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New Zealand – United States Engineering Research Collaborations in the Aftermath of the Canterbury Earthquake Sequence

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ABSTRACT

During the 2010-2011 Canterbury earthquake sequence, earthquake engineering researchers in New Zealand (NZ) and the United States (US) joined forces to rapidly collect perishable field data about ground and structural response. These efforts developed into longer-term bi-lateral collaborative projects in geotechnical and structural earthquake engineering that addressed both fundamental research questions and design requirements for rebuilding the region. While NZ researchers collaborated with many foreign researchers, the NZ-US collaboration has been particularly close, involving a large number of academic and government researchers, students, and consultants from both countries. This strong collaboration was supported by government agencies, in particular the U.S. National Science Foundation and New Zealand's Earthquake Commission and a consortium of research agencies under the umbrella of the Natural Hazards Platform. This paper summarizes the supported geotechnical engineering research areas. Opportunities for support of continued international collaborations in the natural hazards engineering area are presented.

Introduction

The Canterbury earthquake sequence (CES) began with the Mw 7.1 Darfield earthquake, which struck at 4:36 am local time on 4 September 2010. The earthquake epicentre was about 30 km west of Christchurch in a relatively low seismic hazard part of NZ (Stirling et al., 2012). A c. 30 km long surface rupture, now known as the Greendale Fault, was found west of Christchurch (Quigley et al., 2010, 2011). Building damage was concentrated in the Christchurch central city area and outlying smaller commercial areas where older buildings suffered significant damage (Dizhur et al., 2010). Damage induced by liquefaction was extensive particularly in the eastern suburbs of Christchurch and in Kaiapoi (Buchanan & Newcombe, 2010) (Table 1). Aftershock activity on adjoining hidden faults began soon after the 4 September earthquake. For example, on 8 September, only four days after the Darfield earthquake, an aftershock of Mw 5.1 located near Lyttelton was felt strongly in Christchurch, and caused further damage to earthquake-weakened buildings. This aftershock was centred in nearly the same location as the devastating Mw 6.2 earthquake that occurred five months later on 22 February 2011 (Kaiser et al., 2012). On 26 December 2010, aftershocks reaching Mw 4.4 centered very close to the centre of the city abruptly ended what is traditionally a busy shopping day, and caused more damage.

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The 22 February 2011 Mw 6.2 Christchurch earthquake was on an 8 km hidden fault cutting

Table 1. Earthquake comparisons (Berryman, 2012).

Date	4 September 2010	22 February 2011	13 June 2011	23 December 2011
Magnitude (Mw)	7.1	6.2	6.0	5.9
Epicentre[1]	30 km W	10 km SE	10 km SE	10 km E
Time[2]	4:36 am	12:51 pm	2:20 pm	3:18 pm
Max PGA[3]	0.6g (0.3g CBD)	2.2g (0.8g CBD)	2.2g (0.4g CBD)	0.96g [4](0.25g CBD)
Casualties	0 fatalities	185 fatalities	0 fatalities	0 fatalities
Building Damage	To older brick & unreinforced masonry	All pre-1970's & several modern buildings with eccentric design	Further residential damage in Port Hills & already damaged CBD buildings	Minor, but several instances of progressive failure
Liquefaction	Widespread in eastern suburbs	Extreme damage in many eastern Christchurch suburbs	Further damage in eastern Christchurch suburbs	Further damage in eastern Christchurch suburbs
Cost[5]	4-5 billion	15-20 billion	c. 1.5 billion	c. 350 million

Notes:

1. Epicentral distances are with respect to Christchurch Central Business District (CBD).
2. Time is NZ standard time in Sept 2010 and June 2011, and NZ Daylight Saving time in Feb and Dec 2011.
3. Maximum Peak Ground Acceleration (PGA) in the City - may be either horizontal or vertical.
4. This was the maximum PGA on 23 Dec - in the earlier and slightly smaller M5.8 event.
5. In NZ dollars. Generally includes direct costs only.

through the bedrock underlying the volcanic rocks of the Port Hills of Christchurch. More recent studies have identified a network of bedrock faults throughout the region (Jongens et al, 2012) that formed in the Cretaceous age (c. 80 Myr) and are now being reactivated by the stresses from the Mw 7.1 Darfield earthquake.

