Technical Council on Lifeline Earthquake Engineering (TCLEE)
Report of the
4 September 2010 M_w 7.1 Canterbury (Darfield), New Zealand Earthquake

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The ASCE - TCLEE, New Zealand Earthquake lifeline performance investigation team consisted of the following members:

- John Eidinger, Team Leader (water, wastewater, electric power, railway)
- Alex Tang (telecommunication, port, gas, roads and bridges)
- Tom O'Rourke (geotechnical, levees)

With excellent local support from the Canterbury Lifeline Utilities Group, the National Engineering Lifelines Group, the University of Canterbury and many individual utilities, we exceeded our expectation in performance data and perishable information collection.

Summary

The City of Christchurch and the nearby community of Kaiapoi, with combined population of about 400,000 people, were strongly affected by the September 4, 2010 4:35 am (local time) M_w 7.1 earthquake. These communities are located in the province of Canterbury in the South Island of New Zealand. Christchurch is the second largest city in New Zealand.

There were no fatalities. Estimated costs to rebuild damaged buildings range up to $4 Billion and infrastructure range up to $1 billion (all dollar amounts in this report are in New Zealand dollars, $1 NZ = $0.74 US as of September, 2010).

While moderate to strong ground shaking resulted in damage to a number of unreinforced masonry structures, liquefaction was the primary hazard that resulted in widespread damage to buried water, wastewater pipes, and more selectively, to buried power and communications cables. Dozens of highway, road and rail bridges suffered damage due to rotation and spreads at abutments.

Liquefaction-caused settlements and (in some places) lateral spreads damaged thousands of single family residential wood-stud-on-concrete-slab houses.

Tectonic Setting

New Zealand lies along the boundary of the Australian and Pacific Plates. In the South Island, much of the relative displacement between these plates is taken up by a right lateral strike-slip fault, the Alpine Fault. In the North Island, the displacement is mainly taken up along the Hikurangi Subduction Zone, with some on the North Island Fault System.

New Zealand has 1000s of small earthquakes per year. Major earthquakes occur rather regularly in New Zealand, including: M_w 8.2 Wairarapa 1855 (near Wellington); M_w 7.8 Hawke's Bay 1931; M_w 6.5 Edgecumbe 1987; and 18 other large (M_w 6.8 to 7.8) notable large magnitude shallow events since 1848.

The Alpine Fault (Figures 1, 2) is considered highly active (slip rate of 27 mm/year) and capable of producing a M_w 8 earthquake at any time. The actual fault that broke and caused the Canterbury earthquake of September 4 2010 was previously unknown to exist. Figure 2 maps the various faults and recently recorded seismicity in the region, along with the actual rupture zone for the September 4 2010 event (assigned since the earthquake as having a 0.2 mm/year slip rate). The nearest town of Darfield was located about 12 km north of the surface rupture. The City of Christchurch was about 30 km east of the rupture. Canterbury is the name of the province that includes both Christchurch and Darfield.

Figure 1. Tectonic Setting

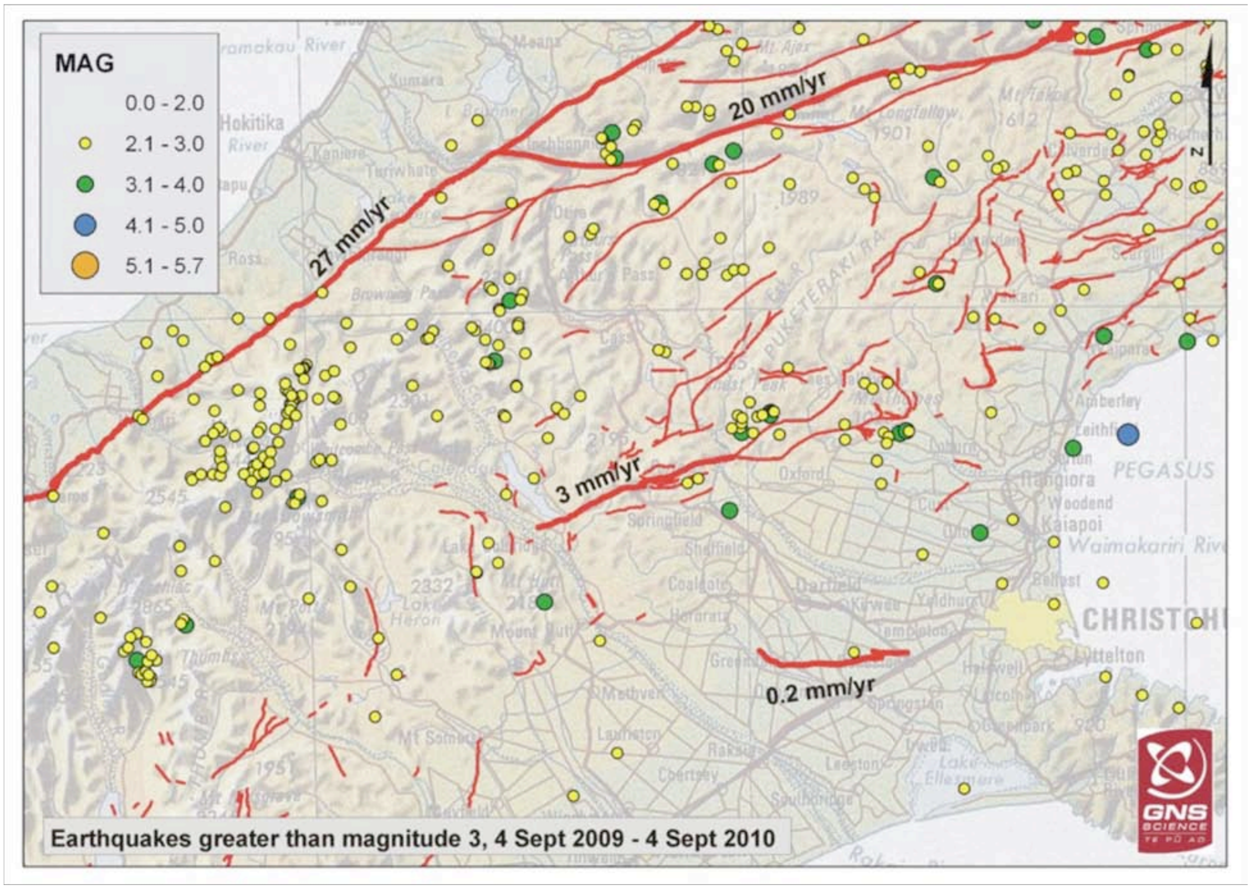

Figure 2. Map of Canterbury Area with Slip Rates of Selected Faults and Earthquake Epicenters, 2009-2010

Geologic Setting

The Canterbury Plains generally consist of alluvial sand, silt and gravel deposits previously deposited by the Waimakariri and Rakaia rivers. Bedrock is often found at depths of 300 to 800 meters. Surface layers in the urban Christchurch area are typically recent Holocene alluvial gravel, sand and silt of the Springston (much of central Christchurch) and Christchurch Formations (eastern portions of Christchurch), see Figure 3. The Springston Formation alluvial deposits include overbank deposits of sand and silt and river flood channels that contain alluvial gravel as the main component. These deposits are the materials most susceptible to liquefaction.

The ground water table affecting the upper 10 to 20 meters of sediments is generally between 2 to 3 meters below the ground surface in the west, and 0 to 2 meters below the ground surface towards the central and eastern portions of the urbanized Christchurch area.

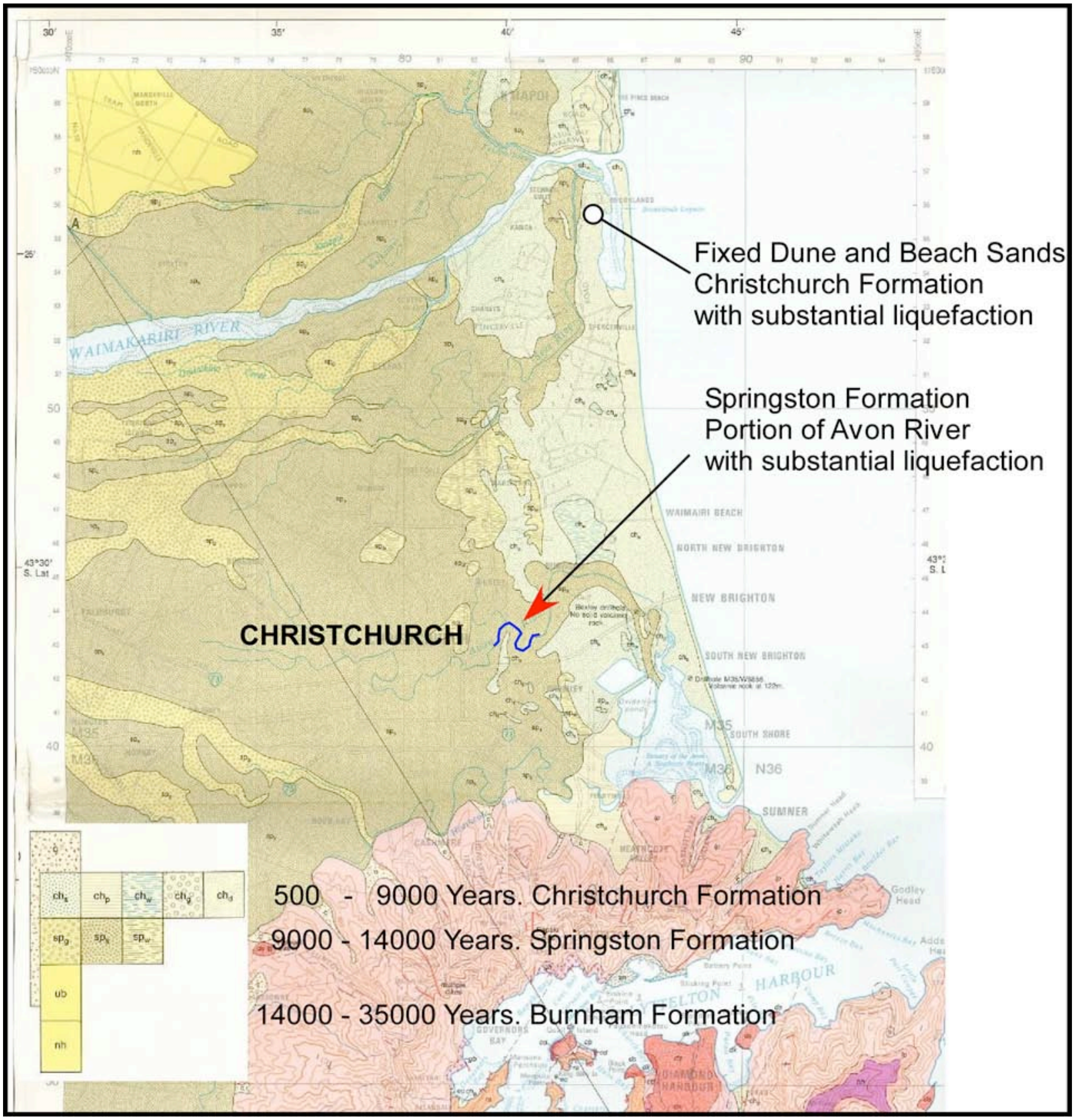

Figure 3. Regional Geologic Map (Adapted from Sewell et al, 1993)

Ground Shaking

Figure 4 shows a map of the area along with instrumented ground recordings.

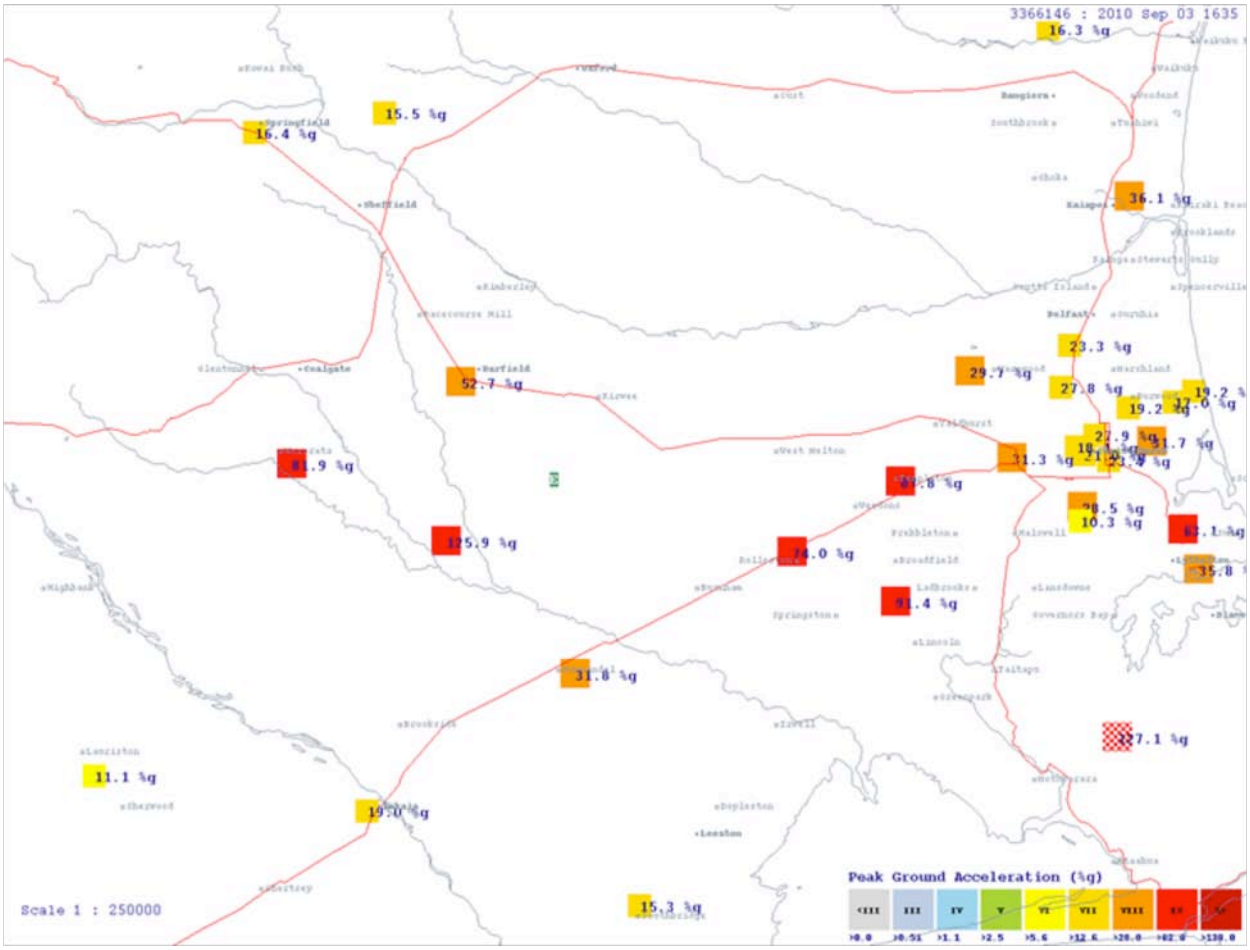

Figure 4. Ground Motion Instruments

Ground motions in the populated areas on the right side of Figure 4 were commonly in the range of horizontal peak ground acceleration of between 0.18 to 0.25g, with a few instruments recording over PGA = 0.35g or so. In the epicentral region, close to the surface rupture, there were three recorded PGA values between 0.50g and 0.9g, and 1 recording of 1.25g (this recording is considered suspect). In the very strong shaking areas (over PGA= 0.50g), there are scattered farm buildings, and population density is very low. Ground motions recorded along the west coast of the South Island were generally in the range of 0.02 g to 0.05g; without significant damage.

The recorded time history motions near the Port of Lyttleton, just south of Christchurch, showed strong motions (PGA > 0.1g) lasting for about 8 seconds. This relatively short duration of strong ground shaking for a M 7+ event is low, and may have contributed to the relatively small areas with triggered liquefaction. It is hypothesized that the short duration may be, in part, due to the epicenter being located at about the middle of the surface-rupture zone, with propagation of rupture in each direction. To date, major directivity effects are not known to have occurred, but this may change as the ground motion records are further studied.

