Learning from Earthquakes

The M_w 7.1 Darfield (Canterbury), New Zealand Earthquake of September 4, 2010

From September 8th to 20th, 2010, a team organized by the Earthquake Engineering Research Institute (EERI) and the Pacific Earthquake Engineering Research (PEER) Center investigated the effects of the Darfield earthquake. The team was led by Mary Comerio, UC Berkeley, and included Lucy Arendt, University of Wisconsin, Green Bay; Michel Bruneau, University of Buffalo, New York; Peter Dusicka, Portland State University; Henri Gavin, Duke University; Charles Roeder, University of Washington; and Fred Turner, California Seismic Safety Commission. Additionally, individuals sponsored by their organizations, or already in New Zealand, joined the team: Tao Lai, AIR Worldwide Corporation; Rob Williams and Oliver Boyd, US Geological Survey; Myrto Anagnostopoulou, University of Buffalo; and William Holmes, Rutherford and Chekene, LFE Program Manager. Thomas O'Rourke of Cornell University visited Christchurch the week of October 11th.

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Introduction

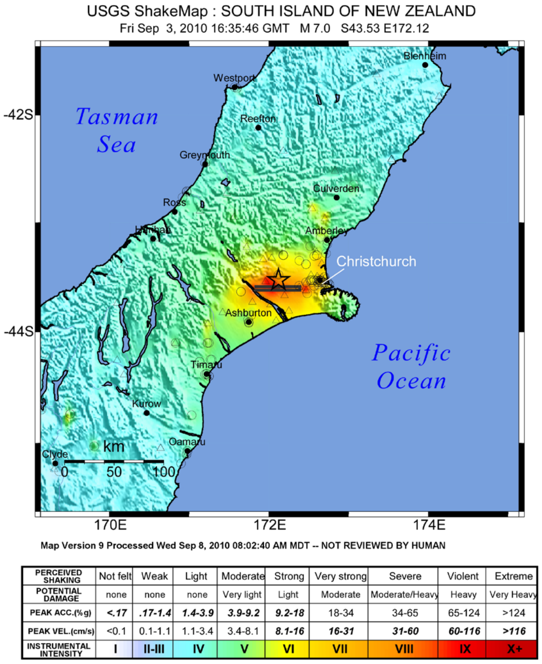
In the early hours of Saturday morning on September 4, 2010, people in Christchurch and the surrounding Canterbury region were jolted awake by the most damaging earthquake in New Zealand since the deadly M7.8 Hawke's Bay (Napier) earthquake in 1931. This time there was no loss of life and only two serious injuries. The low casualties can be attributed in part to the time of the M7.1 earthquake at 4:36 am, as well as to the moderate level of shaking in the most populated areas of the Canterbury region. New Zealand also benefits from a modern structural code and rigorous code enforcement. Regional planning had been undertaken to reduce critical infrastructure and lifelines vulnerability to natural hazards about 15 years ago (Centre for Advanced Engineering, 1997), with improvements in local government and utilities preparedness, as well as the retrofitting of bridges and other lifeline facilities.

Christchurch is the largest city on the South Island of New Zealand, and the country's second-largest urban area, with a population of 375,000. While New Zealand has strict seismic building codes for new construction, Christchurch was not considered a high-risk area and had a passive retrofit policy for its unreinforced masonry buildings. The damage to nonretrofitted URM buildings from the moderate shaking is an important object lesson for other regions with large inventories of URM buildings. Unprecedented residential losses due to liquefaction and lateral spreading represent a considerable portion of the total losses, estimated at $4 billion NZ ($3 billion US). Even for buildings that performed well structurally, there was extensive nonstructural damage to both building components and contents.

Seismicity

The earthquake nucleated about 10 km below a flat-lying agricultural area called the Canterbury Plains, 40 km west of Christchurch, near the town of Darfield (Figure 1). GeoNet (http://www.geonet.org.nz) estimated the moment magnitude at 7.1 with a predominantly strike-slip focal mechanism having a right-lateral focal plane striking east-west. However, more detailed and ongoing analysis has revealed a strong reverse faulting component to the mainshock.

The surface rupture spans nearly 30 km and consists of fault scarps that locally exceed 4 m of right-lateral and about 1 m of vertical dislocation of the ground surface. In most places along and near the fault, the ground surface on the south side has been raised relative to the north side. Ongoing geodetic surveys, including LiDAR and InSAR surveys, are measuring these deformations in greater detail. Surface rupture extends west from the town of Rolleston to just southwest of Greendale and then trends northwest. In the two-week period following the earthquake, there were over 550 aftershocks greater than or equal to magnitude



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	*8.1-16*	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1. *Location of epicenter and shaking intensity by city size (source: USGS)*

