Geotechnical Aspects of the M_w6.2 2011 Christchurch, New Zealand Earthquake

R.A. Green[1], M. Cubrinovski[2], L. Wotherspoon[3], J. Allen[4], B. Bradley[2], A. Bradshaw[5], J. Bray[6], G. DePascale[7], R. Orense[3], T. O'Rourke[8], M. Pender[3], G. Rix[9], D. Wells[10], C. Wood[11], D. Henderson[2], L. Hogan[3], P. Kailey[2], K. Robinson[2], M. Taylor[2], and A. Winkley[2]

[1]Dept. of Civil and Envir. Engrg., 120B Patton Hall, Virginia Tech, Blacksburg, VA 24061; PH (540) 231-9826; FAX (540) 231-7532; email: rugreen@vt.edu
[2]Dept. of Civil and Natural Resource Engrg., Univ. of Canterbury, Christchurch, New Zealand
[3]Dept. of Civil and Envir. Engrg., Univ. of Auckland, Auckland, New Zealand
[4]TRI Environmental, Inc., Austin, TX
[5]Dept. of Civil and Envir. Engrg., Univ. of Rhode Island, Kingston, RI
[6]Dept. of Civil and Envir. Engrg., Univ. of California at Berkeley, Berkeley, CA
[7]Fugro/William Lettis and Associates
[8]School of Civil and Envir. Engrg., Cornell Univ., Ithaca, NY
[9]School of Civil and Envir. Engrg., Georgia Institute of Technology, Atlanta, GA
[10]AMEC Geomatrix, Oakland, CA
[11]Dept. of Civil Engrg., Univ. of Arkansas, Fayetteville, AR

ABSTRACT

The 22 February 2011, M_w6.2 Christchurch earthquake is the most costly earthquake to affect New Zealand, causing an estimated 181 fatalities and severely damaging thousands of residential and commercial buildings. This paper presents a summary of some of the observations made by the NSF-sponsored GEER Team regarding the geotechnical/geologic aspects of this earthquake. The Team focused on documenting the occurrence and severity of liquefaction and lateral spreading, performance of building and bridge foundations, buried pipelines and levees, and significant rockfalls and landslides. Liquefaction was pervasive and caused extensive damage to residential properties, water and wastewater networks, high-rise buildings, and bridges. Entire neighborhoods subsided, resulting in flooding that caused further damage. Additionally, liquefaction and lateral spreading resulted in damage to bridges and to stretches of levees along the Waimakariri and Kaiapoi Rivers. Rockfalls and landslides in the Port Hills damaged several homes and caused several fatalities.

INTRODUCTION

The 22 February 2011, M_w6.2 Christchurch earthquake resulted in 181 fatalities and extensive damage to both residential and commercial structures. Following this earthquake, the NSF-sponsored Geotechnical Extreme Events Reconnaissance (GEER) Team, comprised of both US and New Zealand members, documented the geotechnical/geological aspects of this event. The Team focused on documenting the occurrence and severity of liquefaction and lateral spreading, performance of building and bridge foundations, buried pipelines and levees, and significant rockfalls and landslides (Cubrinovski et al., 2011b). This paper is a summary of some of these observations.

The Christchurch earthquake is significant because it was the second large event to affect the area in less than six months. The first was the M_w7.1 Darfield earthquake, the epicenter of which was approximately 40 km west of the city center, while the epicenter for the Christchurch earthquake was located about 8 km southeast of the city center. It is extremely rare to learn how the same ground and infrastructure responded to two significant earthquakes having different intensities of shaking.

The seismological aspects of the Christchurch earthquake are presented first. This is followed by an overview of the occurrence and impact of liquefaction and lateral spreading on neighborhoods, the Central Business District (CBD), bridges, and levees. Finally, a summary of observed rockfalls and landslides is presented.

SEISMOLOGICAL ASPECTS

New Zealand straddles the boundary of the Australian and Pacific plates, where relative plate motion is obliquely convergent across the plate boundary at about 50 mm/yr in the north of the country, 40 mm/yr in the center, and 30 mm/yr in the south (DeMets et al., 1994). The complex faulting associated with the changing orientation of the subduction zones in the northeast and southwest, causes predominantly dextral faulting through the axial tectonic-belt in the center of the country.