Figure 5 presents the response spectra for recorded strong ground in comparison to the design spectra for a 500-yr return interval earthquake at a Class D soft soil site in Christchurch. Spectral accelerations for the recorded motion in Figure 5 exceeds the design values most prominently at periods of about 0.75 seconds and 2.5 seconds. This trend is similarly noted at other sites in Christchurch, and a future report will examine this in more detail. It has been proposed that the deep alluvial sands and gravels underlying the Canterbury area, with a natural period of about 2.5 seconds, have contributed to the elevated spectral values at the same period (Cubrinovski, personal com.). The shear wave velocity of the deep alluvial deposits is on the order of 300 m/second. Overlying the deep alluvial sands and gravels are recent Holocene soils, many of which are susceptible to softening and liquefaction under strong shaking. High frequency spectral amplification is about 50 - 70% of the design spectra, which may reflect site period de-amplification and/or soil softening at higher soil strains.

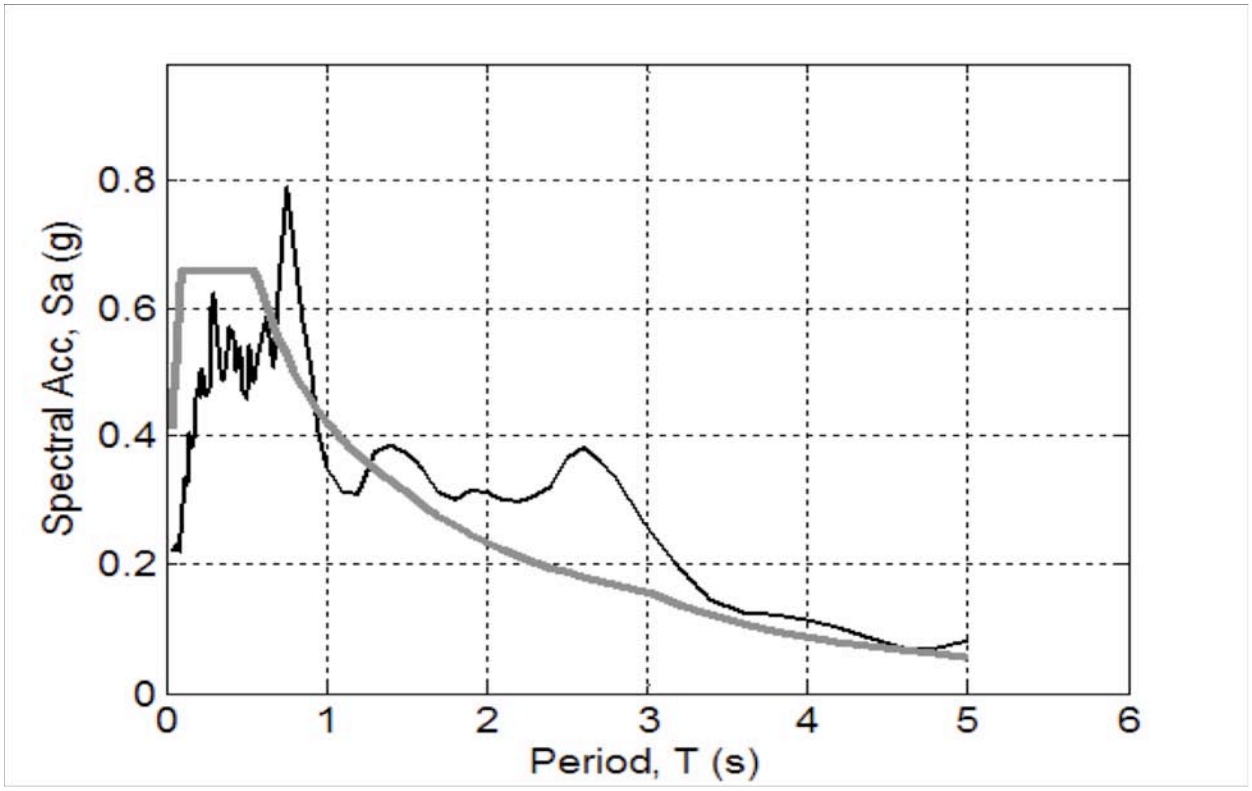

Figure 5. Horizontal Response Spectra (5% Damping), Design (smooth) and Recorded

Fault Offset

The earthquake occurred on a previously unknown fault, since named the Greendale fault. The surface rupture of the main shock occurred in an almost east-west direction, extending for about 29 km, see Figure 6. Surface offsets were largely right lateral in nature, ranging up to about 4 meters of right lateral offset near the center of the rupture zone, reducing to about 1 meter of right lateral offset near the tail edges at either end of the rupture zone. The dip of the broken fault over the top 10 km of the crust was nearly vertical. Common width of offset zone was about 10 meters, characterized by a series of en echelon cracks in the ground. In some places, there was coincident uplift on the south side of the fault of about 1 meter, in other places some uplift was observed on the north side, and in many places there was no coincident uplift. Average right lateral offset over the entire fault length was about 2.3 meters.

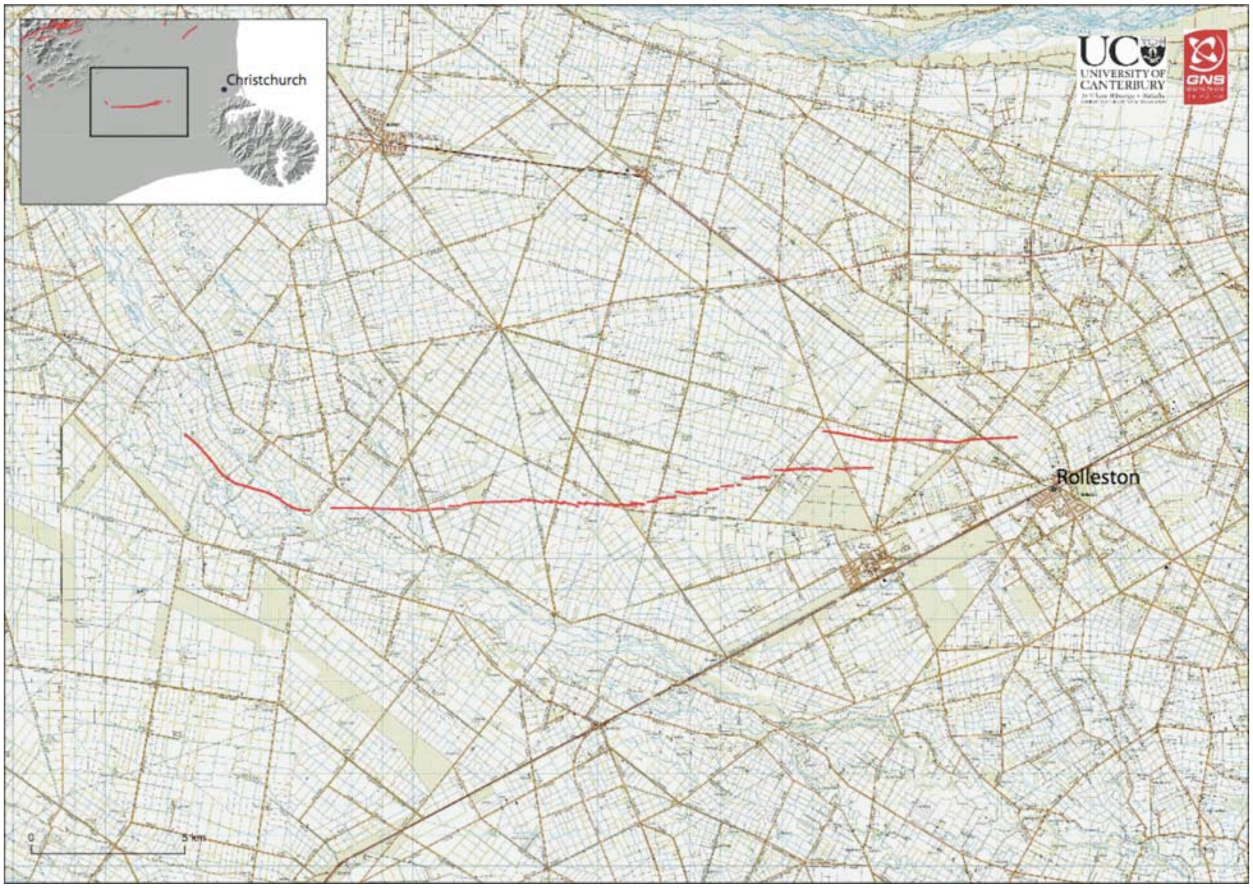

Figure 6. Fault Rupture Map

These offset amounts are the cumulative amounts as of about September 21, 2010 (Figure 7). Almost without doubt the original offset was lower than these values, and there was ongoing aftershock creep that was leading to increasing amounts of total offset; as evidenced by the need to reset train track rails over the fault, multiple times, in the weeks after the earthquake.

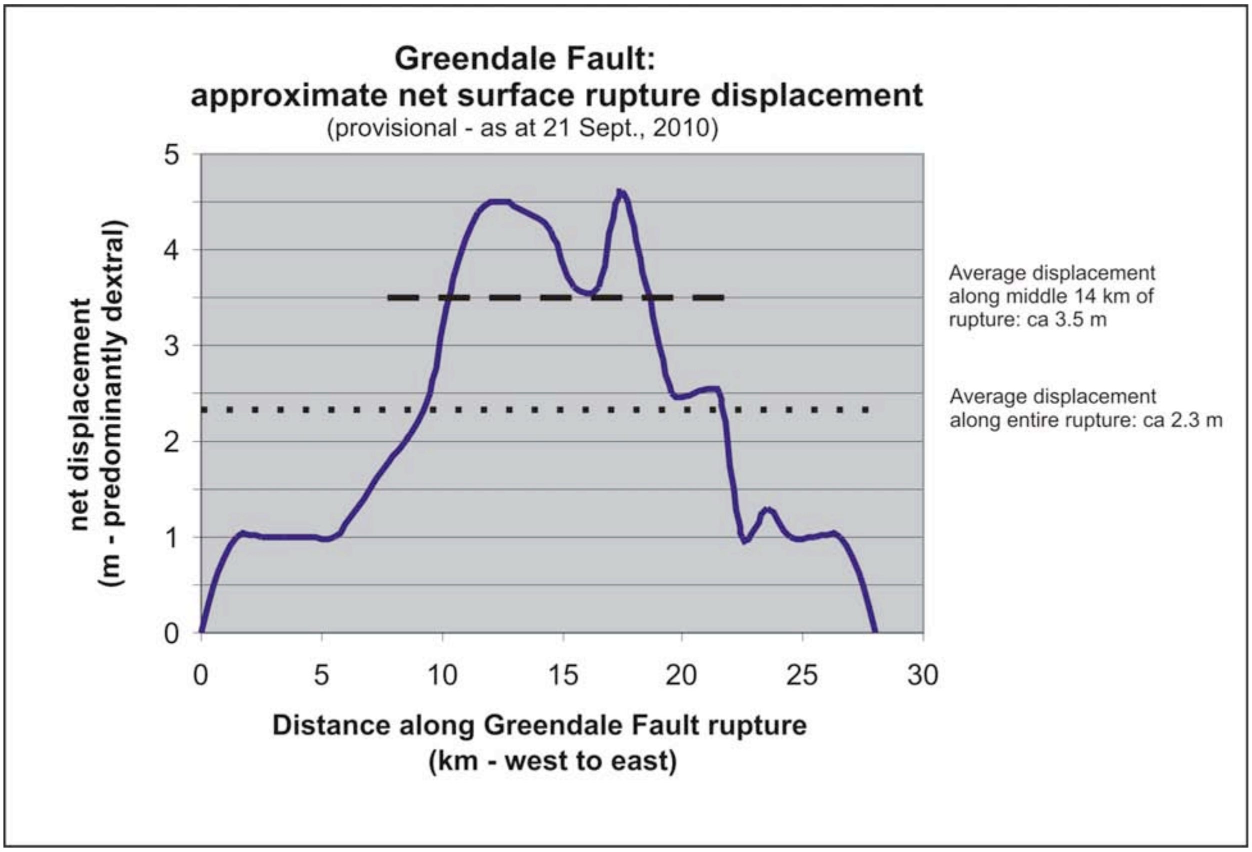

Figure 7. Measured Fault Offset

Figure 8 shows the right lateral offset of a country road. The road was straight prior to the earthquake. Figure 9 shows a paved road that crossed the fault; the right lateral offset of the fault appears to have forced the road to shorten, resulting in many pavement buckles.

Figure 8. Fault Offset Through a Road

Figure 9. Fault Offset Through a Road

Liquefaction

A regional liquefaction hazard map was prepared in 2004 (Ecan, 2004), Figure 10. As can be seen, a major portion of the Christchurch area (about 50% of the urbanized area) has been mapped either as having high liquefaction potential (red zones) or suspected as having high liquefaction potential (red diagonal areas, including much of the area along the coast north of Christchurch). This map assumes a high ground water table. The authors of this report note that not all locations within the zones mapped as having high liquefaction susceptibility in Figure 10 have truly an equal chance of triggered liquefaction in earthquakes; in practice, the chance of liquefaction occurring at a particular location will depend on the local geologic conditions, the local ground water table, as well as the intensity and duration of strong ground shaking.

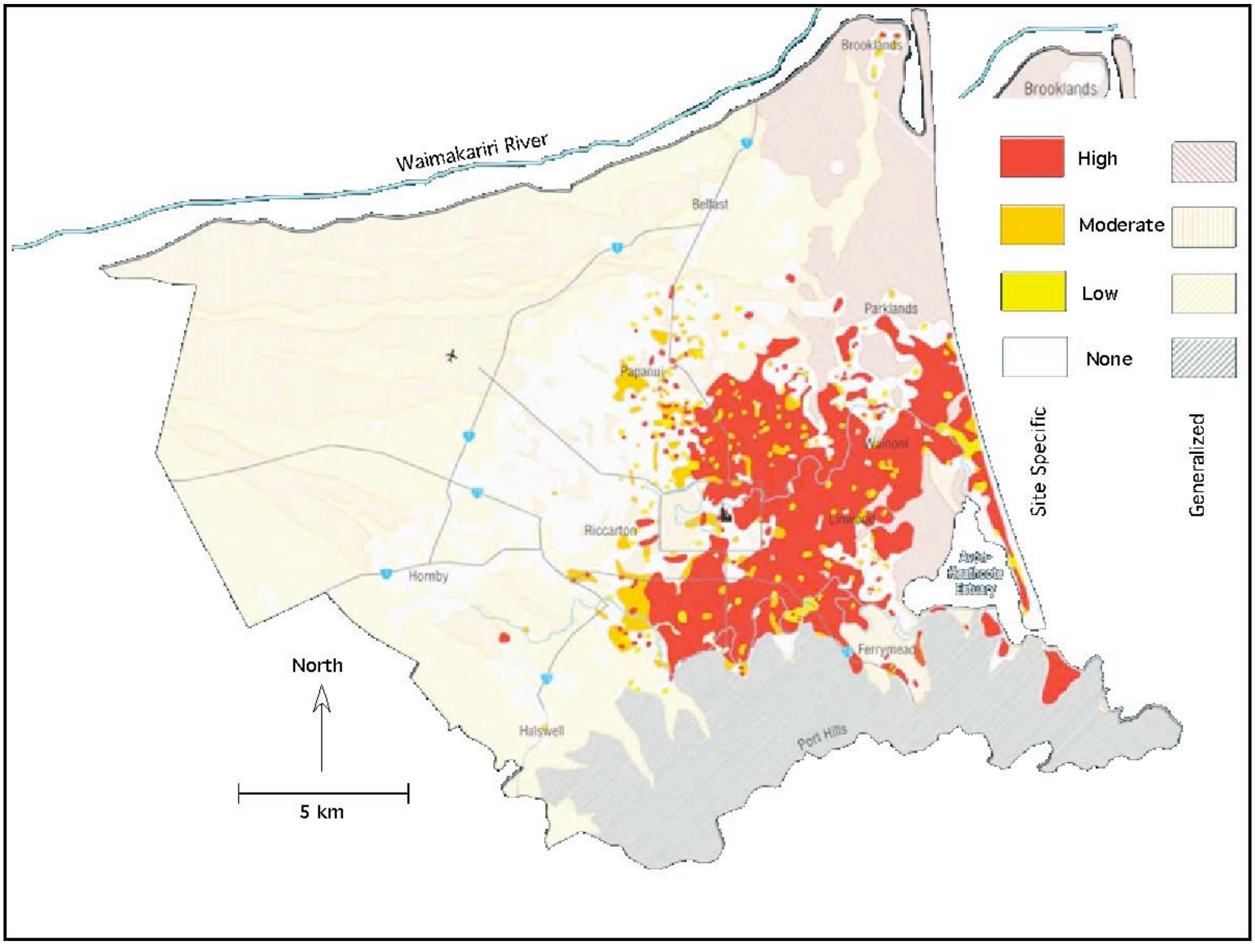

Figure 10. Liquefaction Potential Hazard Map (adapted from Ecan, 2004)

Figure 11 shows the areas that did liquefy, based on an early reconnaissance effort after the earthquake of September 4, 2010. This map was originally compiled by CCC Monitoring and Research, September 17, 2010, based on field reconnaissance work undertaken by contractors for the Earthquake Commission, and confirmed locally by observations by ASCE investigation team. The blue highlighted areas indicated zones where major ground damage was observed. The orange / hatched areas indicate areas with possible ground damage. The red underlying color indicates areas mapped as having high liquefaction potential from Figure 10. Figure 11 does not include areas of liquefaction in various rural areas, and the mapping effort was concentrated in zones with residential construction.