By mid-2011, the aftershocks of the Christchurch earthquake were diminishing in frequency, and reconstruction had begun. A major setback occurred on 13 June 2011, when the Mw 6.0 Christchurch 2 earthquake struck at 2:20 pm, producing ground accelerations of more than two times that of gravity in parts of the Port Hills, and there was renewed liquefaction and further damage to already weakened buildings (Table 1). A further Mw 5.9 event occurred on 23 December 2011 about 10 km east of Christchurch, approximately along-strike of the Christchurch earthquake of 22 February. Activity has declined following the late December 2011 activity and the most recent M>5 event was in May 2012.

The Significance of the CES on Earthquake Hazard Mitigation in the United States

The CES has considerable importance for U.S. research and practice communities, as well as the public living in earthquake prone areas. The state-of-practice for both residential and commercial design and construction, while not exactly the same, is quite similar. Older, masonry and stone structures in the Christchurch Central Business District (CBD) are also similar to those found in the U.S. The rock slides and rock falls, as well as soil slope movements in the Port Hills area, also provide information beneficial to many areas of the U.S. West coast. Near surface geology is well-known and similar enough to many locations in the U.S. that knowledge gained from investigations of damage in NZ will be directly applicable to the U.S. The large number of high quality seismic records and the very detailed post-earthquake reconnaissance discussed below provide the details needed to do significant in-depth post-event research. There is one dissimilarity, however, that makes the Canterbury earthquake series of unique importance. The availability of detailed design and performance data for almost all structures in Christchurch greatly enhanced the ability of researchers to understand this event and to learn from the damage caused. Detailed design and performance data are seldom available in the U.S. due to liability issues.

Collaborative Post-Earthquake Reconnaissance Efforts and Research Projects

Post-earthquake investigations are important for studying the "full-scale" event to learn how to prepare, mitigate, respond, and recover for future earthquakes. Post-CES activities included collaborative research projects between NZ and U.S. researchers that address both fundamental research questions, as well as immediate needs for the rebuilding of Christchurch. The U.S. National Science Foundation (NSF) has a long history of supporting researchers to conduct post-earthquake reconnaissance for ephemeral data collection that can spur new research to understand and mitigate the impacts of earthquakes. Given the significant damage from the 22 February 2011 event and 2011 Japan earthquake and tsunami that occurred the following month, NSF issued a Dear Colleague Letter (DCL) to request proposals for post-event reconnaissance of these events (NSF, 2011). For the CES, through this DCL, NSF supported researchers for reconnaissance and data collection primarily through the NSF RAPID award mechanism, which does not require peer review, as well as through ongoing NSF awards and supplements to existing NSF awards. Many of the NSF-supported teams had prior or ongoing collaborations with NZ researchers, which enabled rapid formation of bilateral teams for post-CES reconnaissance. For example, the NSF-supported Geotechnical Extreme Events Reconnaissance (GEER) Association teams (Table A1, NSF awards CMMI-0825734, -0825507, -0825760), in collaboration with NZ engineers, investigated the 2010 Darfield earthquake (Green and Cubrinovksi, 2010) and the 2011 Christchurch earthquake (Cubrinovksi, Green, and Witherspoon, 2011). Table A1 in the Appendix lists the NSF-supported engineering post-earthquake investigations, follow-on research projects, and workshops related to the CES. The abstracts for these NSF awards can be found at http://www.nsf.gov/awardsearch/advancedSearch.jsp by entering the award number.