As a result of this complex faulting, New Zealand is a region of distributed seismicity, in that the relative movement of the Australian and Pacific plates is not accommodated by one or two faults in a narrow zone, but by many faults across a much wider zone (the axial tectonic belt). It is therefore not surprising to observe that both large historical earthquakes and recent seismicity can occur in almost any region in New Zealand.

The M_w6.2 Christchurch earthquake occurred at 12:51 pm NZ Standard Time on 22 February 2011. The earthquake occurred on a previously unmapped fault, the Port Hills fault located in the Port Hills south of Christchurch. As shown in Figure 1, the epicenter was located at 43.598˚S, 172.714˚E, at a focal depth of 4 km (Ristau, 2011). The faulting was primarily reverse in mechanism, with a rake of 120 degrees, and does not appear to have caused a surface trace. The distance from the epicenter to the center of Christchurch was about 8 km, but the rupture plane was directly beneath some of the southern neighborhoods of Christchurch (e.g., Heathcote Valley) and Lyttelton.

As shown in Figure 1, the earthquake motions were recorded by a network of strong ground motion stations distributed throughout the region. Representative geometric means of the recorded peak horizontal ground motion accelerations (PGAs) were 1.31 g in the epicentral region, 0.42 g in the CBD, 0.20 g in Kaiapoi (north of Christchurch), and 0.11 g in Templeton (west of Christchurch).

Figure 1. Aerial image of Christchurch showing the ruptured Port Hills fault segment, epicenter, strong ground motion stations and the geometric means of peak horizontal accelerations, and zones that liquefied (white shading).

LIQUEFACTION AND LATERAL SPREADING

Overview

Much of Christchurch and its environs was originally swampland, beach dune sand, estuaries, and lagoons that were drained as part of European settlement starting in the 1850s (Brown et al., 1995). Consequently, the near-surface soil stratigraphy is characterized by inter-bedded, loose Holocene aged silt, sand, and gravel that are highly susceptible to liquefaction (ECan, 2004). In the eastern part of Christchurch the ground water table is only 1-2 m below the surface, with water table depth increasing towards the west.

As shown in Figure 1, the Christchurch earthquake caused widespread liquefaction in the eastern part of Christchurch and in Kaiapoi (Green et al., 2011a; Orense et al., 2011). The induced liquefaction during this event was more widespread and severe in developed areas than it was during the Darfield earthquake. Of particular significance is that liquefaction occurred in portions of the CBD during the Christchurch earthquake that did not liquefy during the Darfield earthquake (Cubrinovski et al., 2011a).

Impact on Residential Neighborhoods

The areas most severely affected by liquefaction were the suburbs along the Avon River to the east of CBD (Avonside, Dallington, Avondale, Burwood, and

Bexley), as shown in Figure 1. The soils in these suburbs are predominantly loose fluvial deposits of clean fine sands and sands with non-plastic silts, with the top 5-6 m being in a very loose state (Gerstenberger et al., 2011). The town of Kaiapoi was also affected by liquefaction, especially portions that were built on abandoned river channels and fill (Wotherspoon et al., 2011a).

In total, nearly 15,000 residential houses and properties were severely damaged due to liquefaction and lateral spreading, with more than half of these damaged beyond economical repair. As shown in Figure 2a, the severity of the liquefaction led to large settlements of many houses including differential settlements that caused foundation and structural damage. Lateral spreading also damaged many residences, as shown in Figure 2b for example. (Note that the houses in Figure 2 were initially damaged during the Darfield earthquake and further damaged during the Christchurch earthquake, as were many residences throughout the region.). Lateral spreading ranged from a few tens of centimeters, up to 2 m at river banks and extended as far as 200-300 m inland from waterways.

(a) (b)

Figure 2. Examples of liquefaction damage to houses in: (a) Hoon Hay with differential settlement, and (b) south Kaiapoi with lateral spreading.

Impact on Central Business District (CBD)

The Central Business District (CBD) encompasses approximately 200 ha. The CBD is bounded by four main avenues: Rolleston to the west, Bealey to the north, Fitzgerald to the east, and Moorhouse to the south. The CBD is densely developed with multi-story buildings, a relatively large number of which are historic masonry buildings dating from the late 19th and early 20th Century, residential buildings located north of Kilmore Street (typically 2-5 story structures), and some industrial buildings in the south. In total, about 3000 buildings of various heights, age, and structural systems are within the CBD boundaries. Latest estimates indicate that about 1000 of these buildings will have to be demolished because of excessive earthquake damage.