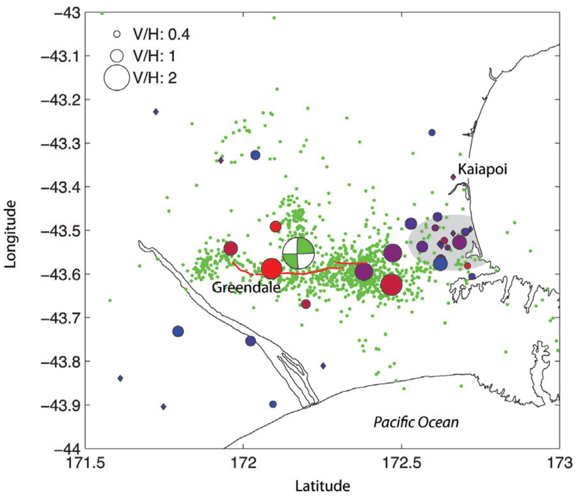


***Figure 2.** Strong motion stations, fault rupture (red line) and aftershocks (green circles). Gray area is the metropolitan area of Christchurch (source: USGS)*

3, including nine greater than M 5.0. The largest aftershock was an M 5.6 about 20 minutes after the main shock. The aftershocks disclose a roughly 60 km long east-west rupture plane just south of the epicenter.

The earthquake was located on an unmapped fault that may not have ruptured in the last 16,000 years, as evidenced by previously undisturbed Pleistocene gravels (GNS Science, 2010). Prior to this earthquake, much of the seismic hazard in the region was ascribed to the Alpine fault, a major northeast striking right-lateral strike-slip fault that separates the Pacific and Australian plates and lies about 100 km northwest of the Darfield earthquake.

Very strong ground motions were recorded by strong motion seismometers near the rupture. Maximum felt intensities reached VIII (Figure 2). Maximum vertical peak ground acceleration at Greendale (located about 1 km north of the fault scarp) was 1.26 g. Horizontal peak ground acceleration at this site averaged 0.74 g. The five sites closest to the surface rupture (all within about 5 km) had vertical ground accelerations greater than 0.7 g and ratios of vertical to horizontal acceleration greater than 1.5 — in spite of four times more horizontal offset than vertical along the surface rupture. The ratio of vertical to horizontal ground acceleration decreases steadily moving away from the surface rupture. The station at Kaiapoi (about 40 km east-northeast of the epicenter) is anomalous compared to the other stations in that it exhibits very low vertical peak ground acceleration (0.09 g) relative to the horizontal (~0.33 g). Charles Clifton (2010) of the University of Auckland reported that ground accelerations in Christchurch were about 70% of the design values for periods less than 1.5 s, and 100% of the design values at longer periods. Farther west, closer to the rupture, ground accelerations exceeded design values at all periods.

Geotechnical Effects and Lifelines

Liquefaction and lateral spreading were pervasive in portions of Christchurch and neighboring communities (Figure 3), causing extensive damage to buried utilities (water and wastewater pipelines), residential housing, and other building structures. To a lesser extent, roads, railroad embankments, and levees were also affected. According to a 2004 liquefaction susceptibility study in Christchurch, approximately 50% of Christchurch residential areas are vulnerable to liquefaction (Environment Canterbury, 2004). Between 5% and 10% of residential properties in the Christchurch area were actually affected by liquefaction.

The Christchurch and Waimakariri Districts, and to a lesser extent the Selwyn District, all had damage to pipeline networks that resulted in the loss of service and discharge of untreated wastewater into the groundwater and surface water. In all three districts, drinking water is untreated well water. Most water mains are asbestos-cement pipelines, with newer pipelines composed of polyvinyl chloride. Wastewater pipelines in Christchurch are predominantly reinforced concrete conduits.

Christchurch City Council (CCC) officials estimate that approximately 25 km of potable water and 70 km of wastewater pipelines will have to be replaced in areas of liquefaction and lateral spreading. Outside

***Figure 3.** Structures damaged by lateral spreading and post-liquefaction differential settlement. (a) ▲ Residential structure in Spencerville; (b) ▶ St. Paul's Church in Dallington (photo: Green).*

the areas of liquefaction, there were approximately 280 locations of damage in water pipelines that were repaired within 6 days of the earthquake. Liquefied sand and water entered sewer lines though breaks and separations in the pipe, and cleaning the sand from wastewater conduits and pump stations slowed service restoration. Furthermore, CCC officials expressed concern about voids that developed beneath pavements due to the estimated 11,000 tons of sand removed from pipes and pump stations (corresponding to a potential volume of approximately 9,000 m3).

The hardest hit communities in Christchurch were perhaps Spencerville and Brooklands. Two weeks after the earthquake, neither community had functioning wastewater collection systems, and Brooklands was without potable water. Liquefaction along Lower Styx road, the primary connection between these two communities, caused ground subsidence, raised the water table, and uplifted 25 manholes. Separation between the manholes and the road surface was 28-46 cm (Figure 4).

The Waimakariri District Council (WDC) was much harder hit than Christchurch, primarily due to the extensive liquefaction and lateral spreading in Kaiapoi. Approximately 30-35 km of water and sewer pipelines and 10 km of storm lines in Kaiapoi were severely disrupted in areas of liquefaction and lateral spreading. The biggest problems were to the deep gravity wastewater mains, in many cases 3-4 m below the ground surface. With ground water only 2 m deep, trenching was difficult. In addition, some mains are located in the backyards of private residences, making access and subsequent repairs more difficult.