Several examples of the bilateral investigations are mentioned below. Site characterization work was done in the Christchurch region utilizing the University of Texas (UT) at Austin tri-axial vibroseis truck, known as "T-Rex," which supported at that time by NSF through its Network for Earthquake Engineering Simulation (NEES) operations program. NSF-supported RAPID awards (Table A1, award CMMI-1303595) enabled UT Austin faculty, technicians and graduate students to operate T-Rex, as well as reduce and interpret the data, in technical collaboration with researchers from the Universities of Auckland and Canterbury and EQC's geotechnical engineering advisors, Tonkin & Taylor. T-Rex was used for Vs profiling of the Canterbury basin, essential for subsequent ground motion analyses. Prior to this seismic profiling, only the first few tens of metres of the subsurface in Christchurch had been characterized. T-Rex data extended this depth in locations to over 1 km. This work also provided the opportunity to evaluate the reliability of merging large active-source and passive-wavefield surface wave methods for deep Vs profiling. Researchers from the UT at Austin, Brigham Young University (BYU), Oregon State University, Cornell University and University of California (UC), Berkeley participated in a large study (~NZ$3 million) sponsored by the NZ Earthquake Commission, to test four different shallow ground liquefaction mitigation methods in an area where all housing was damaged beyond repair by liquefaction. Through additional NSF support (Table A1, award CMMI-1343524), T-Rex was used to investigate liquefaction triggering, with a later phase of the work performed by BYU (Table A1, Award CMMI-1408892) incorporating explosives to test the performance of improved-ground panels under area-wide liquefaction. This study's data had immediate application for the development of design guidelines for housing reconstruction in liquefaction-prone areas in Christchurch, augmented by a $5 million land-repair pilot programme to evaluate the cost-effectiveness of deploying these techniques in a residential urban setting. T-Rex was also used to shake the Woman's Hospital in Christchurch, as part of an NSF-supported investigation of that base-isolated structure's seismic behaviour (Table A1, award CMMI-1128714).

Studies of the seismic performance of lifelines led by researchers from Cornell University, in collaboration with UC Berkeley, the University of Canterbury, Tonkin and Taylor, NZ government agencies and others have led to the very important conclusion that high and medium density polyethylene (HDPE and MDPE) pipe performs significantly better than concrete pipe in areas of seismic shaking and permanent ground displacement (Table A1, award CMMI-1137977; Bray et al., 2013). Based on previous NSF-supported experimental work at Cornell, as well as observations of behaviour of lifelines during the Darfield event, damaged sections of the water distribution system in Christchurch were replaced with HDPE pipe. These HDPE sections survived the 13 June and 23 December 2011 Christchurch earthquakes without damage despite severe liquefaction and permanent ground displacements of two to three meters. This research validates previous work and is likely to have a profound effect worldwide.

A study of rockfall impacts on structures in the Port Hills area was carried out by GNS Science in collaboration with NSF-supported researchers from the University of Washington and Oregon State University (Table A1, NSF awards CMMI-1439773 and CMMI-1439883). This study utilized 3-D ground based LIDAR scans and Structure from Motion (SfM) photographic acquisition of structures impacted by rockfalls. Through coupled runout/structural impact model simulations of the post-initiation rockfall process, data were obtained to aid in the development of guidelines for setback distances in rockfall prone areas, as well as the development of risk-based analysis of landslide hazards. This research also provided the data needed for evaluation of the resistance of various structural systems to boulder impact.

Researchers from the Universities of Auckland and Canterbury have collaborated with colleagues at UC Berkeley, Virginia Polytechnic Institute and State University (Virginia Tech), Cornell University, UT Austin, and BYU to study many aspects of liquefaction, including effects of liquefaction on structures and pile downdrag, and the effects of silt content on liquefaction behavior. A three-year research collaboration between UC Berkeley and the University of Canterbury will investigate the performance of well-built structures with varying types of foundation systems and levels of damage from liquefaction to inform performance-based earthquake engineering (PBEE) design procedures (Table A1, Award CMMI-1332501).

In addition to the geotechnical engineering research projects related to the CES, structural engineering researchers also collected ephemeral data and began research collaborations with their NZ colleagues, as evidenced by the several structural engineering RAPID awards listed in Table A1.

Benefits of the Collaborations

The CES has been widely acknowledged as the largest social and economic issue facing New Zealand since the Second World War more than 60 years ago. The bilateral NZ-US collaborations for immediate response and longer term research have resulted in mutually beneficial scientific advancements for understanding the CES, rapid damage assessment, and policy and planning analysis to enable robust recovery. Rapid reconnaissance efforts by U.S. researchers, in cooperation with NZ researchers, engineers, and officials, provided very valuable assessment of the damage in a wider international context. This calibration against an international backdrop identified the very high level of damage arising from liquefaction and the general soundness of earthquake engineering practice in NZ to what were extraordinary ground motions, especially in the 22 February 2011 event.