The authors found no evidence of liquefaction-induced settlement or lateral spreading resulting in the collapse of CBD structures. However, these mechanisms contributed to the damage of many buildings, beyond economical repair. Liquefaction resulted in global and differential settlements, lateral movement of foundations, tilting of buildings, and bearing failures.

Figure 3 shows a three-story building in the CBD founded on a shallow foundation that was damaged by liquefaction. The building translated and rotated towards an abandoned channel of the Avon River (Cubrinovski et al., 2011a). The photograph was taken facing west and the abandoned river channel is north (or to the right) of the building. There was a large volume of sand ejecta at the northern part of the building. Ground tension cracks propagating east of the building and in the rear car-park are consistent with the lateral movement towards the north. The building has since been razed.

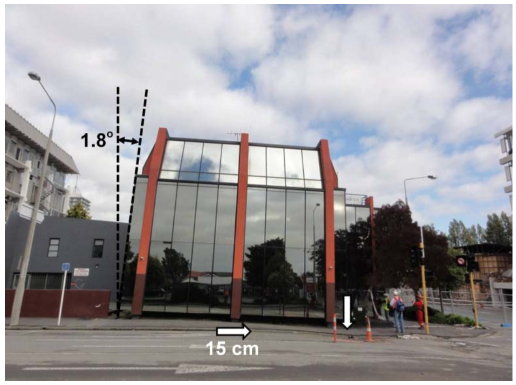

Figure 3. Three-story building in the CBD that was adversely impacted by liquefaction and has since been razed.

Impact on Bridges

The Christchurch region contains more than 800 road, rail, and pedestrian bridges. Most bridges are reinforced concrete, symmetric, and have small to moderate spans (15 – 25 m). Although liquefaction was widespread in central and eastern Christchurch, only five bridges within the city suffered major damage and ten developed moderate damage. Most of the damage was caused by lateral spreading of river banks, with only four bridges in the city having appreciable damage on sites that did not experience liquefaction, two with major damage and two with moderate damage. Because of the location of the earthquake on the southeastern edge of the city, most bridge damage was confined to central and eastern regions. The largest distance from the causative fault to an affected bridge was 17 km (i.e., distance to the moderately damaged Chaney's Overpass). Eleven of the 14 bridges along the Avon River within the CBD suffered only minor damage, mostly to their approaches (Note that the location of the Avon River is shown in Figure 4.). Outside the CBD, two had major damage and five were moderately damaged. The remaining two only had minor approach damage.

The type of bridge damage along the Avon was fairly consistent: settlement and lateral spreading of approaches, back rotation and cracking of the abutments, and some pier damage (Wotherspoon et al., 2011b). In most cases the bridge decks restrained the movement of the top of the abutment, resulting in their back rotation. Damaged bridges had pile foundations, with lateral spreading placing large demands on the abutment piles, and likely resulting in plastic hinging below grade. The approach fill of several bridges subsided by up to a meter, resulting in the bridges being closed temporarily. In most cases, settlement and spreading of the approaches impaired bridge serviceability. Overall, the bridges crossing the Avon River in the CBD performed well, with the most common damage consisting of minor lateral spreading, compression or slight slumping of approach material, and minor cracking in abutments. All bridges were single span and all were passable to recovery vehicles soon after the event. Compared to the Avon River bridges, those crossing the Heathcote River (Figure 4) suffered much less damage. Apart from the Ferrymead Bridge at the mouth of the Heathcote, all bridges were either undamaged or experienced only minor damage. Typical damage was approach settlement, with little impact on the bridge abutments and superstructure.

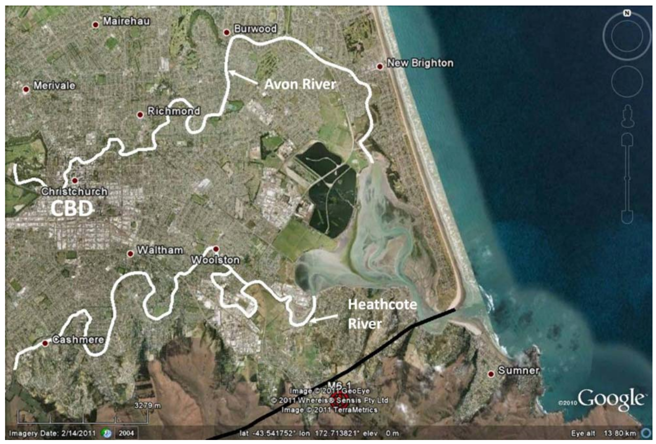

Figure 4. Aerial image of Christchurch with the Avon and Heathcote Rivers.