Of particular interest in Figures 3, 10 and 11 are that only a portion (about 5% to 10%) of the Christchurch and Springston Formations (Figure 3) or the "red" zones (Figure 10) actually did liquefy to the extent to produce observable major ground deformations. This may be in part due to the relatively short duration of strong ground shaking in this earthquake (perhaps 8 seconds or so) coupled with site specific geologic and ground water conditions. Other indications suggest that the zones that did have major ground deformations represent soils which have the highest liquefaction susceptibility; the remaining areas still remain a liquefaction threat in future larger or longer duration earthquakes (Misko Cubrinovski , personal communication, 2010). Maps prepared by the water and wastewater utilities showing actual locations of damaged buried pipes will likely be substantially more accurate indicators of permanent ground displacements, as the broken pipes act like "gages" to show locations of high ground strains.

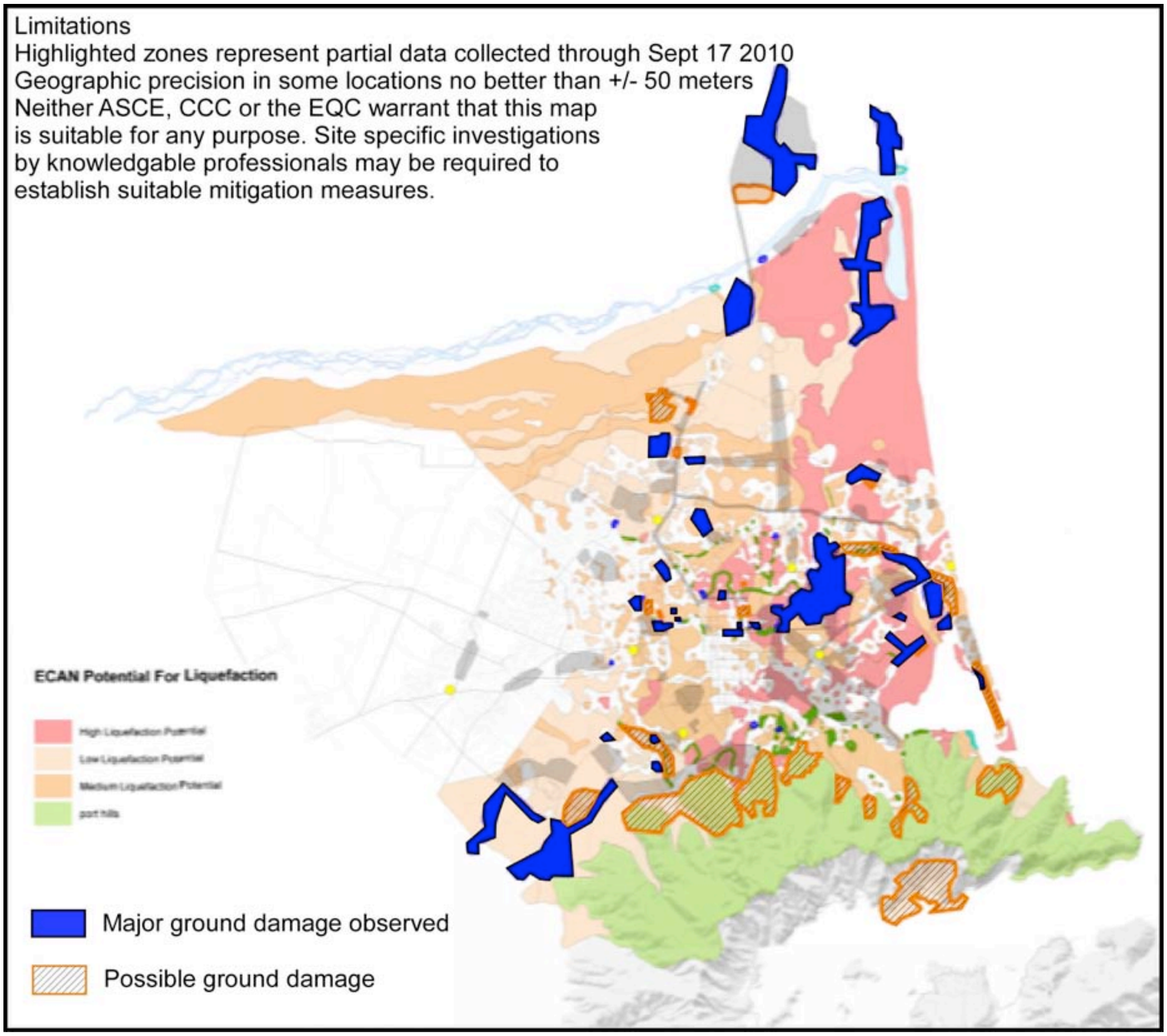

Figure 11. Map Showing Observed Liquefaction (Blue diagonal)

It is evident from Figure 11 that the earthquake triggered widespread liquefaction in Christchurch and surrounding communities (blue zones). Sand boils were a common site. Many of these areas had been developed as single family residential communities, with the most common type of building being wood frame single-story atop concrete slab-on-grade. An estimated 2,900 structures in these blue zones were exposed to some type of settlements, and a portion of these were also exposed to lateral spreads. Estimated permanent ground settlements ranged from about 5 cm (2 inches) (perhaps a third of affected structures) to 10 cm (4 inches) (perhaps another third of affected structures). The remaining third of affected structures were exposed to a combination of settlements and lateral spreads; the spreads ranged from a few inches to as much as 1 meter (3 feet) or so.

Not a single wood structure is known to have collapsed due to the liquefaction settlements or lateral spreads. Many of the structures were "yellow" tagged after the earthquake, often because of loss of water and sewer pipelines serving the house. Many of the "yellow" tagged structures appeared serviceable for shelter purposes, and appeared to pose no life safety threat due to aftershocks.

The liquefaction effects damaged roads and buried utilities. The damaged buried utilities included broken water mains (over 400 repairs), broken sewer pipes (at least 400 repairs, and as yet an undetermined number of replacements), several broken or damaged medium voltage (11 kV to 66 kV) buried power cables, and dozens of broken communication cables. The liquefaction also resulted in temporary loss of bearing capacity for above ground low voltage (11 kV) distribution power poles, leading to 5°± tilts for many poles (perhaps hundreds); none are known to have toppled entirely. Temporary braces were provided for the tilted power poles. Liquefaction occurred at several high voltage steel lattice transmission towers; one was guyed after the earthquake as a temporary measure; none were in imminent danger. Liquefaction was also triggered at some regional substations, leading to cracks in sidewalks, sand ejecta over switchyard rock (needed to be removed for electrical safety purposes), and a few cracked oil spill containment structures.

Landslide

Much of the local region is farming community, with average slopes of 0° (flat). Immediately south of the urban Christchurch area is a hilly area, often referred to as the Port Hills. The earthquake triggered rock falls in this area (see hatched zones in Figure 11), with boulders falling onto hillside roads, resulting in road closure. Continuing aftershocks contributed to more rock falls in this area, with an estimated 100,000 tons of rock falling down the slope through the first month after the earthquake. The area is mostly uninhabited (there are some residential communities built on the slopes of the Port hills), and there were no known impacts to man-made structures other than roads.

To the west of the fault rupture zone are the foothills of the Southern Alps, and then the Alps themselves. There were no known avalanches triggered at commercial ski areas.

Vulnerability Study

In 1997, vulnerability assessment report for natural hazards, including earthquake was prepared by the Christchurch Engineering Lifelines Group (ref: Risks & Realities, 1997). This report included participation by some of the lifeline and utility operators in the area. This report led to an increased awareness of the seismic hazards in the area, including liquefaction, and led to some mitigation efforts by some utilities in the intervening years prior to the 2010 earthquake. Without doubt, the mitigation actions taken ultimately led to a reduced level of damage, and more rapid restoration of essential services than would have otherwise have occurred.

Seismic Codes

In 1931, the M 7.9 Hawke's Bay earthquake (also called the Napier earthquake) occurred about 15 km from Napier, along the east coast of the North Island. The earthquake killed 256 people. Subsequent to this earthquake, New Zealand began to implement seismic codes for new construction.

The 475-year return period motion (as of 2009) for Christchurch had been estimated prior to this earthquake to be about PGA = 0.30g (a little higher to the north of Christchurch, a little lower to the south of Christchurch), see Figure 12. The primary active earthquake fault to threaten the Christchurch is the Alpine fault (slip rate 27 mm/year), capable of producing a M 8 earthquake at any time, but located about 150 km west of the city. Other faults had been characterized closer to Christchurch. It was recognized that perhaps 50% of the seismic hazard for Christchurch was due to "unknown location" faults, and this was factored into the overall hazard. The actual fault that broke (since named as the Greendale fault) is a longer fault (over 30 km) and closer to Christchurch than any of the previously known located faults.

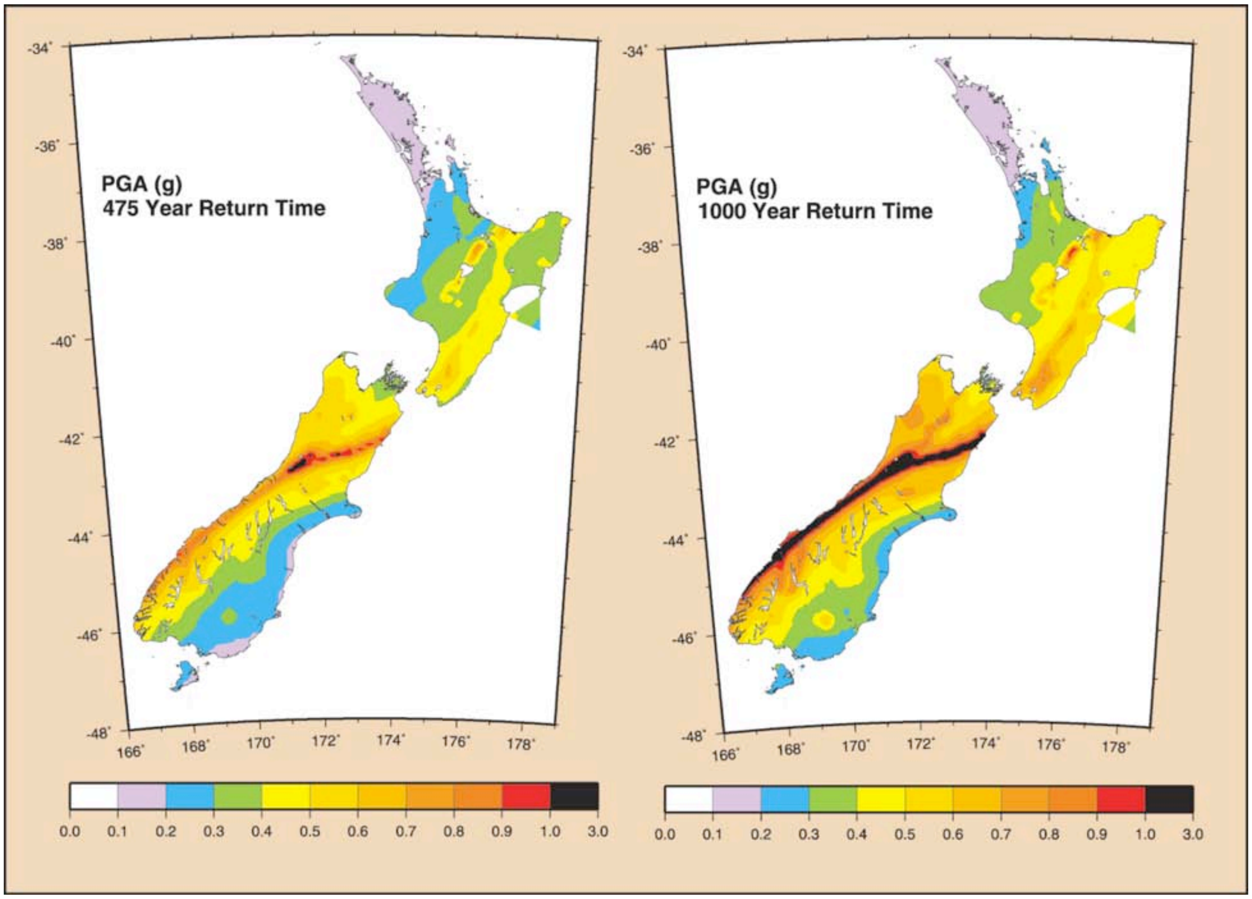

Figure 12. Seismic Hazard Map for New Zealand, Horizontal PGA (g)

By 2010, new engineered- buildings in Christchurch are designed using modern seismic techniques. The New Zealand codes are often patterned after American codes. In some cases the New Zealand codes are even more stringent seismic requirements than in American code counterparts, as for example allowing much lower ductility levels for at-grade steel tanks (about 2) than in AWWA counterparts (between 3.5 and 4.5).

It is reported that there were no complete building collapses in Christchurch for any building constructed post 1935, about the time of implementation of earliest seismic codes.

Christchurch began to be developed in the 1860s, with many unreinforced masonry (URM, either brick or stone) buildings. Many of the Heritage Buildings in service at the time of the 2010 earthquake are unreinforced masonry. It is our understanding that several of these URM buildings had been seismically retrofitted prior to the 2010 earthquake, for "about" V = 0.1W. Many smaller URMs remained either completely unretrofitted, or with only partial retrofits (parapets). It is estimated that at the time of the earthquake that there were about 800 URMs in the Christchurch area; perhaps a few smaller URM shops suffered major collapses (unoccupied at 4:35 am); many lost portions of parapets and gables. Most of the URM inventory survived sufficiently intact as to remain in service after the earthquake.

Electric Power

The Electric Power system serving the Christchurch area is provided by two companies: Transpower and Orion. Transpower operates the high voltage country-wide transmission system, with highest voltages in the Christchurch area of 220 kV, along with some 66 kV. Orion is the local power distribution company, which buys power from Transpower and delivers it to end user customers, with common voltages of 66 kV, 33 kV and 11 kV.