Figure 4. *Uplifted manholes along Lower Styx road.(photo: Green)*

The large vertical movements due to liquefaction caused low points in some sewer lines, and in the community of Kaiapoi sewage is being pumped from one of these low points into the river. The effects of these settlements on surface storm drainage have not been determined; neither have potential effects on river channels and flood plains due to changes in grade caused by local fault movement.

In contrast to the water and sewer system, the gas distribution system performed well. The natural gas pipeline system in Christchurch comprises 170 km of 65-315 mm internal diameter, medium-density polyethylene pipelines with thermal fusion welds. At the time of the earthquake, the gas was a mixture of 60% propane and 40% butane at a pressure of approximately 90 kPa.

There were no leaks or significant fluctuations of pressure throughout the system during and after the earthquake. Most gas pipelines were located outside zones of liquefaction, although some lines were located in a zone of liquefaction-induced ground deformation along the Avon River in New Brighton as well as in an area of liquefaction adjacent to Hagley Park.

By far one of the greatest impacts of this earthquake on the residents in the Canterbury region was the lateral spreading and post-liquefaction differential settlement that damaged numerous residential and other structures (Figure 5). Particularly hard hit were the Christchurch neighborhoods of Dallington, Avonside, and Bexley, outlying neighborhood of Halswell (southwest of Christchurch), outlying neighborhoods of Spencerville and Brooklands (northeast of Christchurch), and Kaiapoi and Pines Beach (northeast of Christchurch, north of the Waimakariri River).

Figure 5. *(a) ▲ Large lateral spreading like a rupture passed through the foundation near Courtenay Drive in Kaiapoi. (b) ▼ This house slid more than 1.2 m and tilted significantly (near Courtenay Drive in Kaiapoi) (photos: Lai).*

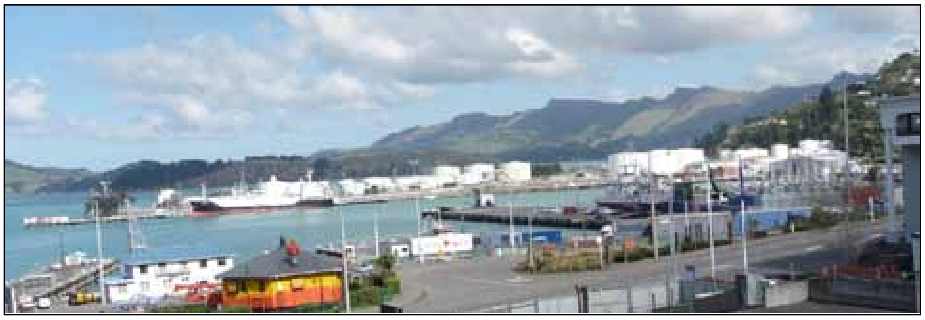


Figure 6.** The port facility at Lyttleton (photo: Roeder).

The Waimakariri River is the source of greatest flood risk in the Canterbury area. Flood protection includes approximately 100 km of stop banks, or levees, along the river. The levees are typically 3-5 m high, 4 m wide on top, with 3H:1V slopes. Earthquake levee damage was especially pronounced in the lower Waimakariri near Kaiapoi, where approximately 5 km of levees along the Waimakiriri and Kaiapoi Rivers suffered severe and major damage. Severe damage involves cracks greater than 1 m in width, with deep-seated movement and settlement; major damage entails large-scale instability, with lateral spreading and settlement that exceeds 0.5 m.

Port

The port serving the Christchuch area and South Island is in the community of Lyttelton (Figure 6). The facility is relatively small, but it has a full range of shipping, including container, dry bulk (coal), finished petroleum products, livestock, and other miscellaneous commodities. The port sustained significant damage during the earthquake, and port engineers estimate total costs at more than $100 million NZ ($75.5 million US). The harbor is a volcanic caldera with wind-blown silt in the upper strata. Seawall areas are constructed with hydraulic infill from harbor dredging. The older wharves have timber piles with precast deck panels, which are approaching the end of their useful life, but newer wharves employ concrete and concrete-filled steel tube (CFT) piling. The wharf construction is somewhat different from that used in many ports in that the piles have shear or pin connections to the wharf superstructure, and lateral resistance is primarily developed through struts or tie-backs anchored into the landward soil. Geotechnical analyses indicated that the stronger and denser reclaimed soils over the weaker harbor silt/clay mud are unstable during seismic loading, and there is potential for liquefaction.

Indeed, significant liquefaction was observed in many areas around the port. Although the soil movements appeared somewhat less severe than in many other areas near Christchurch, the actual magnitude of vertical and transverse movement was not precisely known because geometric surveys were not complete by the date of the visit. However, there was clear differential deformation in Cashin Quay wharves 1 and 2. The landward piles had approximately 200 mm downward movement compared to the rest of the wharf, the timber cap beams for the piles were broken in many locations, and there was considerable deformation of the precast deck panels on the landward side of the wharf. Both crane rails rest on the seaward side of the wharf, and no relative displacement between the rails occurred so that crane operation resumed quickly. These movements caused separation and misalignment of the conveyors (Figure 7) used for loading coal at these wharves. These wharves returned to service shortly after of the earthquake, but they are not operating at full capacity and some parts of the wharves and coal-handling equipment must be replaced.