Impact on Levees

The Waimakariri River flows from the Southern Alps, across the Canterbury Plains between Christchurch, to the south, and Kaiapoi, to the north, and empties into Pegasus Bay in the east (see Figure 1). The Waimakariri River flood protection includes approximately 100 km of levees. A typical levee cross-section in the Canterbury region has 3:1 horizontal to vertical slopes on both the river and land sides. They range in height from 3-5 m above the subgrade and have a 4-m wide top, which also serves as an access road. The levees were often constructed by pushing up river gravels and silts. A typical cross section is made up of a gravel core with 1-m thick silt cap, which extends from the river side across the top. The levees typically sit on sandy soils at or near the ground water level. During the 1960 river improvement scheme, some new levees were constructed and benches were added to some of the existing levees, both of which were compacted using vibrating rollers (Boyle, 2010). However, no compaction control or foundation analysis was conducted (Heslop, 2010).

The majority of the damage to the levees during the Christchurch earthquake was a consequence of liquefaction in the foundation soils that resulted in lateral spreading, slumping, and/or settlement (Green et al., 2011b). Longitudinal cracks were observed along the crest of the levees (e.g., Figure 5). Transverse cracks in the levees were less commonly observed than longitudinal cracks and were often associated with sharp bends along the length of the levees and/or slumping of the embankment. Because these cracks provide a direct seepage path from one side of the levee to the other, they can severely impact the functionality of the levees. Even transverse cracks having minor widths could potentially rapidly enlarge due to internal erosion and piping at high river levels and lead to the failure of that section of the levee.

Figure 5. Example of longitudinal cracks running along the crest of the levee.

Settlement of levee sections resulted from both post-liquefaction consolidation in the foundation soils and bearing capacity failures due to the reduced strength of the liquefied foundation soil. In addition to the degradation of levee functionality due to settlement-induced cracking (similar to that discussed above), settlement also reduces the amount of freeboard at high river levels. The significance of this loss depends on the amount of settlement, but in general it is not thought to be a significant issue with the levee system.

The majority of levee damage from the Christchurch earthquake occurred east of State Highway 1 (SH1) as shown in Figure 6. In this figure, damage severity is categorized using the scale developed by Riley Consultants (2011). The scale has five grades that range from No Damage to Severe Damage, as summarized in Table 1. The damage patterns shown in Figure 6 are very similar to those from the Darfield earthquake, but are in general less severe for the Christchurch earthquake. Note that some portions of the levees were already under repair by the time of the authors' reconnaissance inspection following the Christchurch earthquake. In these cases, the authors supplemented their field observations, to the extent possible, with both observations from high-resolution aerial images taken the day after the Christchurch earthquake and field observations made by ECan consultants, Riley Consultants (2011).

Impact on Underground Lifelines

Differential settlements and lateral spreading caused widespread disruption of both potable water (mostly asbestos cement and PVC) and wastewater (mostly gasketed concrete and PVC) pipelines, with thousands of repairs needed to restore these systems. Buoyancy of concrete vaults at potable water and wastewater pump stations, compounded by liquefaction-induced settlement, caused pipeline breaks at their connections with the vaults. Approximately 1 m of settlement at the Bexley Pump Station ruptured the well, flooding the surrounding neighborhood at 140 m^3/hr. Silt and sand from liquefaction washed into the Bromley sewage treatment plant from broken wastewater pipelines, causing damage in the primary settling tanks. Nearly all facilities at the sewage treatment plant were affected by liquefaction, which caused differential settlement of the clarifiers, thereby seriously impairing secondary treatment capabilities.

There was serious damage to the underground electric power system, with failure of all major 66 kV underground cables supplying the Dallington and New Brighton areas caused by liquefaction-induced ground movements. Over 50% of all 66 kV cables suffered damage at multiple locations.