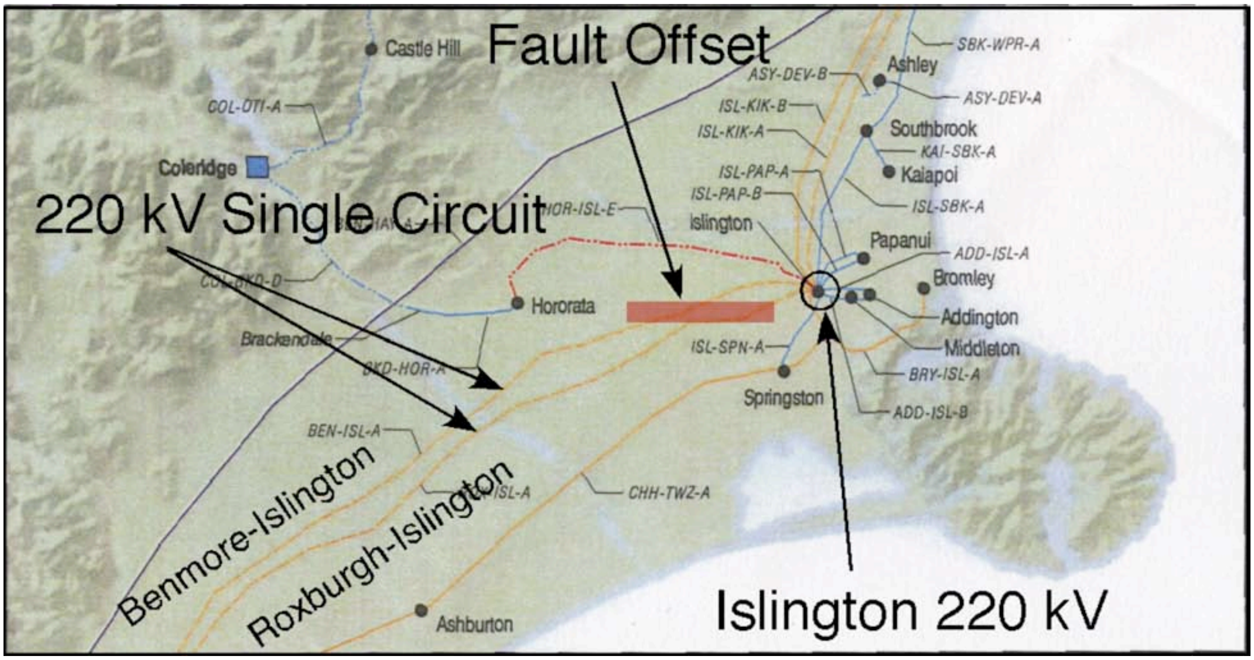

Figure 13. Transpower Regional High Voltage Grid

Both Transpower and Orion had implemented a variety of seismic mitigation measures in the decade prior to the September 4 earthquake. These countermeasures, in combination with the relatively modest levels of ground shaking (commonly about PGA = 0.2g at most Transpower and Orion substations), resulted in relatively excellent performance by both power companies.

Electric Power - Transpower

Figure 13 shows the Transpower system serving the Christchurch area. Most power is generated to the south (well outside the strong shaking area, and no damage reported) and imported to the Christchurch area. The Islington substation (220 kV – 66 kV) serves the bulk of the load for Christchurch area. Figure 14 highlights the smaller Transpower substations in the Christchurch area.

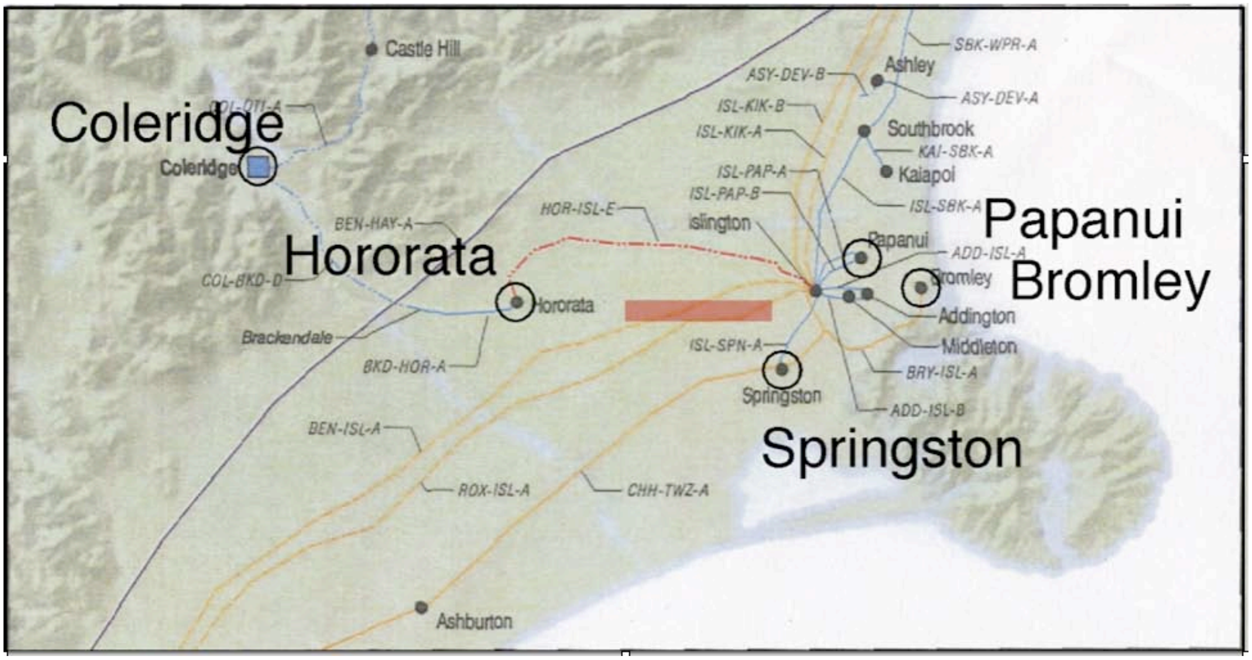

Figure 14. Other Transpower Substations

Two single-circuit 220 kV overhead transmission lines crossed the rupture zone. The fault rupture passed nearby the legs of the steel lattice towers, but not through them. There was no observed damage to any towers due to inertial shaking. Due to the fault offset, on the order of 4 meters, the conductor sags on either side of the fault became unbalanced. On the ROX-ISL-A line, the unbalanced sag is indicated by the diagonally-swung insulators (normally they would be straight down) in Figure 15; this sag remains unbalanced 6 weeks after the earthquake; Transpower reported that they would adjust the sag during some future outage. On the Benmore-Islington line, the fault offset resulted in high tension loads in a ground wire, which bent the tower extension that supported the ground wire; again, this did not led to an outage, but could be repaired during a future outage.

Figure 15. Displaced Insulators on Suspension Tower Adjacent to Fault Offset

There was a modest number of items damaged at the various Transpower substations. The cumulative repair cost for damage at Transpower substations (through early October 2010) is estimated at about $150,000 (NZ). Power supply restoration times on September 4, 2010, and observed damage at the Transpower substations and circuits and facilities (this is not the same as power restored to end customers via Orion) were as follows:

- Papanui: 8:28 am. The Islington-Papanui 66 kV overhead circuit broke at the terminal tower and fell down onto another phase. There was liquefaction at this substation, as evidenced by sand boils. Sand was ejected through the switchyard rock, and had to be removed. The gate at the entrance dropped. Oil containment tanks need to be inspected internally. Spill prevention containment walls around transformers were cracked. There was a broken window in the relay room. There were two cracks in the control building.
- Springtson: 7:48 am. Two transformers tripped due to vibration causing false operation of mercury switches in high pressure protective devices. Loose items rattled off ledge of walls. One fuse holder fell out of the carrier. A cabinet door broke off a SF6 circuit breaker. Two Orion 33 kV poles were leaning.
- Hororata: 8:23 am. Two transformers tripped due to vibration causing false operation of mercury switches in high pressure protective devices. (PGA between 0.3g and 0.7g).

Older style multi-level reinforced concrete building had broken windows (Figure 17). Three spare (unanchored, in process of relocation) current transformers toppled. A desk collapsed. Florescent lights on chains, hanging from the ceiling, became loose; florescent tubes fell out. Some data cable tray tie rods ripped out of the ceiling. Lightning poles swayed and loosened their foundations.

- Coleridge: 12:16 pm. One line tripped due to a feeder fault.
- Bromley: One 220 kV angle steel lattice tower on the Bromley to Islington transmission line was tilted, likely due to liquefaction. Repair was to install guy wires. Crack in wall of control building. A small amount of oil sloshed out of the tap changers of three transformers. 66kV wood bus poles have a slight lean. One disconnect switch was not properly closed.
- Addington – Middleton – Islington 66 kV circuit tripped due to fault protection.
- Addington warehouse: two storage racks partially collapsed.
- Regional Operations Center. A computer cabinet on a base isolation unit atop a raised floor toppled. Lighting diffusers in a control room suspended ceiling fell. Tiles in a suspended ceiling fell over a lunch room.

At the main Islington substation, (estimated PGA = 0.20 to 0.25g) the following occurred: All three 220 kV – 66 kV transformer banks tripped, likely a few seconds (perhaps a minute?) into the earthquake. On two of the older banks, vibration of mercury switches led to false over-temperature readings, tripping the transformer. On the newer transformer, oil sloshing likely led to a high oil pressure warning, tripping the transformer. By daybreak, the yard was inspected and no other damage (at that time) was observed, the transformers were reset and re-energized. Two days later, high winds toppled a lightning arrestor atop the new transformer, see Figure 16. This lighting arrestor was replaced. Several weeks after the earthquake, a fire damaged a component in voltage regulating equipment; the cause of the fire (earthquake-induced damage or otherwise) was unknown as of the time of writing this report. Other damage at this substation included cracks in the wall and floor of a battery room; bolts atop the condenser building were sheared. Equipment in the substation control building was either very well anchored or in some cases reasonably well anchored; none were damaged. Battery racks were anchored, but batteries in one rack were held in place only by friction; there was no battery movement.

Figure 16. Broken Lightning Arrestor

Figure 17. Hororata Control Building

Electric Power - Orion

Orion is the third largest electric power distribution company in New Zealand. Prior to this earthquake, Orion had spent about $5 million ($NZ) on seismic upgrades for its system, including reinforcement of unreinforced masonry buildings, and seismic upgrade of a small bridge supporting two 66 kV cables, located in a liquefaction zone. All of these upgraded facilities remained serviceable immediately after the earthquake; although the cables in the liquefaction zone were damaged and will need ultimately need to be replaced or bypassed.

Had these upgrades not been done, and if all the upgraded facilities had been damaged, then Orion estimated they would have suffered between $30 million to $50 million ($NZ) in repairs.

The earthquake caused loss of power to Orion from Transpower, as well as some damage within the Orion system. The combined effect was to cause a total of 90 million customer-minutes of outages. Orion has 198,000 customers; so this is the same as saying the "average" customer had about an 8 hour outage. In comparison, Orion customers have had long outages due to several events in the past 18 years: 1992 wind storm: ~36 million customer-minutes; 2006 winter storm: ~20 million customer-minutes. In some respects, the outages from this earthquake were similar to about 3 to 4 times worse than major winter storms. Figure 18 shows the customer outages at selected times; the Magnitude 5.1 aftershock of early September 8 resulted in the spike in outages; these lasted a short time, and were largely a result of shaking-induced activation of safety devices on power transformers. The data in Figure 18 include an estimated 1,000 customers off due to faults in low level (400 volt) circuits (as of September 6), reducing by about 200 per day to zero by September 11.

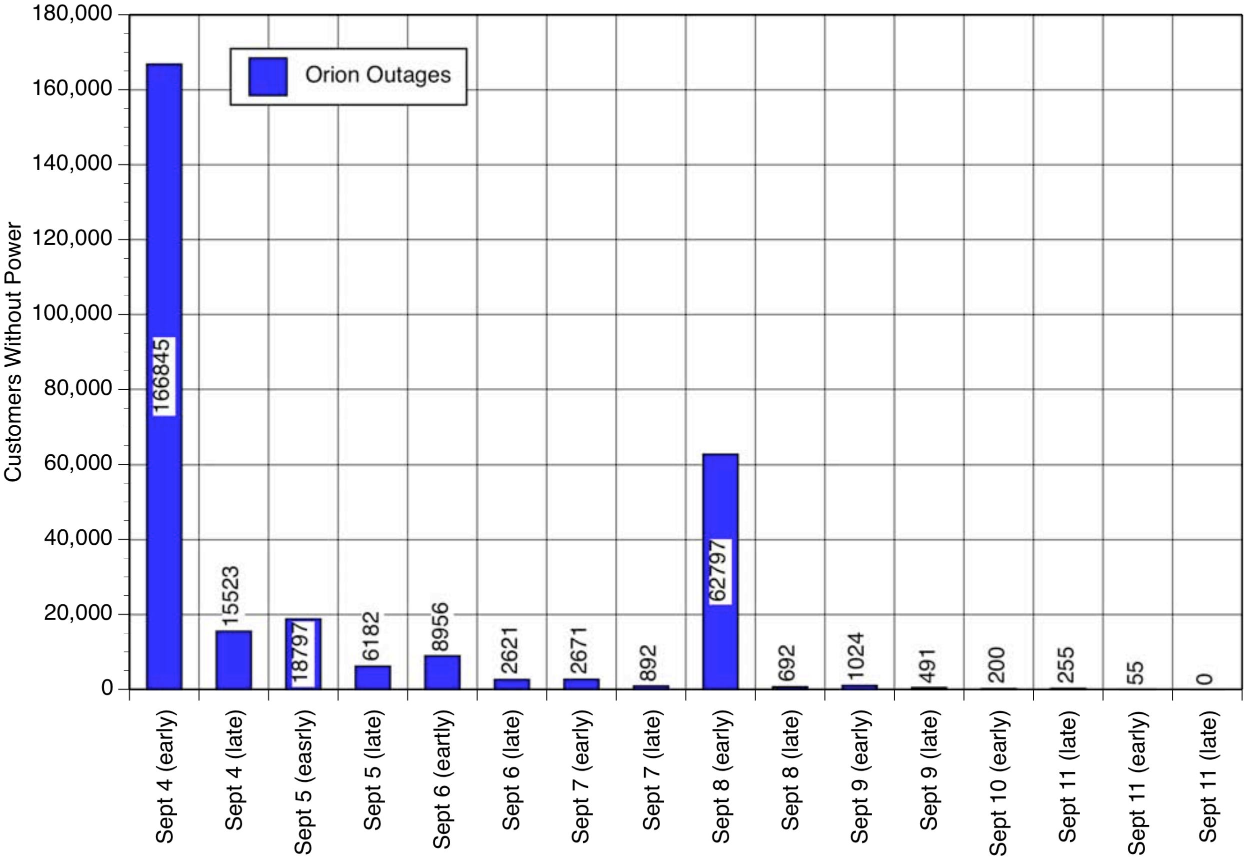

Figure 18. Customer Outages, Orion System

Figure 19 shows the main transmission lines of the Orion system. The circled location on the Bromley-Dallington double circuit 66 kV line was damaged due to settlement and lateral spread.