Container ships are loaded at Cashin Quay wharves 3 and 4, which are newer structures on concrete or CFT piles, and had limited damage. The petroleum products wharf had extensive liquefaction, but limited damage to the loading berths, since these were seismically retrofitted in recent years. Coal loading resumed 26 hours after the earthquake, and an LPG ship sailed into port one week afterwards.

***Figure 7.** (a) ◄ (b) ▲ The coal loading machinery at the port (source: Roeder).*

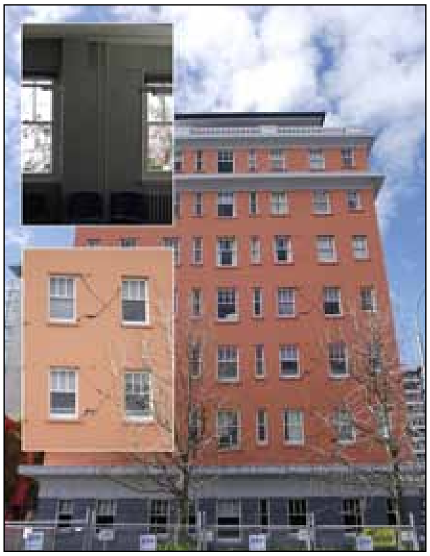


Figure 8. *Shear cracks in perimeter masonry walls of an eight-story reinforced concrete frame building in downtown Christchurch (photo: Dusicka)*

Figure 9. *Cracks at beam seats of gravity load precast members used in parking garage, along with undamaged eccentrically braced frame lateral system in Christchurch area (photos: Dusicka).*

Engineered Structures

Newer engineered buildings generally performed well, but preliminary indications are that the ground shaking was below the design response spectra for shorter-period buildings (periods less than about 2 seconds). The majority of larger and multi-story buildings in the affected area are located in downtown Christchurch and on the University of Canterbury campus. Reinforced concrete construction is prevalent, with older buildings being typically reinforced concrete moment frames. A number of these older buildings also had masonry infill walls, but we observed very limited structural damage to these structures. This is likely attributable to the lower-than-design-level demands that are suspected to have been imposed on the shorter-period structures. One of the most visible exceptions was an eight-story building consisting of reinforced concrete frames with a double cavity wall of unreinforced masonry bricks around the building. Severe shear cracks were visible in the masonry on both the exterior and interior of the building (Figure 8).

More modern engineered buildings are also reinforced concrete, often utilizing precast structural components and sometimes mixed (concrete and steel) construction. One such example was the Westfield Riccarton Mall, a multi-story shopping complex where precast panels were combined with steel eccentrically braced frames (EBFs) on a multi-story garage. Relative movement of the precast panels of approximately 0.25 in was apparent from the steel connector brackets and cracking damage to a couple of the precast beam seats; however, the steel lateral system did not appear to be affected (Figure 9).

One reinforced concrete building constructed about 1960 was situated alongside the Avon River in an area with significant liquefaction and lateral spreading. This building sustained significant damage (Figure 10) because of lateral spreading under the foundations of the columns. The column line adjacent to the river shows soil movement. Most damage is concentrated in the beam-column connections since many bays of the building have masonry infill that provides a very stiff structure.

A number of modern buildings had broken windows, and a few showed signs of structural distress. The WestPac Trust Building is a 14-story reinforced concrete frame structure in central Christchurch with concrete core walls and diagonally reinforced coupling beams (Figure 11). The perimeter beams were precast concrete elements that form an apparent truss. A secondary shallow concrete beam appears to be located behind the truss, but does not connect to the centerline of the column. The columns are spalled at the beam-column connection for all connec-

Figure 10*. Damage to a reinforced concrete building from lateral spreading at a site near the Avon River (photo: Roeder)*

***Figure 11.** Perimeter column spalling throughout the height of a reinforced concrete frame with perimeter precast trusses in WestPac building in downtown Christchurch (photo: Dusicka)*

***Figure 12.** (a) ▲ Yielding in the link beam of an eccentrically braced frame (b) ▶ and a severely damaged concrete column in a parking garage in downtown Christchurch (photos: Roeder).*

tions at lower levels, and for many levels of the structure. The spalling was increasingly more severe and clearly distributed throughout the height when observed two days after the initial survey. The spalling was mitigated by manual removal of loose concrete and clearly exposed the main and transverse reinforcing at some locations.

Steel structures are not common in Christchurch, and the relatively few performed quite well. However, steel eccentrically braced frames (EBFs) were used with concrete columns in several buildings, in some cases as a retrofit. One relatively new parking garage employed this concept to provide lateral resistance to other framing made of precast concrete, likely to enable rapid construction. Numerous EBFs indicated yielding in the link beam, illustrating the engagement of the lateral system and protecting most of the precast beam and column gravity structure (Figure 12a). The garage had long inclined concrete ramps along one edge of the building, which possibly caused torsional deformation that might explain the non-uniform yielding in the steel frames. In addition, several concrete columns located on the upper ramp were severely damaged (Figure 12b).