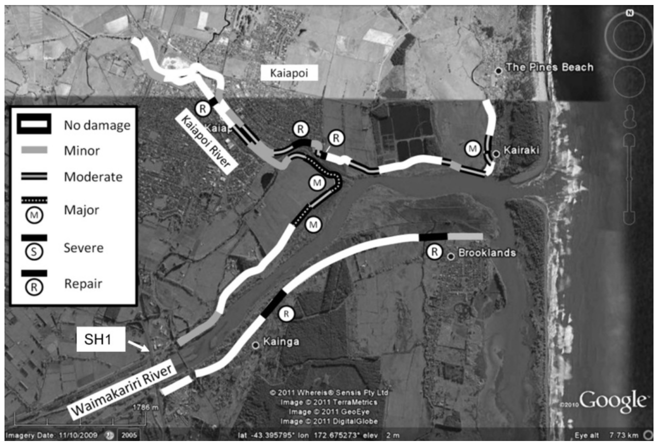

Figure 6. Observed damage to levees following the Christchurch earthquake. (Adapted from Green et al., 2011b and Riley Consultants, 2011).

Table 1. Damage severity categories (Riley Consultants, 2011)

Category	Description
No Damage	No observed damage
Minor Damage	Cracks up to 5 mm wide and/or 300 mm deep. Negligible settlement of crest.
Moderate Damage	Cracks up to 1 m deep. Some settlement of crest.
Major Damage	Cracks greater than 1 m deep. Evidence of deep seated movement and/or settlement.
Severe Damage	Severe damage or collapse. Gross lateral spread and/or settlement, cracks showing deformation of 500 mm or more.

LANDSLIDES AND ROCKFALLS

Rockfalls, block failures, and other forms of landslides were widespread in the near-fault region around the Port Hills south of Christchurch. These slope failures resulted in five deaths and damaged or destroyed many roads, tracks, and structures. Almost every cliff face in the Port Hills generated a rockfall, while over-steepened road cuts and quarry walls were subjected to block collapse or large volumes of rockfall. Rockfalls were the most widespread manifestation of slope failure, causing five deaths and the most structural damage. Deep-seated landslides were found only at a few locations, most of which were at the top of coastal headlands. Numerous failures occurred in retaining walls and fill slopes, resulting in damage to roads, property, and commercial and residential structures.

Both natural and modified (quarry) volcanic rock faces were sources of rockfall and block collapse, forming large talus slopes at the base of cliffs, or rockfall run out on some slopes. The volcanic rocks exposed across the northern part of the Banks Peninsula are part of the Lyttelton Volcanic Group, and include dominantly basaltic to trachytic lava flows interbedded with breccia and tuff, and lava domes (Forsyth et al., 2008). More than 20 residential and commercial buildings downslope of the cliffs in Redcliffs and Sumner were destroyed by rockfall debris.

Several types of rockfall protectitive measures were observed at the base of the quarry wall in the Redcliffs. These included a gabion, rockfall fences, and a rock berm. The gabion performed well in stopping the block collapse of the cliff from impacting the house below the gabion. Two rockfall fences adjacent to the gabion were less successful, as both were filled and overtopped by the large volume of the block failures. A rock berm was constructed along the schoolyard border at the base of the quarry wall, possibly using debris from a more limited rockfall that may have been generated by the 2010 Darfield earthquake (the berm is not present on the 2009 pre-earthquake imagery). This berm was successful in protecting the schoolyard, as no rocks were observed in the area beyond the rock berm.

CONCLUSIONS

The 22 February 2011, M_w6.2 Christchurch earthquake is the most costly earthquake to affect New Zealand. Geotechnical failures from this earthquake were significant, resulting in widespread damage. Of particular note was the impact of liquefaction and lateral spreading on residential and commercial structures, bridges, levees, and underground lifelines. In total, approximately 15,000 residential structures and 1000 commercial structures were severely damaged during the earthquake, many from liquefaction and lateral spreading. Overall, the bridges in the Christchurch area performed reasonably well, relative to residential and commercial structures. However, a handful of bridges were moderately to severely damaged, mainly as a result of lateral spreading. Damage to the levee system was primarily confined to the east of the SH1, with most (if not all) of the damage being a direct result of liquefaction and lateral spreading of the foundation soils. Rockfalls, block failures, and other forms of landslides were widespread in the near-fault region around the Port Hills. These slope failures resulted in five deaths and damaged or destroyed many roads, tracks, and structures.

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