Ground improvement studies in liquefaction prone land are now available for the recovery phase, to a significant extent due to the NZ-U.S. collaboration. Aspects of the seismicity and impacts of the earthquakes on social disruption have also evolved into longer term in-depth studies and extended further under the auspices of the bilateral NZ-U.S. science collaboration agreement. Under this framework, collaboration on earthquake hazards in low seismicity regions and the social, engineering and political challenges associated with infrequent, but potentially calamitous events, are being jointly investigated, along with improved hazard communication to the public and policy-makers. The collaboration with NZ has been very beneficial to the U.S. research and practice communities. The availability of such a large amount of data is unprecedented, and likely never to occur in the U.S. Some research projects, such as the evaluation of four liquefaction mitigation methods, would have been very difficult and perhaps prohibitively expensive to accomplish in the U.S.

Lessons Learned

A strong case can be made that post-disaster reconnaissance investigations, international workshops, and collaborative research projects can have very significant long-term benefits to the countries involved. As a follow-up to the RAPID awards made for the 2011 NZ and Japan earthquakes, NSF supported a workshop to gather research needs emerging from the lessons learned from these earthquakes (EERI, 2012)

Much of the joint research listed in Table A1 was supported on an ad hoc basis with little to no formal coordination between the NZ and U.S. funding agencies. On the NZ side, the need to respond to immediate demands and the differing needs and agendas of the varying agencies inhibited a fully coordinated response. However, alongside the initial emphasis on emergency management there was significant collaboration effort in data collection and applied research. The Earthquake Commission invested significantly to acquire geospatial and geotechnical data, both to inform its insurance operations and to fulfill its mandate for research facilitation and education. The Natural Hazards Research Platform (NHRP) also invested heavily, in collaboration with EQC, and the U.S. funded research teams, to provide timely advice to emergency management and recovery planning. In the U.S., agencies such as NASA and USGS offered help and NSF and issued a Dear Colleague Letter - NSF 11-045 in support of proposals and supplements to investigate these events (NSF, 2011).

Formal interagency agreements on future collaborations in response to natural disasters may be problematical. On-going researcher level interactions are extensive and strong and will always be activated at times of crisis. A continued dialog between NZ and U.S. program managers and others directly involved in hazards mitigation and research would be beneficial in facilitating a more coordinated effort after future events in either country.

Path Forward for Collaborative NZ-US Hazards Collaboration

The CES has produced an enormous amount of data that will take decades to fully exploit. There are clearly opportunities for continued research and most of the future work will, of course, be done by NZ researchers. For those situations where a collaboration with U.S. researchers is beneficial, NSF funding is available through several sources, including the new Engineering for Natural Hazards (ENH) program in the CMMI Division: (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505177&org=CMMI), as well as specific solicitations related to hazards and infrastructure such as hazard SEES: (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504804 Opportunities also exist for collaborations in other natural hazards such as wind, storm surge and tsunami, floods, and landslides. NSF encourages both multi-hazard research, as well as international collaborations.

Conclusions

Beginning with the Darfield earthquake, NZ and U.S. researchers have collaborated closely, first with the collection of ephemeral data, and later on research projects that capitalize on the huge wealth of data available. The close relationships between the two earthquake research communities that already existed prior to the Darfield event encouraged the close collaboration, and relationships developed during the NSF-supported investigations further enhanced the formation of research collaborations. U.S. faculty and graduate students, as well as equipment and instrumentation, supplemented the already strong, but small, NZ research community. Research activities to data have been directed toward both the immediate needs of the Canterbury area in its struggle to rebuild, as well as fundamental research questions. Both countries have benefited greatly from this research effort and researchers from both countries are encouraged to continue utilizing the great opportunities presented by the CES data.