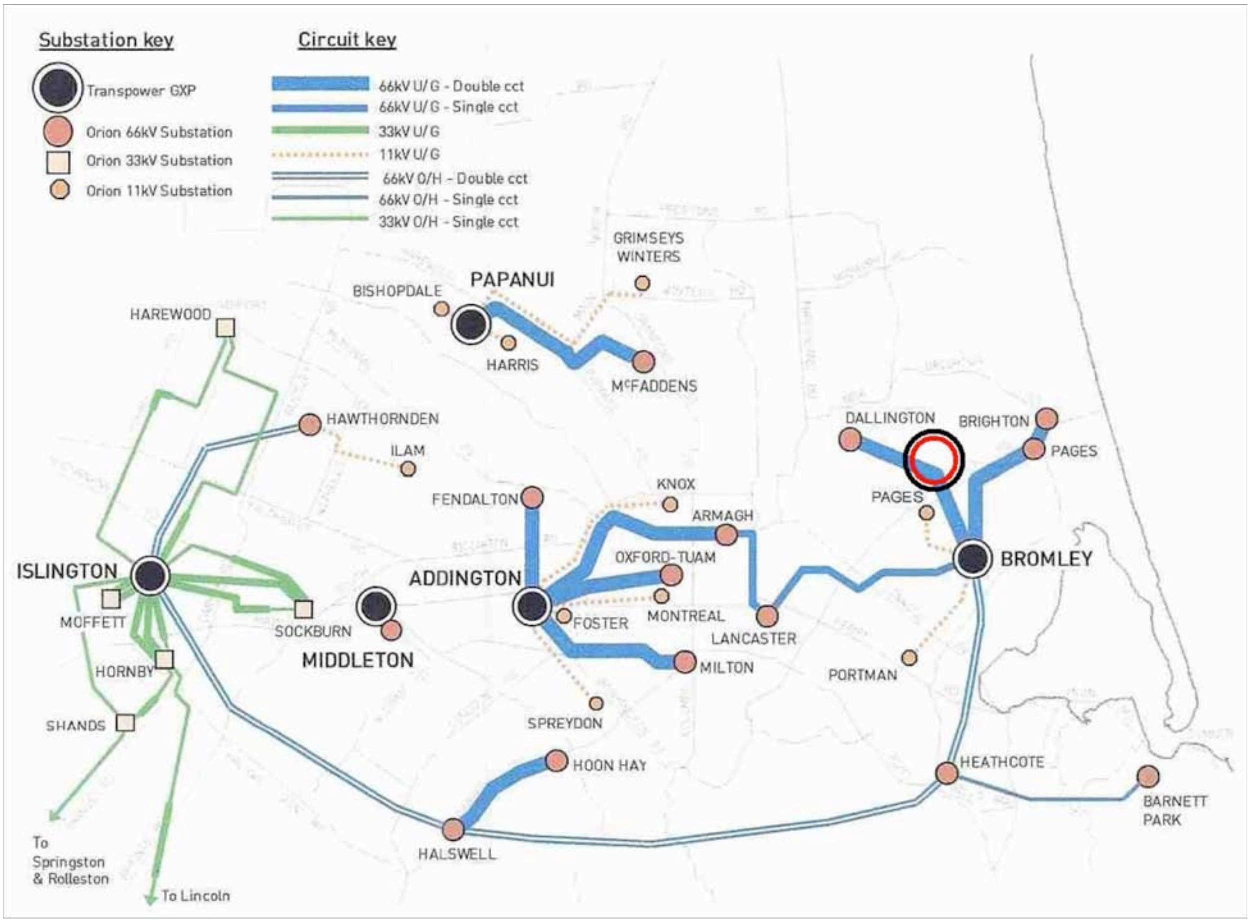

Figure 19. Orion System

Figure 20 shows one of Orion's seismically upgraded small URM substations. Note the steel supports outside the building, that had been installed as part of the seismic upgrades instituted over the prior years. Figure 21 shows another URM and non-retrofitted building; instead of upgrading this building, Orion abandoned it; the amount of damage observed is common to that observed at other URM buildings in Christchurch.

Figure 20. Orion URM Upgraded Small Substation

Figure 21. Orion URM Non-Upgraded Former Small Substation

Figure 22 shows two partially crushed 66 kV oil-filled low pressure cables. This occurred where the buried cables transitioned from a buried condition, and went onto a pile-supported bridge across the Avon river. While the cables remained functional after the earthquake, they will ultimately need to be replaced or otherwise bypassed; as part of a temporary measure after the earthquake, Orion braced the bridge on which the cables are located. There were several other 11 kV buried cables that were completely broken; we believe all of the broken cables were in the areas with lateral spreads and/or settlements.

Figure 22. 66 kV Cables

Telecommunication

There are two major cell phone operators in the Christchurch area: Telecom and Vodafone. Both had similar set backs by this earthquake. The primary set backs were:

- Ran out of reserve battery power at base Transceiver Stations (BTSs, also called cell sites)
- Call congestion
- Cellular network tower out of plumb due to liquefaction (Figure 23)
- Underground cable damage due to liquefaction-induced permanent ground deformations.

Both land line and cellular phone systems suffered little structural damage. We observed switching facilities that had good seismic detailing, apparently in conformance with seismic standards used elsewhere in the world for high seismic hazard zones.

Within a few hours after the earthquake, due to the loss of offsite power, Vodafone had 31 out of 93 BTSs run out of battery power within Christchurch. Recognizing the rapid drain of power from limited-size backup batteries, Vodafone temporarily switched off portions of the high power demand "3G" network to reduce current draw and extend the life of sites with both lower power demand "2G" services. While this may have delayed some outages, it did not prevent outages at locations where offsite power outages were more than a few hours long. Many of the small radius cell phone sites ran out of battery power within 2 to 4 hours after the earthquake, quicker than the time needed to mobilize backup generators to those sites, and quicker than the time when Orion was able to restore offsite power to those sites.

Similarly, Telecom had 500 sites including BTSs impacted by power outages. While almost all Telecom sites (both Central Offices and BTSs) had backup batteries, only a few critical sites had permanent standby generators. In general, BTSs within the city have about 2 hours of backup batter power, and rural sites have about 5 hours of backup battery power. When the batteries were drained, the sites without a power generator went offline.

Telecom had one instance where a backup generator failed to start, reportedly due to coolant sloshing.

For both operators, portable power generators were brought in within 24 hours from other locations within the South Island and then from the North Island.

The number of cell phone sites that lost power might have been higher: however, the severe winter storm of 2006 blanketed the South Island in snow and caused widespread power outages to the Orion distribution (see power), resulting in an increased effort to obtain more backup generators in the Christchurch area.

As a result of the earthquake, both service providers transferred 111 (similar to 911 in the USA) emergency call centers to North Island. Call center staff of Telecom were allowed to stay away from work to take care of their personal problems caused by this earthquake, which was the reason to transfer the call center to Hamilton in the North Island. There was no reported significant structural damage to Telecom building structures. One Telecom office in the city was yellow tagged due to non-structural damage, which was fixed within 24 hours, allowing a change to a green tag allowing staff to work inside the building.

The two service providers both had data transmission problems due to damaged buried communication cables; dominantly in the liquefaction zones. By 13 September most landline and DSL services were back to normal.

At two cell phone tower sites, liquefaction resulted in rotation of the tower (see Figure 23). The towers were out-of-plumb by 2° to 5°. These rotations did not affect service, and no effort to restore the towers to vertical had been made within the first 6 weeks after the earthquake.

Figure 23. Cellular antenna tower out of plumb due to ground deformation.

Water – Christchurch City Council

The Christchurch City Council (CCC) operates the water system for Christchurch (population about 375,000 people).

Metropolitan Christchurch is located above the Christchurch West-Melton aquifer system, which is recharged by the Waimakariri River to the north and local rainfall to the west. CCC extracts the water from five aquifers (Figure 24) via a series of wells and about half with standby diesel capacity in case of power outage. The standby diesels have enough capacity to supply water at the average day demand rate.

The condition of the aquifers does not allow microbiological organisms to exist and therefore the water quality from the aquifer is high enough such that there is no water treatment or disinfection. While chlorination is commonly used in New Zealand (67% of all water systems country-wide use it), a Christchurch survey in 2000 indicated a strong preference for unchlorinated water. As of 2008, there were 169 wells at 60 sites.

Over the past five years, average day water demand in CCC was about 142 million liters (38 million gallons) per day. Common winter time demand is 295 liters per person per day; peak summer time demand is about 1,100 liters per person per day. The extra summer time demand is used largely for outdoor irrigation.

The CCC water system includes about 3,317 km of pipe, of which 1,709 km are water mains (generally 100 to 200 mm in diameter) and 1,608 km are sub-mains (service laterals). There are about 128,000 connections. Common water main pipes are either cast iron, fibrolite (often called asbestos cement), or PVC; common sub-mains / service laterals are 15-50 mm MDPE. 95% of the cast iron pipe is unlined. Fire hydrants are attached to mains to provide water for fire flows.

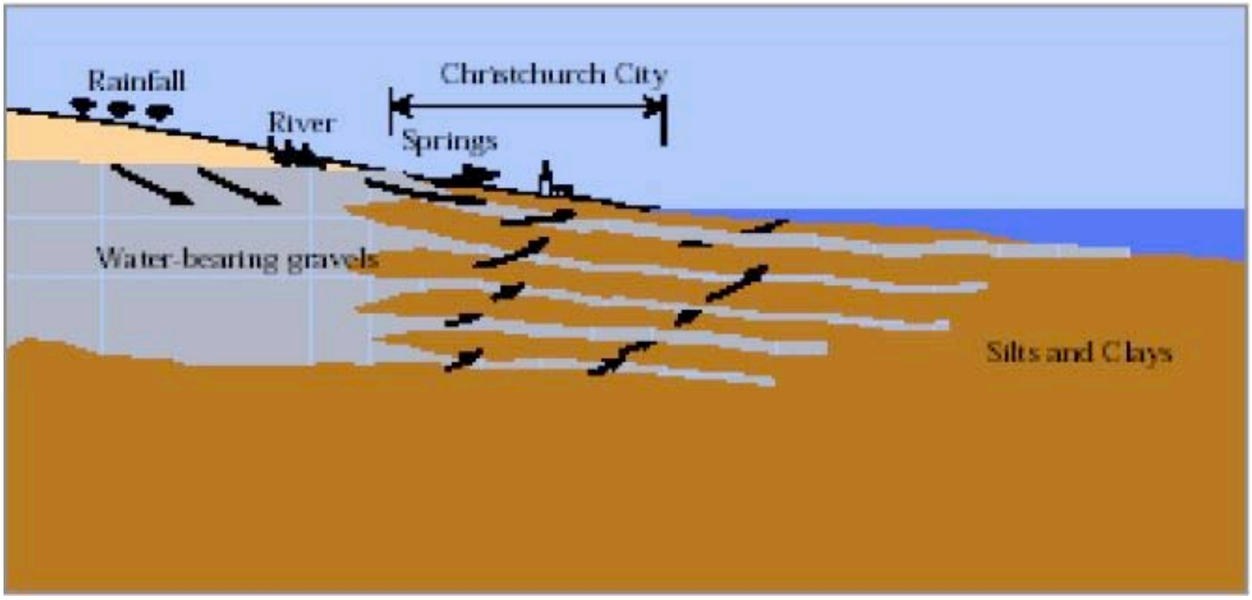

Figure 24. Christchurch's Aquifers (from Water Supply Asset Management Plan, 2002).

Of the 1,709 km of mains, 9.4% are pre-1960 AC pipe; 41% are post-1960 AC pipe (1960-mid 1980s); 28% are PVC (mid-1980s and later); 9% are cast iron (1910-1960, lead joints); 2% are cast iron (1960s to 1990s, rubber joints); 3% are ductile iron (1986 to present); 3% are cement-lined steel; 2% are "other" steel (including spiral riveted, mostly replaced due to high leakage).

Of the 1,608 km of sub-mains, 12% are galvanized steel (1900-1985); 2% are AC; and 83% are HDPE or MDPE (1960 to present).

As of 2000/2001, there was 18% "unaccounted" for water, possibly due to a somewhat leaky water distribution system (water systems with under 10% unaccounted for water are considered fairly "tight").

At some locations in the distribution system, there are 27 water pump stations to boost pressures to end users. These pump stations commonly include small tanks (commonly 10,000 gallons). There are standby diesels to operate these pumps in case of power outage.

There are 130 pump station and well buildings, most are constructed using masonry or reinforced concrete. There were no reported building collapses in the water system, but it is understood that about 5 of the oldest structures were unreinforced. Most of the tanks are reinforced concrete; 6 are prestressed concrete, 3 are wood-stave.

At well sites, the base water demand is usually obtained form the deeper aquifer, often obtaining free flow into a suction tank; supplemented by the shallower aquifers using submersible pumps during periods of high water demand. Suction tanks are used to balance the flow between wells in different aquifers, and provide storage for short term peaks, reduce surges on wells, and settle sand that may come from the well. Pump configurations vary at different well sites:

- A free flowing well into a suction tank with a main pump from the suction tank into the distribution system

- A well pump n the surface, pumping into a suction tank and a main pump from the suction tank into the distribution system
- A submersible well pump, pumping into a suction tank, and a main pump from the suction tank into the distribution system
- A well with a submersible pump that pumps directly into the distribution system.

Mild steel screens were used in wells prior to 1960 (about 60 total still in service).

There are 59 potable water tanks with capacity over 50,000 liters, including 21 with capacity over 1,000,000 liters in the CC water system. Of these, 7 are relatively large (capacity over 5,000,000 liters), located in the Port Hills area (common PGA level in these hills was 0.15g to 0.25g). The tanks have total storage volume of 124 million liters (33 million gallons). There are pump stations that pump water up to the tanks in the Port Hills. These pump stations do not have standby backup power, and instead use the water in the tanks to provide pressure during common power outages. There is one mobile portable pump available for use.

Diesel-operated pumps / generators are provided at 28 of the 55 primary pump stations. These diesel-fueled facilities are also used to offset peak power costs at times of high power demand. The diesels are usually sized to have three days of fuel under continuous operation. CCC also has two portable diesel units.

In the decade prior to the earthquake, CCC performed a seismic upgrade program for its water tanks. With the exception of one tank (describe below) there was no reported damage to the tanks in this earthquake.

Due to widespread liquefaction, covering perhaps 5% to 10% of the urbanized area within the CCC system (Figure 10), there have been a great number of failures to buried water pipes.

AC pipe sustained massive damage where exposed to 2 to 4 inches of settlement or 12 to 40 inches of lateral spreads. In many such areas, the AC pipes will need to be replaced entirely. Where damage was more limited, pipes were repaired using external clamps; new sections of PVC pipe cut into damaged pipes, etc.

In the western edge of the CCC service area, one circular buried concrete tank with segmented concrete roof sustained damage to the roof. It is thought that water sloshing uplift forces exceeded the capacity of the concrete segments, resulting in uplift, and then damage when the segments dropped back down. CCC was actively repairing this roof after the earthquake.

Within the CCC water system, about 8 water wells failed, and 1 additional well was damaged. The damage is believed to be primarily due to casing pipe failures in wells situated in liquefaction zones. As of mid-October, CCTVs have not yet been used to investigate the wells. In some areas, the depth to ground water increased, and in some places decreased, due to the earthquake. Well pumps were submersible, and no damage to the pumps is known to have occurred.

Due to power outages in the first day after the earthquake, the CCC wells lacking diesels had no power. As some wells in the CCC system were artesian with as much as 30 feet of head, these provided water supply locally post-earthquake.

Major portions of the CCC water system became depressurized very rapidly after the earthquake, owing to the large number of broken pipes in the liquefaction zones, and the loss of water supply form the wells due to power outages. With only one significant fire in the CBD in the first few hours post-earthquake, loss of piped water supply did not result in fire spread.

Through mid-October, 2010, the CCC had spent about $12 million on repairs to water and wastewater pipes. A much higher cost will be required to completely restore CCC's water and wastewater systems entirely. CCC staff estimate that as much as 25 km of potable water will have to be eventually replaced entirely; the location of these replacements coincides with the zones that underwent substantial liquefaction-caused settlement or lateral spread.

Through October 14, 2011 (6 weeks post-earthquake), there have been (so far) about 280 repairs made to CCC water pipes and their service connections; most of these repairs were in the liquefaction zones. Most of the water pipes were repaired within 6 days post-earthquake. There were no reports of disease due to water quality impacts, and post-earthquake water sampling tests showed no contamination in the water system in Christchurch.

