated key regional ground motion parameters produced under Research Aim 1.1 (i.e. stress drop, attenuation and site amplification), providing more accurate simulations for Canterbury conditions. We were able to produce and validate broadband time series and spectra for 'linear' conditions (i.e. rock or stiff soil sites under all levels of shaking or soft soil sites under weak or moderate shaking). The simulation results were validated through comparisons against available recorded data at strong motion stations, showing a good match of key characteristics. This framework has subsequently been used to produce simulated ground motion for hypothetical Alpine Fault and Hope Fault ruptures (Holden 2014). Furthermore, the synthetic motions have been used in Research Aim 1.2 as input to 1-D numerical simulations to assess the nonlinear soil response under strong shaking at central city soil sites.

UC-led research under this task used an alternative approach to simulate broadband ground motions for 10 events in the Canterbury earthquake sequence. Simulations extended the previous approach of Graves and Pitarka (Graves and Pitarka 2015, Graves and Pitarka 2010), in which the low-frequency ($f<1Hz$) portion of the simulations is obtained from 3D wave propagation simulations in a 3D heterogeneous velocity model, and the high frequency ($f>1Hz$) portion utilizes a semi-empirical 'stochastic' approach based on a 1D velocity model. Based on prior studies of others we performed simulations using a range of source-related parameters (principally fault geometry, magnitude, hypocentre, average rake, and Brune's stress drop; since the finite fault parameterization is stochastically generated from these parameters). Comparison of the simulations with observations at strong motion stations is summarized in several publications (Bradley and Graves 2014, Bradley and Graves 2015, Bradley et al. 2015, Razafindrakoto et al. 2015) (with two journal papers in prep). Results to date indicate that these simulations can provide predictions with an equivalent or lower degree of uncertainty than that of empirical GMPEs. Other on-going research is investigating the further incremental benefits that can be obtained by coupling such conventional ground motion simulation methods with site-specific near surface response analyses (e.g. as performed in Research Aim 1.2).

This simulation framework developed here allows linear ground motion to effectively be modelled and estimated at any location of interest. Simulated ground motions for the Port Hills have been used to underpin assessments of slope stability in the Port Hills under past and future shaking scenarios (e.g. Holden et al. 2014b; Massey et al. 2015; Massey et al., submitted). Furthermore, synthetic motions modelled at UC have been archived, and are presently being made publically available through QuakeCoRE's data repository.

Outputs

Publications

Holden, C. and A. Kaiser (2016) Stochastic ground motion modelling of the largest M5.9+ aftershocks of the Canterbury 2010–2011 earthquake sequence, *New Zealand Journal of Geology and Geophysics*, "Advances in geodesy and active tectonic deformation: A Special Issue in memory of John Beavan". In press (soon to be available online).

Holden, C.; Kaiser, A.E.; Gerstenberger, M.C. 2014. Time-dependent hazard for Canterbury, New Zealand and modeling of expected ground motions. IN: Proceedings, 10th U.S. National Conference on Earthquake Engineering : frontiers of earthquake engineering. Earthquake Engineering Research Institute.

Contribution to: Holden, C.; Kaiser, A.E.; Massey, C.I. 2014. Broadband ground motion modelling of the largest M5.9+ aftershocks of the Canterbury 2010–2011 earthquake sequence for seismic slope response studies. Lower Hutt, NZ: GNS Science. GNS Science report 2014/13. 48 p.

Conference presentations

Bradley BA and Graves RW. 2014 Low frequency (f≤1Hz) ground motion simulations of 10 events in the 2010–2011 Canterbury earthquake sequence, in *Southern California Earthquake Centre (SCEC) Annual Meeting*: Palm Springs, California. (poster)

Bradley BA and Graves RW. 2015 Broadband ground motion simulations of major events in the 2010–2011 Canterbury earthquake sequence, in *New Zealand Society for Earthquake Engineering Annual Conference*: Rotorua, New Zealand, (poster).

Bradley BA, Jeong S and Razafindrakoto HNT. 2015 Strong ground motions from the 2010–2011 Canterbury earthquakes and the predictive capability of empirical and physics-based simulation models, in *10th Pacific Conference on Earthquake Engineering*: Sydney, Australia, 16pp. (Invited plenary presentation)

Holden, C.; Kaiser, A.E.; Gerstenberger, M.C. 2014. Time-dependent hazard for Canterbury, New Zealand and modeling of expected ground motions. IN: *Proceedings, 10th U.S. National Conference on Earthquake Engineering : frontiers of earthquake engineering, July 21–25, 2014, Anchorage, Alaska.* Earthquake Engineering Research Institute

Holden, C.; Kaiser, A.; Gerstenberger, M. 2014. Near source broadband ground motion modelling of the Canterbury aftershocks and implications for assessing engineering metrics. Poster presented at 2014 SCEC Annual Meeting, Palm Springs, September 2014.