Bridges

Overall, bridges in the Canterbury area suffered little damage. This was due a complex set of circumstances: 1) most have small to moderate spans, which are recognized to exhibit a more sturdy seismic response because of their symmetry and limited reactive mass; 2) most were designed to resist forces substantially larger than the demands imparted by this particular earthquake; and 3) they shared a number of common design features that gave them high seismic resistance, including a sturdy monolithic structure in both their longitudinal and transverse directions, wide wall piers that provided stiffness and strength in excess of the values needed to resist severe excitations transversely to the axis of the span, and continuity of the superstructure from abutment to abutment that provided a rigid behavior in the longitudinal direction. While the wall piers of these bridges were likely supported on piles, damage to such piles would be difficult to identify even if it were present.

Six pedestrian bridges, not endowed with similar strengths and stiffness to resist the demands applied to them as a consequence of the liquefied soils, did not fare as well and will need replacement. One notable example is the pedestrian steel truss bridge over the Avon River in Christchurch that buckled axially under thrust imposed by the movements of its abutments due to the lateral spreading action of soils on top of liquefied layers (Figure 13). This introduced compressive forces in the bridge truss chord, forces unanticipated in the original design that led to local buckling of some chord members, twisting of the superstructure, and uplifting at a support location above one of the braced pier in the river.

Schools

Most schools in the Christchurch (171 schools, 59,736 students), Selwyn (30 schools, 7,818 students), and Waimakariri (25 schools, 6,618 students) districts opened one week after the earthquake. The oldest schools have heritage buildings — typically multi-story unreinforced masonry structures almost a century old. Newer school campuses typically contain timber-frame single-story structures with unrein-

Figure 13. *Pedestrian bridge, River Road–Avonside Drive, Christchurch (photo: Bruneau).*

forced slab-on-grade foundations. Nine schools remained closed beyond one week for further structural evaluations and repairs.

While very few schools sustained significant losses to contents, 75% of them required minor repairs (rearranging toppled contents, repairing broken windows, replacing ceiling tiles). Most schools reopened after 50 person-hours or less of work in each one, but about 20% of them required 200 person-hours or more to make necessary repairs.

Halswell Primary and St. Paul's School suffered significant liquefaction-induced damage to foundation slabs and piled foundations; Halswell School is sited near a former river bed and St. Paul's School is within a bend of the Avon River. At Halswell, eight classrooms, the staff room, and the administration area are slated for demolition and reconstruction in the summer. Students are being split among three other school campuses for the remainder of the year.

Hospitals

The Canterbury District Health Board manages 15 hospitals, including three major ones in Christchurch, a rural hospital, six small community hospitals, two small maternity hospitals, a psychiatric hospital, an older-persons care hospital, and an outpatient hospital. There are also two large private hospitals in Christchurch.

Immediately following the earthquake, all area hospitals remained operational, including the Christchurch Hospital Emergency Department. Backup generators for Christchurch and Burwood Hospitals were operational within 15 seconds of losing power, and full power to these facilities was restored within 80 minutes. The two urgent care facilities in the affected area (Riccarton Clinic and Moorehouse Medical and Pharmacy) opened by 8:00 a.m. the morning of the earthquake.

Staff at three small community hospitals (Lincoln Maternity Hospital, Burwood Birthing Unit, and Akaroa Hospital) were relocated to the main Christchurch Hospital campus in order to ensure that it had adequate staff to run in 24/7 shifts. These three facilities were closed from September 5th to 15th, although there was no significant damage to any of them.

The Christchurch Women's Hospital opened in 2005 and is the only base-isolated structure in the South Island. The superstructure consists of an exterior precast frame with steel Vee bracing up to Level 4 (out of 9), and was detailed to a ductility capacity of 1.8. Following the earthquake, a 25 mm residual displacement in the isolator system was observed in the E-W direction. The estimated 70-90 mm peak isolator drifts are well below the 420 mm design displacement, for a 2,000-year return period demand. The estimated peak displacements are probably not inconsistent with the observation that spectral demands in Christchurch for this event were close to the 10%/50yr level for long-period structures (Figure 14).

The base-isolated Christchurch Women's Hospital building connects to the adjacent Christchurch Hospital through seismic joints, with sacrificial wall panels, ceilings, and floor mats. Damage to these sacrificial components increased up the height of the structure, with evidence of larger motion in the NS direction. An unsecured bookshelf on level 5, the only unsecured shelf on that floor, toppled. Most of the water in a half-full birthing pool on level 3 sloshed out, and carts rolled across the floors. The aftershock sequence has led to motion-sickness complaints from staff working in levels 4 and 5 of the base-isolated facility.

Housing and Insurance

Almost all housing in the Christchurch region is single-family wood-frame, most of it one story. Many of the older homes had unreinforced masonry chimneys, highly vulnerable to earthquake damage, and to date there have been more than 14,000 claims for damaged chim-

Figure 14. *Aspect of the base-isolated hospital building (source: Gavin).*

neys. The homes are predominantly concrete slab on grade with a light perimeter grade beam, as opposed to the US approach of using wood-framed first floors over crawl spaces. Although crawl spaces create their own earthquake vulnerability, such a system is probably better under severe liquefaction conditions, because the wood floor is more tolerant of slight differential settlements and the crawl space can be used to raise and/or relevel the superstructure.