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APPENDIX A

TABLE A1. NSF-Supported Engineering Research Related to Canterbury Earthquake Series

Award Number	Title	Principal Investigator	Budget
CMMI-0825734 CMMI-0825507 CMMI-0825760	Collaborative Research: Geotechnical Extreme Events Reconnaissance (GEER) Assn: Turning Disaster into Knowledge	J. Bray, UC Berkeley; D. Frost, Georgia Tech; E. Rathje, UT Austin	$374,302 (total)
CMMI-1132381	RAPID: Learning From Earthquakes: Targeted Research Questions Emerging from the February 22, 2011 Christchurch Earthquake	J. Berger, EERI	$49,818
CMMI-1137977	RAPID: Liquefaction and Its Effects on Buildings and Lifelines in the February 22, 2011 Christchurch, NZ Earthquake	J. Bray, UC Berkeley	$99,554
CMMI-1138634	RAPID: Forensic Analysis of Eccentrically Braced Frame Fracture during the February 2011 Christchurch, New Zealand Earthquake	A.Kanvinde, UC Davis	$26,000
CMMI-1138609	RAPID: Collection of Data on the Performance of Wood Diaphragms in Buildings during the February 2011 Christchurch, NZ Earthquake	R. Leon, Georgia Tech	$40,597
CMMI-1138612	RAPID: Data Collection on the Performance of Adhesive Anchor Retrofits in Unreinforced Masonry Buildings during the February 2011 Christchurch, New Zealand Earthquake	A.Schultz, U. Minnesota	$49,679
CMMI-1138358	RAPID: Mapping of Damage in Precast Concrete Buildings from the February 2011 Christchurch, New Zealand Earthquake	J. Restrepo, UCSD	$59,223
CMMI- 38714	RAPID: Performance of the Base-Isolated Christchurch Women's Hospital during the Sequence of Strong Earthquakes and Aftershocks in NZ from September 2010 through 2011	H. Gavin, Duke	$44,470
CMMI-138612	RAPID: Immediate Behavioral Response to Earthquakes in New Zealand and Japan	M.Lindell, Texas A&M	$44,989
CMMI-154279	CMMI-1154279: RAPID Awardee Workshop to Identify Research Needs Emerging from the 2010 and 2011 New Zealand Earthquakes and the 2011 Japan Earthquake and Tsunami	J. Berger, EERI	$49,000
ECCS-1138655	RAPID: Impact of Earthquakes on Electricity Infrastructure	G.Venayagamoorthy, Clemson	$49,783
CMMI-1201026	Preliminary Study of the Seismic Performance of Improved Ground Sites during the 2010-11 NZ Earthquakes	J. Martin, VPI	$79,464
CMMI-1258466	EAGER: Instrumentation and Modeling of Seismic Isolation in Aftershocks	H. Gavin, Duke Univ.	$169,910
CMMI-1303595	RAPID: Deep Shear Wave Velocity Profiling for Seismic Characterization of Christchurch, NZ - Reliably Merging Large Active-Source and Passive-Wavefield Surface Wave Methods	B. Cox, UT Austin	$197,683
CMMI-1306261	RAPID: Liquefaction and its Effects on Buildings and Lifelines in the 2010-2011 Canterbury, New Zealand Earthquake Sequence	R. Green, VPI	$101,916
CMMI-1332501	Effects of Liquefaction on Structures in Christchurch	J. Bray, UC Berkeley	$399,883
CMMI-1343524	RAPID: Field Investigation of Shallow Ground Improvement Methods for Inhibiting Liquefaction Triggering; Christchurch, New	K. Stokoe, UT Austin	$197,996

	Zealand		
Award Number	**Title**	**Principal Investigator**	**Budget**
CMMI-1407033 CMMI-1407364 CMMI-1407428	RAPID: Collaborative Research: Liquefaction Triggering & Consequences for Low-Plasticity Silty Soils, Christchurch, New Zealand	T.O'Rourke, Cornell; J. Bray, UC Berkeley; R. Green, VPI	$199,891 (total)
CMMI-343524	RAPID: Field Investigation of Shallow Ground Improvement Methods for Inhibiting Liquefaction Triggering; Christchurch, New Zealand	K. Stokoe, UT Austin	$197,996
CMMI-1408892	RAPID: Pile Downdrag Behavior Based on Blast Liquefaction Behavior	K. Rollins, BYU	$199,940
CMMI-1439773 CMMI-1439883	RAPID/Collaborative Research: Investigation of the Effects of Rockfall Impacts on Structures During the Christchurch Earthquake Series	J.Wartman U Washington; M.Olson, Oregon State U	$169,619 (total)