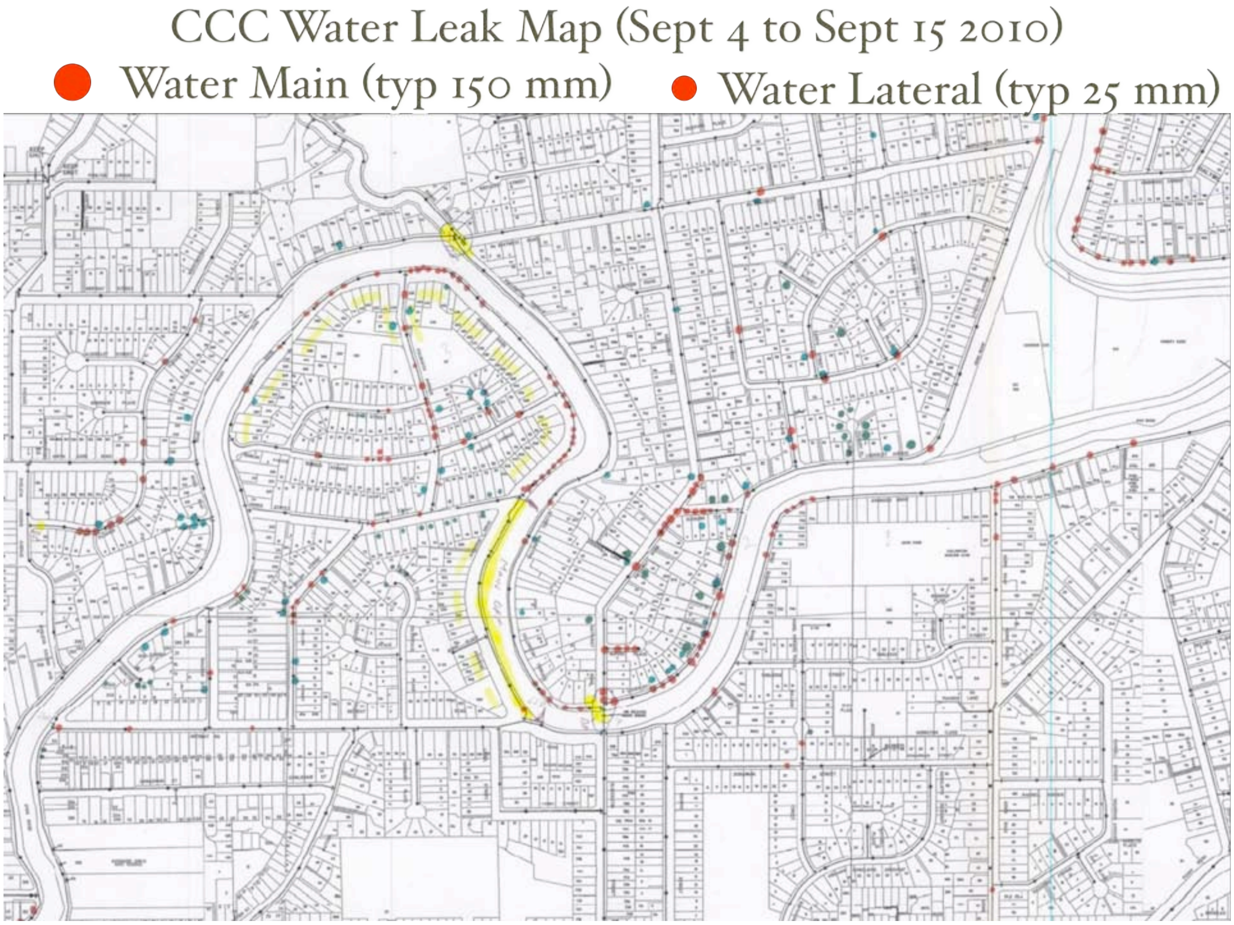

Figure 25. Map of Water Pipe Repairs, Christchurch City Council, as of September 15, 2010 (partial)

Water – Waimakariri District Council

The Waimakariri District Council (WDC) operates the water system for Kaiapoi and Rangiora (population about 45,000 people). Kaiapoi is a small town immediately northeast of Christchurch.

The WDC water system contains about 109 km of pipe. The common styles of pipeline mains in the potable water system is Asbestos Cement (AC), or PVC, both with push-on type rubber-gasketed joints, similar to pipelines used in many areas in the USA. The most common water pipeline diameters are 150 mm to 200 mm (6 to 8 inches). About half the total length of the WDC water pipe system are polyethylene pipes (commonly 25 to 50 mm) that branch off the mains and run parallel to the roads, that serve as headers to the final laterals that serve individual customers.

AC pipe in the WDC water systems sustained massive damage where exposed to 2 to 4 inches of settlement or 12 to 40 inches of lateral spreads. In many such areas, the AC pipes will need to be replaced entirely. Where damage was more limited, pipes were repaired using external clamps; new sections of PVC pipe cut into damaged pipes, etc.

Liquefaction was widespread in Kaiapoi, affecting about one-third of the streets. In this area alone, 31 km of sewer pipes, 32 km of water pipes, 12 km of drainage pipes, and 37 km of roads were damaged, with most (95%+) due to ground settlements or lateral spreads. Emergency repairs included 200+ potable water pipe repairs at a cost (through mid-October) of $1,800,000.

A boil water alert was maintained in the Kaiapoi area. One positive coliform reading was found during the post-earthquake water quality testing. There were no reports of disease due to water quality impacts.

Wastewater

There are two major wastewater operators in the affected area. The Christchurch City Council (CCC) operates the wastewater system for Christchurch and the Waimakariri District Council (WDC) operates the wastewater systems for Kaiapoi and Rangiora (population about 45,000 people).

Figure 26 shows the Christchurch (Bromley) wastewater treatment plant (CWTP). This facility treats most of the sewage for urban Christchurch, treating from 130 million to 160 million liters per day (33 to 42 MGD). The treated effluent was formerly discharged into the Avon-Heathcoate Estuary, with plans for a 3 km-long ocean outfall. Processes at the WWTP include removal of debris and grit; aeration to minimize odors; primary sedimentation to remove settleable organic matter and suspended solids; biological treatment in trickling filters and an activated sludge process; and oxidation pond treatment to reduce pathogen content.

Figure 26. Christchurch CWTP at Bromley

The Christchurch wastewater system includes about 1,767 km of sewer mains, 950 km of laterals, and 86 pump stations. Available data shows that 1,337 km of collection pipe are "brittle" (including concrete pipe, vitrified clay pipe) and 430 km are "ductile". There are about 26,000 manholes. Rates at the CWTP are about 2.5 to 2.8 m^3/second during dry weather, peaking to about 8 m^3/sec during 2-year storms. The system is sized with recognition that overflows from large storm events will occur about once every two years.
The common styles of sewer pipelines in the CCC system include segmented concrete and vitrified clay pipes. The common styles of sewer pipelines in the WDC system include AC and PVC of the same type of construction as water pipes.

Through October 14, 2011 (6 weeks post-earthquake), there had been (so far) about 200+ repairs (CCC) and 100+ repairs (WDC) made to wastewater pipes and their service connections; most of these repairs were in the liquefaction zones. The order of repair, using substantially the same work crews, was water pipelines first, followed by wastewater pipes.

While both CCC and WDC suspect damage to their storm water drain pipes, their priority to repair such damage was lower than for water or wastewater pipes, and actual repair efforts for drain pipes are not yet known.

Two of CCC's wastewater lift stations (Figures 27, 28) next to the Avon River were subjected to liquefaction and lateral spreads, and they floated and tilted. While the equipment within the lift stations may not have been damaged, the sewers leading to and from the lift stations were broken, and CCC bypassed these lift stations using portable pumps and flex hose.

Damage to sanitary sewers (Figures 29, 30) in many places led to direct discharge of untreated sewage into local rivers, leading to contamination warnings. Damage to the sewers has also resulted in substantial inflows of silts, leading to clogging of sewers, as well as infiltration of water. Figure 31 shows a map for Kaiapoi highlighting where the wastewater collection had failed and portable toilets were still in use 6 weeks after the earthquake; more than 200 structures were also so-affected in Christchurch.

Through mid-October, 2010, the CCC had spent about $12 million on repairs to water and wastewater pipes. A much higher cost will be required to completely restore CCC's wastewater systems entirely. CCC staff estimate that as much as 70 km of wastewater pipes will have to be eventually replaced entirely; the location of these replacements coincides with the zones that underwent substantial liquefaction-caused settlement or lateral spread. The majority of the cost for these long term improvements will be to replace deeply-buried (commonly about 10 feet) sanitary sewers.

Rebuilding of water and wastewater pipes in liquefaction zones using HDPE might be considered. It would be fair to say that previous use of push-on-rubber-jointed AC, PVC, vitrified clay or concrete pipe in liquefaction zones resulted in most of the adverse impact to buried utilities in Christchurch and Kaiapoi; a similar observation was made in Adapazari, Turkey in the Anatolian fault earthquake of 1999. This lesson learned needs to be communicated so that it is not repeated again. Many cities in the USA include large quantities of AC water pipe in areas mapped as having high liquefaction potential, and these American water utilities should take careful note of the results in Christchurch and Kaiapoi.

Figure 27. Floated and Tilted Wastewater Life Station 26, Porritt Park, Avonside

Figure 28. Floated and Tilted Wastewater Life Station 27, Avonside

Figure 29. Floated Sewer Manhole, Brooklands (one of fifteen)

Figure 30. CCTV picture of Broken Sewer, MDC

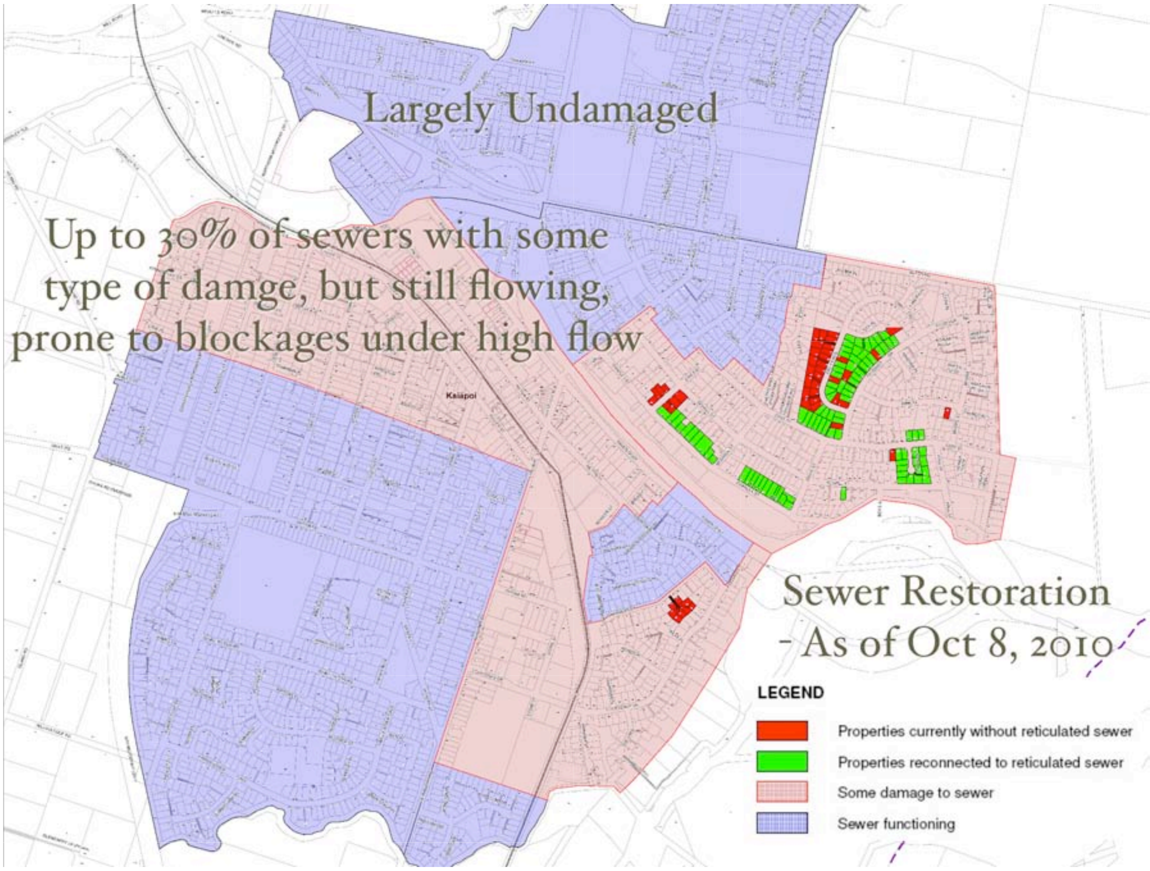

Figure 31. Map of Sewer Restoration, Kaiapoi, MDC, as of October 8, 2010

Gas

There is a LP (liquid petroleum) gas reticulated (piped) distribution system that serves the Central Business District and other parts of Christchurch, owned by Contact Energy operating under the Rock Gas brand.

Most of the LPG for the distribution system is supplied from Woolston Terminal (Figure 32) linked by a pipeline to Lyttleton Power. In Figure 32, the red lines show streets with gas pipes; the blue lines indicate planned future pipes; the remaining streets shown in light colour do not have piped gas service. A small amount of the LPG is supplied by rail and truck.

The distribution pipe system includes about 170 km of pipe, ranging in size from 63 mm to 315 mm; all are medium density polyethylene (MDPE). The common pipe wall thicknesses are about 9 mm (90 mm pipe) to 14 mm (160 mm pipe). The network is supplied from one main feed plant, supplemented by a pressure peaker plant on one extremity of the system, and three backup plants.

The distribution network is subdivided into about 189 separately valved zones. To close off a zone, service people must be dispatched to manually shut off a valve.

Beyond the main distribution network, several standalone networks are fed from gas cylinders or tanks.

At the time of the earthquake, the gas was a mixture of 60% propane and 40% butane, at a common network pressure of about 90 kPa.

Overall, the system performed well in this earthquake. Per one account, gas service was not interrupted. Per another account, gas service was restored to about 95% of customers by late Saturday September 4, 2010. The shortfall was mainly related to the loss of offset electric power to the feeder plant, and the failure of the backup generator from working as intended (failure to start); but the passive backup system remained active. In either case, the performance of the gas system in this earthquake was much better than observed in other parts of the world, where the use of cast iron distribution pipe is still common.

There was no damage to the distribution pipes. These are uniformly made of MDPE. None of the gas company's pipes traversed through the zones of large PGDs, although some were located close to one such zone adjacent to Hagley Park. One 160 mm PE Land Fill Gas pipe, owned by the Christchurch City Council (CCC), did traverse northeast Christchurch from the Burwood landfill, along Bower Avenue, Palmers Road and Carisbrooke Street, where minor PGDs may have occurred, but was not known to suffer any damage.

One of the risks identified as part of the post-earthquake recovery of the area was potential damage to gas meters due to demolition of buildings. Contact Energy staff worked with the local Civil Defence during the first week post-earthquake to address this risk.

Contact Energy performed a gas leakage survey after the earthquake. It was found that there were a handful of valve pits where the surface of the road sustained permanent ground deformations relative to the buried valve. These require repair, but none resulted in damage to the pipe below.

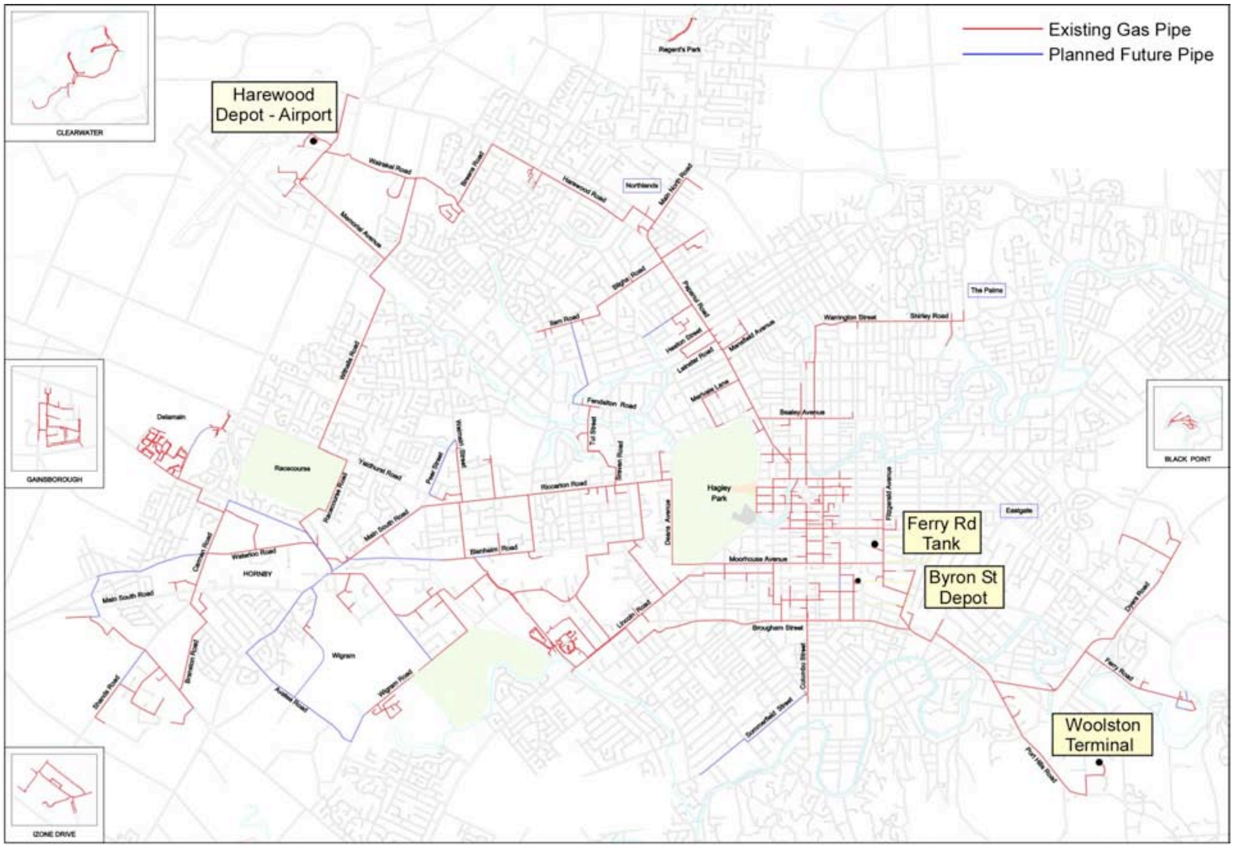

Figure 32. Contact Energy Service Areas and Pipeline Network

Ports

The deep water port of Christchurch is located at Lyttleton Harbor, Figure 33. The main port consists of four wharves (right side of Figure 33) named the Cashin Quays 1, 2, 3 and 4), an oil / liquid fuels berth (left side of Figure 33), a container yard (middle right in Figure 33), and office building facilities (top of Figure 33). There are several breakwaters and piers.