In 1945, the government established an insurance program to protect its residents from the financial impacts of war. Later, this was repurposed as coverage for natural catastrophes such as earthquake, landslide, tsunami, volcanic eruption, hydrothermal activity, and flood (land only). It is administered by the Earthquake Commission (EQC), which provides fire insurance as well, and is required with every mortgage. Commercial owners are not under the EQC umbrella, and have to purchase protection solely from private insurers.

The EQC insurance policy costs homeowners $67.50 NZ per year, and provides protection of up to $100,000 NZ for a dwelling (building), and $20,000 NZ for contents (personal belongings). In addition, if the site is destroyed (originally conceptualized for landslides, but applicable in the liquefaction zones), an amount for the land lost can also be added. When the actual damage is beyond the EQC limit, either private insurers or homeowners will be responsible for the difference, depending on the additional insurance purchased by homeowners.

Approximately 85% of New Zealand homeowners have EQC-backed earthquake insurance coverage through private insurers. Over the past 60+ years, EQC has been collecting premiums from the insureds and has generated around $5.6 billion NZ for the Natural Disaster Fund, which is further backed up by a government guarantee and international reinsurers. The government guarantee ensures that EQC will always be able to meet its obligations, regardless of the circumstances, and the reinsurance program provides protection for the fund in case of a large natural disaster.

After a major disaster, the EQC works through its Catastrophe Response Program (CRP) with local engineering consultants to augment their capacity to cope with the substantial increase in demand for services and resources. EQC also actively participates and funds earthquake-related research. Because liquefaction damage after this earthquake was widespread and quite severe, EQC developed a process to standardize the assessment of liquefaction damage. EQC proposed the classifications below, and formulated a calculation of land damage given the liquefaction damage state and a normalized residential land area that varies by rural and urban dwellings:

- Significant liquefaction land damage: major lateral spreading
- Major liquefaction land damage: major settlements and minor lateral spread
- Moderate liquefaction land damage: moderate settlements
- Minor land damage: no surface evidence of liquefaction
- Structural shaking damage only: no obvious land damage

As an example of the complications involved, Figure 5 shows two dwellings in Kaiapoi that were severely damaged due to large lateral spreading. In the first photo, the lateral spreading created a large ground rupture passing through the foundation and leaving this house uninhabitable. In the second case, the entire house moved, mostly with the surrounding soil about 1.2 meters to the rear, which overlooks a wetland. It is expected that both dwellings will have to be demolished; however, it will be difficult to determine financial responsibility since the large lateral spreading could be associated with the development's location adjacent to public wetlands. The role of the development approval process is likely to be an issue for insurance and reconstruction. Furthermore, the damage will represent a devastating loss to homeowners unless they have private insurance in addition to the EQC coverage. Even then, the additional cost of demolition and foundation strengthening will leave the homeowners in a dilemma concerning the suitability of the site for rebuilding. City regulators, insurers, and the EQC must decide if the sites can be reused and, if so, under what required structural or soils modifications.

At the time of this report, EQC reported a total of 87,928 claims from the earthquake. Since new claims are being submitted daily and claims settlements are in process, it is still too early to determine the exact monetary loss for residential dwellings. However, given the pattern of claims submission, it is very likely the total number of claims will reach 100,000, as the EQC had originally expected. Given the current damage statistics — more than 14,000 chimneys damaged, approximately 3,000 dwellings likely to be demolished, and average dwelling damage cost of $300,000 NZ — the total residential loss will likely be around $3 billion NZ. EQC will be responsible for more than half that figure.

Post-earthquake assistance is also available to local governments through the Local Authority Protection Programme (LAPP) (Civic Assurance, 2010), which is a trust fund established in 1993 to help New Zealand local authorities pay the infrastructure replacement costs for water, sewerage, and other essential services damaged by natural disasters. Of 85 local authorities, 59 are currently fund members. For example, the CCC and Waimakariri District Council are members, but the Selwyn District Council is not. Under the fund, 60% of replacement cost is to be covered by the national government, with the remainder covered by member contributions. The cost of the earthquake repairs exceeds the size of the insurance pool (approximately $40 million NZ), and the role of the national government in attending to the additional costs is yet to be determined.

Unreinforced Masonry Building Performance

New Zealand's building stock resembles that of the western part of North America. With the shaking intensity in Christchurch varying between VII and VIII, the Central Business District had severe damage in some unreinforced masonry (URM) brick commercial and stone institutional buildings. The Canterbury Region has 958 URM buildings; of the 595 URM buildings assessed after the earthquake in Christchurch (apparently concentrating on the CBD), 21% received red "unsafe" placards, and 28% received yellow "restricted use" placards. Over 160 buildings suffered more than 10% damage and many of these have since been demolished (Ingham and Griffith, 2010).

Stair-step and X-cracking in the plane of walls was observed in two seven-story URM buildings in the district, but was only rarely noted in the low-rise URM buildings. Many of the severely damaged buildings had relatively low mortar strength.