Razafindrakoto HNT, Bradley BA, Thomson EM and Graves RW. 2015 Hybrid broadband simulations of the 2010–2011 Canterbury earthquakes, in *Southern California Earthquake Centre (SCEC) Annual Meeting*: Palm Springs, CA (oral).

Student Theses

Lee, Robin (PhD ongoing; expected March 2017)

Thomson, Ethan (PhD ongoing; expected March 2018).

End-users

1. Ground motion simulations of Holden et al. 2014b and Holden & Kaiser (2016) have been used to underpin slope stability assessments for the Christchurch City Council (e.g. Massey et al. 2014 and accompanying series of reports). Simulated ground motions were produced at each slope of interest in order to determine relationships between shaking and rockfall (Massey et al. submitted to Landslides) and also to model detailed 2D hillside response.
2. Ground motion simulation framework of Holden & Kaiser (2016) developed under this project has been used to simulate expected ground motions from a future major Alpine Fault and Hope Fault earthquake (Holden 2014).
3. The ground motion simulations performed at UC over the Canterbury region have been archived, and are presently being made publically available through QuakeCoRE's data repository, to enable them to be utilized by structural and geotechnical engineers to obtain simulated ground motions at a generic location (i.e. other than just at strong motion station locations).

CONCLUSIONS AND RECOMMENDATIONS

Ground motions recorded during the Canterbury earthquake sequence reached some of the highest levels documented worldwide, and varied significantly across the region in terms of its amplitude and frequency. This joint GNS and UC project has sought to incorporate lessons learned from the Canterbury earthquake sequence into efforts to understand and predict future ground motion in the region.

Firstly, we have introduced state of the art spectral inversion techniques to separate and quantify source, path and site contributions to strong ground motion. Our results suggest that earthquakes in Canterbury tend to release higher than average energy for the size of the rupture area. This characteristic has been associated with “intra-plate” tectonic settings (i.e. further from the plate boundary), where rare events occur on strong faults. Earthquakes in other historically more active regions of New Zealand are likely to behave differently, and we are testing this hypothesis by applying similar analysis to the recent 2013 Cook Strait earthquake sequence. The work also produced a database of Canterbury source and site amplification parameters, as well as a frequency-dependent attenuation model. Our future goal is to extend these databases by applying similar methodology to other regional datasets within New Zealand. This is an important step towards developing regional and site-specific ground motion predictions.

Secondly, given that many urban areas of Canterbury are located on deep and/or soft soils, we have used 1-D numerical simulations at selected GeoNet strong motion sites to model the local site response under strong levels of shaking. We show the importance of site effects in reproducing amplification peaks in the observed spectra. We also show the importance of choosing an appropriate input motion in assessing the soil response. Given that no ideal rock input motion was available for the Canterbury earthquakes, the use of simulated input motions (produced under the next task of this project) was demonstrated to be a viable alternative. We also conducted a more detailed 2D soil response study that explains the very large horizontal and vertical ground motions observed at Heathcote Valley. In addition, regional modifications to ground motion prediction equations based on observed data have been included in the National Seismic Hazard Model to provide a practical interface to use results in structural design and liquefaction assessments.

Finally, using the outcomes of the first two tasks, we have simulated regional broadband ground motions for the largest aftershocks of the Canterbury sequence, including the destructive February 2011 Christchurch earthquake. The simulations were able to reproduce the general characteristics of ground shaking observed at GeoNet stations across the city, particularly under ‘linear’ site conditions (e.g. at rock and stiff soil sites). Modelling of ‘nonlinear’ ground motions (at deep or soft soil sites under strong shaking) requires accurate knowledge of the soil profile. Our future goal is to extend models of nonlinear soil behaviour to a wider number of sites in the Canterbury region as detailed soil profile information becomes available. Our project establishes a framework for the use of synthetic approaches to simulate regional and local ground motion for hazard assessment. We recommend future work focus on further validating and comparing different modelling approaches by comparing a suite of key ground motion metrics against observed data. We also recommend this framework be expanded to other regions of New Zealand and benchmarked where possible with GeoNet data from recorded earthquake sequences (e.g. Cook Strait, Eketahuna, Wilberforce earthquake sequences). Our ultimate goal is to provide accurate site-specific ground motion predictions for use in structural design using physics-based methods.

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