Figure 33. Lyttleton Port

By the afternoon of the day of the earthquake, coal loading recommenced. Oil, car loading and container operations were all returned to service either the day of the earthquake, or shortly thereafter. All wharves were restored to service shortly after the earthquake.

Quays 1, 2, 3 and 4 all underwent some permanent lateral movements, in the range of 5 cm to 18 cm. Quay 1 and 2 are timber supported (1960s design); Quay 3 is steel pile supported (1970s design) and Quay 4 is prestressed pile supported (1990s design). There is settlement behind these wharves. The moles sustained as much as 0.5 meters of settlement. There was slumping of the rubble mound sea wall at the oil berth.

There was no reported damage to any of the at-grade steel tanks in the tank farm seen on the left side of Figure 33.

Airports

The commercial airport for Christchurch is located immediately northwest of the city, and northeast of the fault rupture. Recorded ground motions near the airport were about PGA = 0.30g. Known damage at the airport included some broken signs and broken windows in the passenger arrival area, but no damage to suspended ceilings. A new airport facility building was under construction in 2010, and was reported to have sustained some type of damage, but we did not observe it. Runways, fueling facilities and hangers were not known to have been damaged. A nearby air traffic control facility sustained limited structural damage, but with no material non-structural damage (Figure 34), and it was in service shortly after the earthquake.

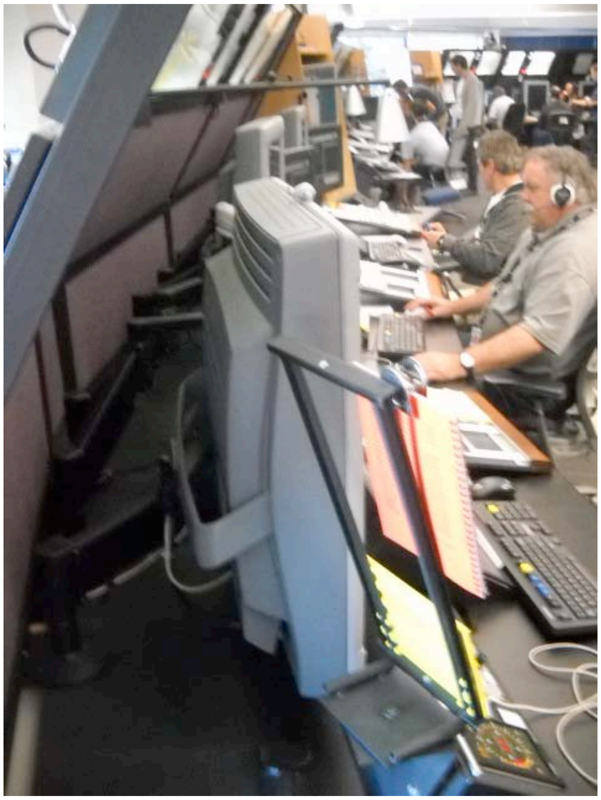

Figure 34. Air Traffic Control (photo J. MacKenzie)

Roads and bridges

The automobile road and bridge system serving the Christchurch area are owned and maintained by four separate organizations: NZTA, CCC (Christchurch City Council), SDC (Selwyn District Council) and WDC (Waimakariri District Council).

Roads

Fault offset resulted in damage to several surface roads. Figure 35 shows one such road with vertical uplift. Several roads that crossed the fault showed right lateral offsets of up to 4 meters, over a width of about 10 meters. In almost all cases, the damage to the roads would have been passable by most passenger vehicles; in a few with uplift, most vehicles (including almost all four wheel drive vehicles) would have been able to cross, although perhaps with some difficulty.

Liquefaction caused widespread road damage in Kaiapoi and Christchurch. These failures were confined to roads close to creeks and rivers where lateral spreading caused road surface cracks and fissures. Most of these roads would be passable at slow speeds (under 5 mph / 10 kph). In a few roads, uplift of sewer manholes by about 1 m or so presented severe hazards at night-time; cones were placed around these manholes, along with speed restrictions, and left in place for weeks after the earthquake.

Final repair of damaged roads may take many months to complete. Repairs of damaged roads need to be coordinated with final repairs or replacements of buried water and wastewater pipes and other buried utilities. Complete re-builds of roads may take a year or more to complete, covering more than about 60 km of roads.

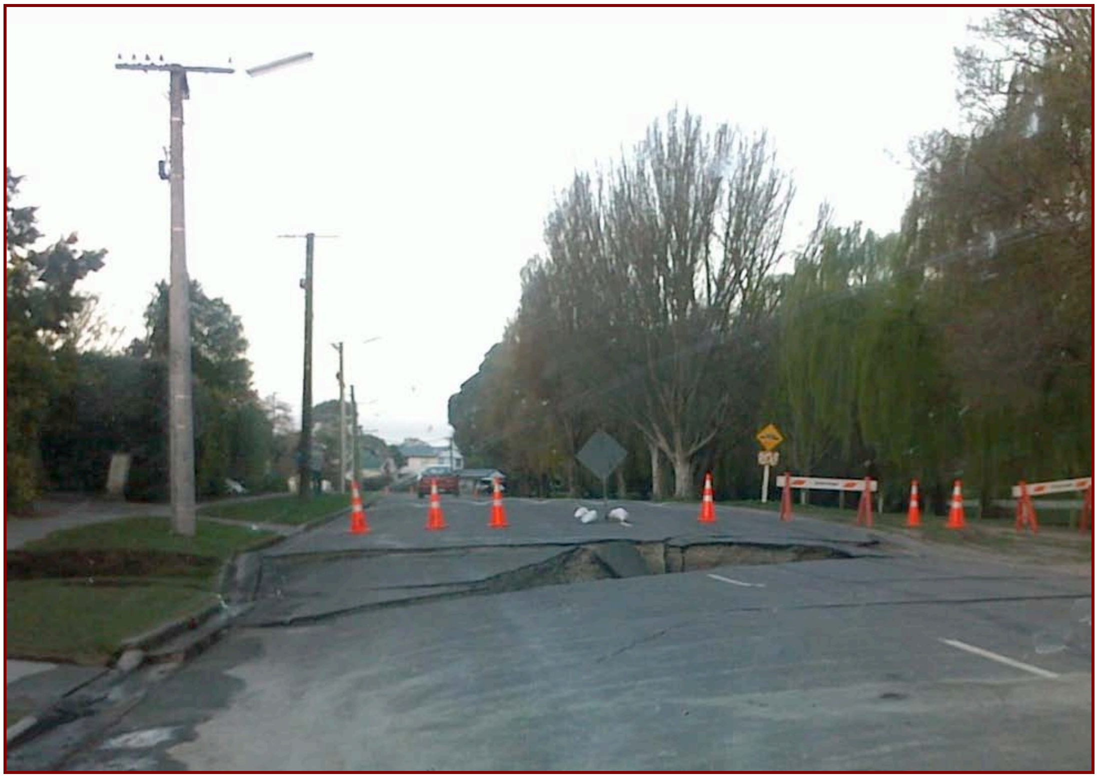

Figure 35. Road surface up heaving due to permanent ground deformation

Highway and Pedestrian Bridges

There were no outright bridge collapses in the area. A few pedestrian bridges, even though they did not collapse, suffered so much damage that they will likely have to be torn down.

Most damage to bridges occurred at the abutments due to ground settlement and lateral spreading (Figures 36 and 37).

At most of the bridges that we visited that suffered abutment damage, if there were pipes hanging from the bridge, then the pipes were broken. Figures 38 and 39 show a broken sewer pipe crossing a bridge; the broken pipe remained in service and was discharging into the creek below.

Figure 36. Rubber bearing deformed

Figure 37. Deck and abutment impact damage

Figure 38. Plastic hose connected to broke pipe to discharge wastewater to stream

Figure 39. Close up of the damaged wastewater pipe

Repair to both road and bridge damage was surprising quick and effective.

There are two large bored tunnels in the Christchurch area, both leading to the port: one for automobiles and the other for heavy rail. The estimated ground motions at these tunnels was about PGA = 0.20g to 0.25g. Neither tunnel suffered any significant damage, neither to the liner or to the portals; it was reported that some tiles were cracked in the automobile tunnel. The local transportation agencies exercised caution by limiting and controlling traffic through the tunnel.

A large landslide occurred on September 10 (6 days after the earthquake) along the highway 1 corridor on the east side of the South Island. The slide (about 90,000 cubic materials) occurred near Kiakoura, about 175 km north of Christchurch. This slide cut off both the highway and co-located rail line for four days. In order to reopen this key freight route, both the rail and highway were temporarily relocated partly onto slip material placed on the foreshore.

Railway

Kiwirail operates a heavy rail network for the South Island. The rolling stock includes about 59 mainline diesel locomotives.

The main rail traffic in the Canterbury region is transport of coal from the western side of the South Island to the Port of Lyttleton, via the Midland Line, see Figure 40. Figure 41 shows the buckled rails where the right lateral fault (red line in Figure 40) crossed the Midland Line. This track was repaired within 5 hours after the earthquake. Ongoing fault creep required the track to be repaired a few times in the days and weeks following the earthquake.

Prior to the earthquake, there were an average of 5 or 6 coal trains (each with about 1,500 tons of coal) per day to the port. Within 48 hours, rail traffic had been restored and the system was carrying about 7 coal trains per day.

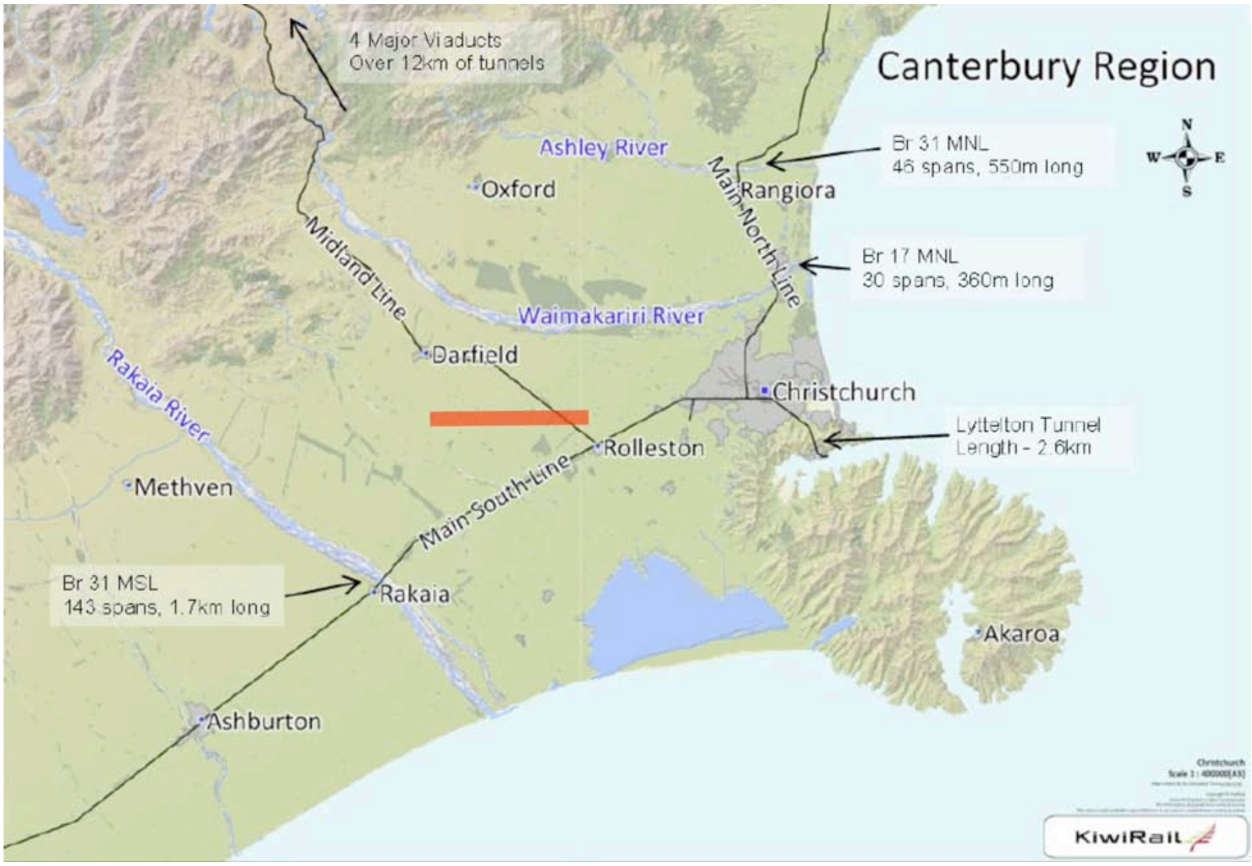

Figure 40. Rail System in the Canterbury Region

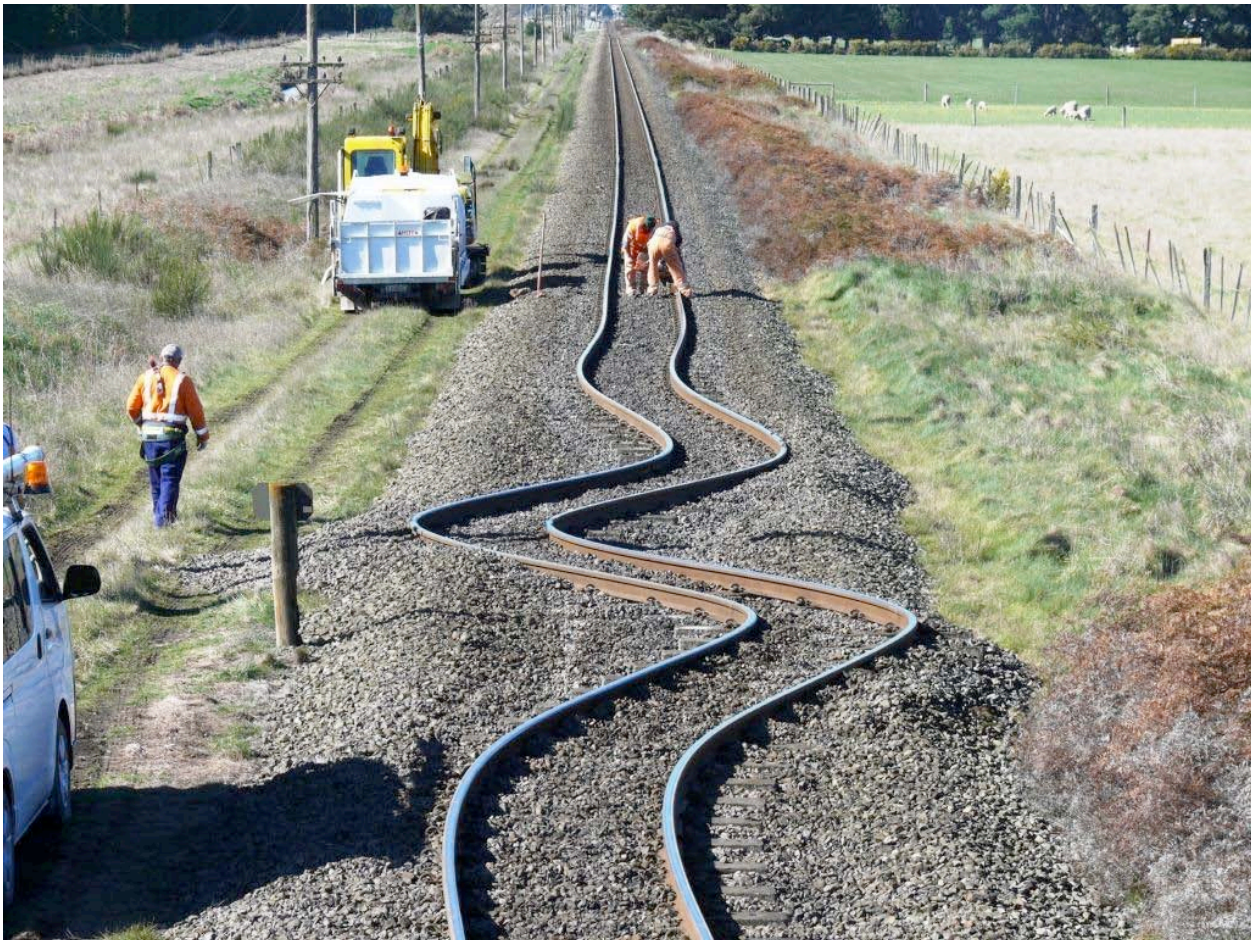

Figure 41. Buckling of Rails at Fault Offset Location

Fire Following Earthquake

Table 1 lists the possible structure fires related to the earthquake that possibly might have been caused by the M 7.1 earthquake or its aftershocks, for the period from September 4 through September 17, 2010. This list was developed by the New Zealand Fire Service.