Throughout the city, loose masonry fell from unbraced parapets and gable walls (Figures 15 and 16). In a large number of cases, entire parapets and upper walls not adequately attached to roofs fell onto streets, sidewalks, and adjacent smaller buildings.

Only some of the URM buildings appeared to be partially or fully retrofitted prior to the earthquake. Parapet bracing was apparent in some, often only on walls over busy streets. Because Christchurch was considered to be in a region of moderate seismic hazard, the regional government had encouraged voluntary retrofits of collapse-prone buildings. Although statistics are not available at this time, anecdotal evidence indicates that retrofitted or partially retrofitted URMS performed well compared to similar unretrofitted buildings nearby.

Various techniques were used for retrofitting URMs: through-bolts, adhesive anchors, fiber reinforced polymers, grout injections, added steel moment frames and braced frames, concrete moment frames and walls, new roof diaphragms, and external steel rods, angles and plates. These retrofit methods appeared to preclude collapse and did not exhibit systematic vulnerabilities to the particular ground motions of the earthquake. However, there was minor damage in several retrofitted buildings, as would be expected. Efforts to document the performance of retrofitted buildings are particularly relevant to U.S. and Canadian practice, since New Zealand's methods are quite similar to those in North America.

In older commercial districts, many modern and generally lightly damaged buildings and their occupants were indirectly affected by severely damaged URM buildings nearby. Several blocks throughout were closed for cleanup and stabilization of buildings with loose masonry falling hazards, handicapping traffic and commerce. The masonry falling on sidewalks, on outdoor restaurants, and on neighboring smaller buildings would have caused many casualties if the earthquake had struck during the day or early evening hours. The extremely high risk in and around these few buildings again confirms the high life safety risk of URM buildings very similar to those found in many parts of the U.S.

In response to the earthquake, Christchurch's City Council followed prior recommendations from New Zealand's national government and enacted a policy requiring 7,600 "earthquake-prone" buildings (those with less than 33% of the lateral strength required for new buildings) to be evaluated and retrofitted within 15-30 years, depending upon their occupancy, to ensure that they have at least 67% of the strength required for new buildings. All construction types except low-rise

***Figure 15**. This corner building had braced parapets only fronting on the main street, left. The secondary street wall separated from the roof, falling onto the street and sidewalk below (photo: Turner).*

***Figure 16**. Blackwell's Department Store on William Street in Kaiapoi suffered extensive structural damage (photo: Arendt)*

Figure 17. Nonstructural damage at the University of Canterbury: fallen ceiling tiles and hangers (photo: Comerio)

dwellings are included in the 7,600 buildings affected by this new policy. Efforts are also underway to establish funds for repairing high-priority heritage buildings to minimize the loss of integrity to historical districts (Christchurch City Council, 2010).

There was only one fire in a URM building in the Central Business District caused by restored electricity igniting liquid propane gas.

Nonstructural Losses, Multihazards and Impacts on Universities

Much of the nonstructural damage at universities and in office, commercial, and warehouse buildings was removed before the EERI team arrived, but discussions with engineers and news reports suggest that there was significant nonstructural damage to both building components and contents.

Storage racks for food supplies at two regional distribution centers collapsed during the earthquake, losing a month's food supply for Christchurch. To compensate for the lost storage, food shipments by truck and train were undertaken from the North Island down the transportation corridor of Highway 1 along the South Island east coast. Six days after the earthquake, a large landslide (approximately 90,000 m3) closed the transportation corridor (both highway and railroad) near Kiakoura, about 175 km north of Christchurch, for four days. Food shipments were then diverted onto Highway 73 in mountainous terrain, which was threatened by severe weather.

***Figure 18.** At the University of Canterbury, laboratory experiments had to be rebuilt. (photo: Comerio)*

Damage to industrial storage racks was observed at many locations after the earthquake. Such damage, especially with respect to the food supply, illustrates the importance of nonstructural mitigation for secondary building systems and contents. The disruption of transportation routes to Christchurch illustrates the effects of multiple natural hazards on critical lifelines. To dispose of the food lost by storage rack collapse, a new cell was opened in the city landfill to expedite removal and thereby avert a health hazard.

The University of Canterbury is the 2nd oldest in New Zealand. The original campus is now the downtown "Art's Centre," and the current campus (with about 13,500 students) was built in the 1950s-1970s on the west side of Christchurch. The building stock is predominantly 3-12 story concrete construction. University staff had done excellent earthquake preparedness planning and immediately organized safety inspections and detailed building assessments. About one third of campus buildings had some nonstructural damage, while 75% had contents damaged (files overturned, books off shelves, shelves overturned, fallen lab equipment, broken beakers). The nonstructural damage was primarily to stairs, finishes at seismic joints, ceilings and elevators (Figure 17). Some sprinklers were set off by ceiling movement, and one eight-story building had an open water tank on the roof. The water sloshed out of the tank and caused water damage in labs.

The university was initially closed for one week, but during the clean-up, it was decided to extend the closure for a second week, with a phased return of staff and students in the second week. Staff and graduate student researchers were allowed in to clean up their offices and make repairs (Figure 18), and faculty met to organize the teaching and exam schedule for the end of the semester.

At Lincoln University, an agricultural research university with 4,000 students in SW Canterbury, the damage to pre-76 code buildings was similar to that at UC, with 181 broken windows in one building. Library books were knocked off shelves and lab beakers were broken, but there was not significant contents damage. A complex of historic URM buildings suffered significant cladding and gable damage (Figure 19), but the exterior bay and wall of an adjacent building were undamaged, since it had been retrofit with a new interior structure. The institution was closed one week, after which students were back in class and in their labs. Many students (particularly international students) stayed in dorms

Figure 19. *Ivey Hall (a) ▲ at the Lincoln University campus was partially retrofitted prior to the earthquake and performed remarkably well, whereas (b) ▶ the adjacent unretrofitted Memorial Hall had severe damage at its gable walls (photos: Turner).*

on campus during the week the university was closed and helped with the clean-up.

Response and Recovery

Injuries: There were no fatalities directly attributable to the earthquake. Two people were reported seriously injured, one by a collapsing chimney and another by flying glass.

Disaster response: Local and national government response to the early morning earthquake was swift. The National Crisis Management Centre in Wellington was activated immediately after the quake, and Civil Defense declared a state of emergency for Christchurch, the Selwyn District, and the Waimakariri District less than six hours after the quake. Both the mayor of Christchurch and the country's Prime Minister were quick to reassure citizens of the government's support.

Radio and web-based announcements urged citizens to stay home and to check on their neighbors. Concerns about water and sewage prompted Christchurch's mayor to tell citizens to conserve water, not flush toilets, and avoid going out to see damage. Without power, wireless phone systems in homes connected to landlines were unusable. People were encouraged to use wired landlines or cell phones, but to limit their use to emergency calls. Power was restored within 18 hours to 90% of the Christchurch area. In Kaiapoi, just outside Christchurch, water and sewage were still not restored to all locations ten days after the quake.

A curfew was established for parts of Christchurch's Central Business District (CBD), mainly due to damage to many unreinforced masonry buildings and debris in the streets. Large sections of the CBD's streets were cordoned off to protect potential shoppers and those wanting to see the damage. Street clean-up in the CBD began early in the afternoon after the quake, but areas of the CBD remained cordoned off even two weeks after the event (Figure 20).

Conversations with citizens suggested strong support for the government's response and a strongly held belief that overall recovery would be quickly achieved. People were generally stoic about the earthquake and its aftermath, stating that they needed to get on with their lives and planned to do so. Some manifestations of stress were evident, but they were infrequently expressed. The New Zealand government created a website containing a wealth of information for citizens (http://www.canterburyearthquake.govt.nz/) about the earthquake and planned recovery. National legislation was passed within two weeks of the quake to expedite recovery.

Business and insurance: Businesses in Christchurch fared well overall. There was minimal observable structural damage, other than in URM buildings. Smaller businesses that had nonstructural or contents damage generally reported that they had addressed problems themselves or with contractor help. Most Christchurch businesses reopened within a few days of the quake, many reporting that they had "no business interruption, but also

Figure 20. *The building housing Angus Donaldson, and other businesses on Colombo St. in Sydenham, is cordoned off two weeks after the quake (photo: Arendt).*

Figure 21. *This Asian Supermarket on Riccarton Rd, Christchurch, reopened two weeks after the quake despite damage suffered when the adjacent URM collapsed (photo: Arendt).*

no business" because people stayed home in response to the government's request that they do so.

Businesses in URMs or those adjacent were the hardest hit (Figure 21). Within 14 days of the quake, many of the smaller damaged URMs had been demolished, leaving their previous tenants without a venue. Signs were posted in front of many demolished buildings or those closed to occupancy to inform customers about new locations.

In Kaiapoi, a community that suffered significant liquefaction and lateral spreading, about 40% of the businesses reopened within a week of the quake, and 70% reopened within two weeks. Access through the main shopping area in Kaiapoi was disrupted by retail buildings that had been heavily damaged, including Blackwell's, a department store that had been a mainstay for more than 135 years (see Figure 16). Due to soil movements, Kaiapoi had major issues with its water supply and sewage system, both of which conspired to hamper business reopening.

Some small businesses reported that they had some business interruption insurance (e.g., $2,500 NZ per week) in addition to insurance for their structure and contents, but it was not possible to ascertain precisely how many did and whether they were adequately covered. A large number were still in the process of determining claim amounts.

Issues for Future Scrutiny

The earthquake was notable for three main reasons: 1) serious liquefaction and lateral spreading damage to homes (as well as schools and other low buildings) located on soft soils and sand; 2) considerable damage to non-retrofitted URM buildings, many of which are historic structures; and 3) widespread nonstructural damage to both building components and contents, even in buildings with little structural damage. Effects in each of these areas will require considerable expense to repair. For homes, the universal insurance provided by the EQC will fund a portion of the repairs, but URM losses and nonstructural repair and clean up costs will exceed coverage when the costs are fully estimated. The damage leaves the city of Christchurch and the region with a number of major planning and engineering questions regarding residential neighborhoods on soft soils and rebuilding the downtown. In addition to structural and geotechnical lessons, the earthquake will provide instruction in the long-term efficacy of the recovery and policy decisions made in the next few months.

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