The date and time reflects local New Zealand time. The M7.1 earthquake occurred at Sept 4 2010 at 04:36 am.

Date and Time	Address	Event Cause
Sept 4 2010 05:03 am	Moorhouse Ave	Electrical component failure – earthquake
Sept 4 2010 12:11 pm	Royleen St	Heat source close to combustibles
Sept 4 2010 08:33 am	Thurlestone Pl	Chimney fire (cracked / damaged chimney)
Sept 4 2010 19:17 pm	Hoonhay Rd	Chimney Fire
Sept 5 2010 10:30 am	Raxworthy St	Fallen Heater
Sept 8 2010 07:47 am	Moorhouse Ave	Electrical component failure
Sept 9 2010 03:49 am	Worchester Blvd	Suspicious
Sept 16 2010 04:14 am	O'Briens Rd	Water cylinder moved, worn insulation

Table 1. Fire Ignitions for the 13 Days Following the Main Shock (Ref: NZ Fire Service)

The following observations are made:

- FFE ignition models (Scawthorn, Eidinger and Schiff, 2005) are primarily concerned with fire ignitions within the first 24 hours (or so) of the earthquake. This is because it is during this time frame when water supply is weakest (owing to concurrent damage to the water system, power outages, etc.), gas leaks are at the highest, and the fire department staff and equipment at highest demand between responding to the fires, search and rescue, and other emergency response actions.
- Christchurch's underground piped gas distribution system covers just a portion of the city, in the area largely without ground failures (liquefaction). This may have limited the fuel to feed ignitions.
- The list in Table 1 is a subset of some 20+ structure fires over this period. The fires not listed in Table 1 were related to cooking, and not identifiable as being "caused" by the earthquake.
- Initial reports in the first weeks after the earthquake for FFE ignitions were 1, with possible 2 additional due to arson. The above list, developed 7 weeks after the earthquake, show that in fact there were more fire ignitions than initially reported.
- In one case, the cause of the fire was that a building was being demolished while the gas service was still active; this case illustrates the need for close communication and coordination between the local gas distribution company and construction crews performing emergency demolition of buildings.

Levees (Stopbanks)

A system of levees (known in New Zealand as "stopbanks") was built to prevent Waimakariri River flooding. Christchurch is within the flood zone and flood can reach as far as downtown Christchurch. Flood protection includes about 100 km of stopbanks along this river. The levees are typically 3 to 5 m high, 4 m wide on top, with 3H to 1V slopes.

The stopbanks impacted by the earthquake are in the area close to river mouth of Waimakariri River and the junctions of Kaiapoi River and Kairaki River, Figure 43. About 5 km of levees suffered severe to major damage. Severe damage included cracks greater than 1 m in width, with deep seated movement and settlement. Major damage included large scale instability, with lateral spreading and settlement exceeding 0.5m.

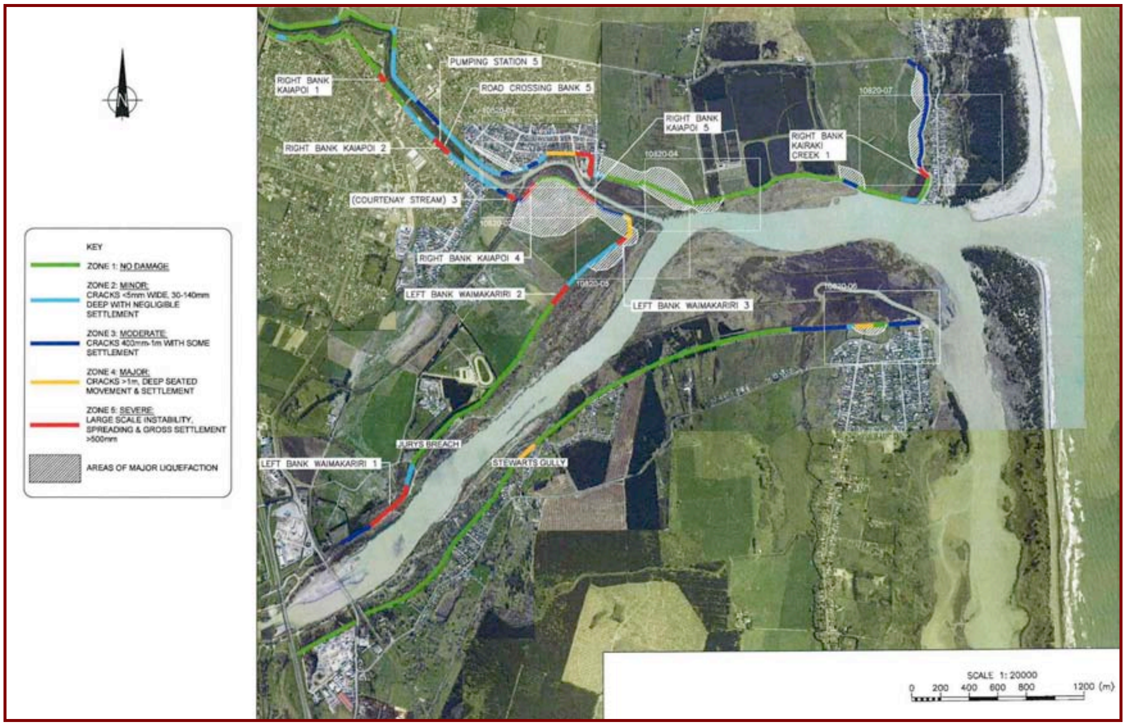

Figure 43. Stopbank damage surveyed by Riley Consultants

As the rainy season will soon arrive, the focus to keep water from flooding the urbanized areas is high. Priority and repair strategy were set to minimize the impact of loss due to flooding.

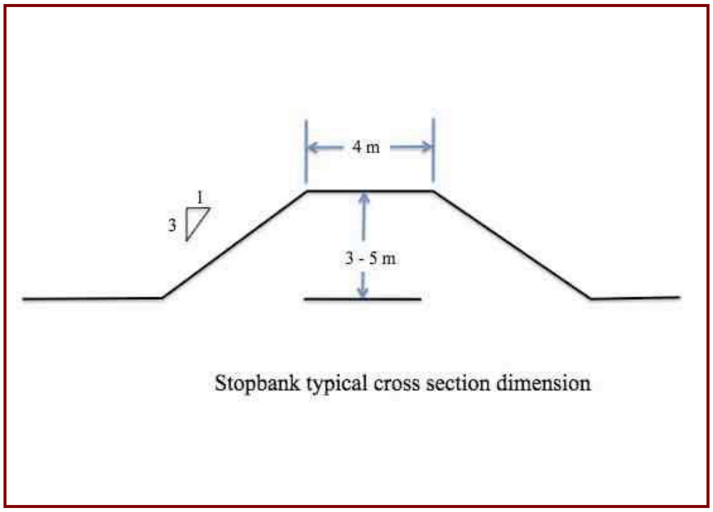

Figure 44. Stopbank Cross Section

The typical cross section of the stopbank is shown in Figure 44. It is designed to contain a 5,000 m^3 per second flood while keeping about 900 mm available above the highest expected flood level.

A survey reported by Riley Consultants indicated the following damage to stopbanks: 10 severe, 4 major, 11 moderate, and 14 minor damage: see Figures 45 to 47.

Figure 45. Severe Damage – Stopbank

Figure 46. Major Damage – Stopbank

Figure 47. Moderate Damage - Stopbank

Lifeline Interdependence

The following general observations are made about lifeline interdependence, as evidenced by this earthquake.

- The loss of Orion power to cell phone sites, for up to 12 hours in many cases, led to loss of cell phone service once the batteries at these sites ran down. While both cell phone providers had implemented proper seismic anchoring or battery racks and equipment, and had some portable generators, neither firm could mobilize a sufficient number of generators fast enough to prevent outages. Once Orion power was restored, cell phone sites were again functional.
- Much of the water systems were de-pressurized in the first day after the earthquake, due to water pipe damage, a few broken wells, and loss of power to supply to most wells. The loss of Orion power to the wells likely had limited impact on the overall performance of the water system. The water supply for both systems (CCC, WDC) are from wells, which require power: CCC wells generally did not have on site generators; critical wells in the WDC system (in Kaiapoi, Pines Beach and Kairaki) did. The liquefaction-caused damage to the water pipeline distribution systems grossly de-pressurized the systems, a few wells were able to supply without power, so any additional water supply from wells in the first few hours after the earthquake would have had only modest impact to overall water system performance.
- The road network suffered no gross failures like bridge collapses. As communications, power and the road network were all more-or-less functional within about 12 hours after the earthquake, the restoration of the city services (like water, wastewater and others) was largely governed by the time needed to inspect and make repairs (manpower limited).

General Building Stock

The building stock in the region that was shaken at PGA greater than about PGA = 0.05g includes perhaps 200,000 individual structures. This building stock includes unreinforced masonry (URM), reinforced concrete, precast concrete, steel, and wood frame construction.

Most damage was concentrated to the older building stock, built prior to circa 1935. After the Napier, NZ earthquake of 1931 that killed 256 people, building codes were modified to include some level of earthquake protection. With the exception of buildings in the Christchurch area subjected to liquefaction, few, if any, post-1935 buildings suffered major damage in the 2010 earthquake (but many suffered minor damage).

The URM buildings include several large, ornamental Anglican Churches, as well as many small commercial stores. The bulk of the URM buildings experienced ground motions from PGA = 0.15g to 0.30g, and most sustained minor damage (fallen parapets, etc.); a few had major damage and outright collapses. Some small URM buildings with many walls and few windows showed no distress. Some of the more massively built URMs, including churches, the cathedral, etc. sustain only minor damage beyond loss of parapets. Some 1 and 2-story small URM commercial buildings had complete wall failures.

Residential single family buildings compose the largest inventory of buildings, using wood frame stud-wall / gypsum board type construction, not too different from that commonly used in the USA. There are no known collapses of these residential wood frame buildings, although up to about 3,000 of these types of buildings sustained various ranges of damage due to liquefaction. Brick chimneys for wood frame residential buildings are common throughout the area; perhaps 50% of these chimneys had some type of failure. There are no known injuries due to fallen chimneys.

The high density commercial areas of Christchurch include many multistory reinforced concrete and steel buildings, all designed for earthquakes. Damage to these buildings was generally minor. There are no known collapses to these engineered buildings. There are no known "soft story" failures for multi-story wood frame construction; the inventory of such buildings appears to be very small.

Nonstructural

Widespread collapses of storage racks in warehouses, including two regional food distribution centers, led to a concern that the food supply might be disrupted. To compensate for the lost storage, food shipments by truck and train were undertaken from the North Island down to Christchurch along the Highway 1 corridor along the east coast of the South Island. Rapid restoration of highway, rail and port facilities, coupled with the redundancy on the transportation network such that at no time was Christchurch cut-off from re-supply via land or water, reduced the potential impact of loss of food stuffs. To dispose of the food lost by storage rack collapse, a new cell was opened in the city landfill to expedite removal of the spoiling food and thereby avert a health hazard.

The seismic design standards for the existing steel storage racks will need to be reviewed, as the actual earthquake motions were generally within design levels, but the performance of heavily-loaded racks was poor. If the earthquake had occurred during working hours, no doubt the collapse of the racks would have led to many injuries or fatalities.

In the United States, the seismic design basis for anchor steel storage racks to meet the California Building Code in high seismic regions such as Oakland California incorporates factors such as R (response modification), C (spectra amplification), PGA (horizontal peak ground acceleration) and W (weight of the rack, including 100% of the weight of the stored contents. Depending on the actual rack configuration, the code-specific values can result in design horizontal base shears (V) for racks anchored to a concrete slab at the ground level of about V = 0.08W to V = 0.12W or so, for firm soil sites with site-specific ground motions of about PGA = 0.44g.

The actual design basis used for the failed heavily loaded storage racks in Christchurch is uncertain, but the level of ground shaking at the locations with the failed racks was commonly about PGA = 0.15g to PGA = 0.35g. Recognizing that a warehouse-by-warehouse inventory is not yet available, we estimate that the percentage of collapsed heavily loaded racks in the Christchurch area may be as high as 20% or so. This rate of failure is substantially higher than anticipated by most in the engineering community.

A more thorough investigation into the proper seismic design of storage racks is called for, both in the USA and in New Zealand. Possible promising approaches would be to require storage racks to be designed for 100% of their rated loads; be anchored; have heavy loads restrained to the rack (or use friction systems capable or preventing the load from sliding off the rack) in any area adjacent to regular human occupation; that the "ductility" of cold-rolled steel members be limited to perhaps 4 (up to M 7 events) or 3 (up to M 8 events); that response modification coefficients (R) for long period (T greater than 1 second) racks be limited to avoid a nearly "static"-type overload condition from occurring.

Another consideration for storage racks is that lift-trucks or other similar devices may occasionally impact the structure of the racks, creating dents or buckles, especially to the lower columns. These damaged columns can collapse under dead loads, resulting in a life safety threat; or even if not collapsed, have substantially weakened the rack below the original design basis. This can be mitigated by incorporating bollards near the racks; or by the facility owner by instituting a suitable maintenance / replacement program for damaged racks; or by the engineer by over-sizing the rack columns to be able to accommodate some level of vehicle impact. The collapse of storage racks under non-seismic conditions has been known to happen; this can be partially mitigated by including a full safety cage for the operators of lift trucks.

Units and Abbreviations

This report uses both common and metric units: inches, feet, millimeters (mm), meters (m). The conversion is 12 inches = 1 foot. 1 inch = 25.4 mm. 1000 mm = 1 m. 100 cm = 1 m. 1 kilometer (km) = 0.621371 miles. MPH = mile per hour. KPH = kilometers per hour. 1 kPa (kiloPascal) = 1 kN/m^2 = 0.145 psi (pounds per square inch). 1 pound (force) = 4.448 Newtons = 0.45 kilograms (force). 1 liter = 0.264 gallons (US liquid measure). MGD = million gallons (US liquid measure) per day.

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While every effort has been made to present the findings in this report as accurately as known at the time of writing, it must be recognized that the findings may be incomplete, misinterpreted, incorrect or become outdated as further detailed studies are performed. Hidden damage might become known only some time after the earthquake. Neither ASCE or the authors of this report assume any responsibility for any such omissions or oversights.

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