# CHRISTCHURCH, NEW ZEALAND EARTHQUAKE SEQUENCE OF $M_w$ 7.1 September 04, 2010 $M_w$ 6.3 February 22, 2011 $M_w$ 6.0 June 13, 2011: LIFELINE PERFORMANCE

**Edited by**
**JOHN EIDINGER, PE., M ASCE and ALEX K TANG, PE., F ASCE**

**Technical Council on Lifeline Earthquake Engineering**
**Monograph No. 40**
**February 2012 – Revision 0**
**ASCE**

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# CHRISTCHURCH, NEW ZEALAND EARTHQUAKE SEQUENCE $M_w$7.1 SEPTEMBER 04, 2010 $M_w$ 6.3 FEBRUARY 22, 2011 $M_w$ 6.0 JUNE 13, 2011 LIFELINES PERFORMANCE


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# ABSTRACT

A sequence of strong earthquakes affected the City of Christchurch and nearby urban centers. There were three major earthquakes in the sequence: Mw 7.1 (September 4 2010); Mw 6.3 (February 22 2011); Mw 6.0 (June 13 2011). There were many aftershocks after each of these events.

The September 4, 2010 Darfield, New Zealand earthquake occurred at 4:30 a.m. local time had a moment magnitude ($M_w$) of 7.1. The epicenter of this earthquake was located west of Rolleston at 43.53°S, 172.12°E with a depth of 10 km; about 30 km SW of the central business district of Christchurch. There was about 22 km of surface rupture, with up to 4 meters (average along the entire fault rupture zone of about 2 meters) right lateral offset; there was some surface uplift at various places along the fault. Heavy localized damage occurred to water and wastewater pipelines caused by liquefaction-induced lateral spreads and settlements in Christchurch and nearby Kaiapoi; liquefaction damaged the Port of Lyttleton; surface faulting and liquefaction damaged railroad tracks; moderate levels of ground shaking in Christchurch (commonly around PGA = 0.2g) caused sporadic damage to electric power substations. Liquefaction also sporadically damaged roads, buried telecommunication cables, and levees. Moderate levels of ground motion damaged some unreinforced masonry buildings, but there were no fatalities. This earthquake caused a few fire ignitions.

The February 22, 2011 magnitude 6.3 Christchurch Earthquake occurred at 12:51 p.m. local time. The epicenter of this earthquake located about 10 km SE of Christchurch (43.58° S, 172.70° E) in the hills close to Lyttleton Port with a depth of 5 km. The epicenter's close proximity to Christchurch central business district as compared to the 9/4/2010 event led to much higher ground shaking (commonly over PGA = 0.5g) and far more damage in this Mw 6.3 event than in the prior Mw 7.1 event. This event triggered widespread liquefaction, with severe damage to buried utilities in central and eastern Christchurch (water pipes, wastewater pipes, power cables, several water wells, the wastewater treatment plant); and more damage to the port, roads, bridges. Very high levels of shaking in the Port Hills led to substantial rock falls and some landslides; the largest City potable water reservoir was destroyed. This event resulted in significant damage to buildings in the central business district and 181 fatalities. Due to (perhaps) concern for more damage due to potential aftershocks, much of the central business district was "closed" to the public for many months, creating a "ghost town" with accumulating economic impacts to the community.

The June 13, 2011 magnitude 6.0 Christchurch Earthquake occurred at 2:21 p.m. local time. The epicenter of this earthquake located about 10 km SE of Christchurch (43.58° S, 172.74° E) in the hills close to suburban Sumner with a depth of 9 km. Its close proximity to Christchurch central business district led to very high levels of ground shaking for the eastern side of Christchurch, further damaging previously-weakened unreinforced buildings. Liquefaction again damaged some buried water and wastewater pipes.

A fourth notable earthquake occurred on December 22, 2011, at 1:58 p.m. local time, with magnitude 5.8. The epicenter of this earthquake was located near Brighton beach, east of the city, and just offshore. Within 3 hours, it was followed by several aftershocks, including a M 6. Liquefaction again occurred in the eastern suburbs of Christchurch. Being further east of most of the populated area, damage was less severe than the prior three earthquakes.

# PREFACE

The Earthquake Investigation Committee of the Technical Council of Lifeline Earthquake Engineering (TCLEE), American Society of Civil Engineers (ASCE), was established to initiate, organize, train for, coordinate, and evaluate the performance of lifelines following earthquakes. Members of the committee are employees of lifeline industries, consulting engineers, and academics from the United States and Canada. Committee members provide services on a voluntary basis. For some earthquake investigation, companies of participants do not require an individual to take vacation time for the investigation and may provide some support for expenses. ASCE also provides support to reimburse expenses. In addition to the time associated with the reconnaissance trip, the substantial effort by each individual to prepare a short report for the TCLEE Web page and the full report for the monograph series is all done on a voluntary basis. The cost of this effort is substantially more than the support provided by ASCE.

Individuals participating in the investigation need not be members of the committee or members of ASCE, but they are expected to follow the committee's earthquake investigation practices as described in the ASCE publication, TCLEE Monograph 11, "Guide to Post-Earthquake Investigation of Lifelines." Members of the investigation team coordinate with other groups and may participate in groups organized by other organizations. They gather both good and poor performance data from earthquakes to provide information for practitioners to improve the performance of the lifeline systems. Foreign earthquakes that have been investigated include the 1985 Chile, 1988 Soviet Armenia, 1990 Philippines, 1991 Costa Rica, 1992 Turkey, 1995 Kobe (Japan), 1999 Kocaeli (Turkey), 1999 Chi-Chi (Taiwan), 2001 Gujarat (India), 2002 Atico (Peru), 2004 Zemmouri (Algeria), 2004 Sumatra, 2007 Kashiwazaki (Japan), 2008 Pisco (Peru), 2008 Wenchuan (China), 2009 L'Aquila (Italy), the 2010-2011 Christchurch earthquake sequence (New Zealand) and the 2011 Great Tohoku (Japan) earthquake. Domestic earthquakes that have been investigated include 1989 Loma Prieta, 1992 Landers, 1994 Northridge, 2000 Napa, 2001 Nisqually, 2002 Denali, 2003 Paso Robles, and 2008 Alum Rock. TCLEE also started to document major storm impact on lifelines, the Pacific Northwest Storm of December 2007 was our first post wind storm investigation.

The Kobe earthquake report, Monograph 14, was the first foreign earthquake investigation report published by ASCE as a TCLEE monograph. The first domestic earthquake investigation report published by ASCE as a TCLEE monograph, number 8, was for the Northridge earthquake. Prior to this time, TCLEE prepared a lifeline report that was published by the Earthquake Engineering Research Institute (EERI). The Earthquake Investigation Committee continues to cooperate with EERI to provide an abbreviated version of lifeline performance in Earthquake Spectra (EERI publication). TCLEE publishes brief preliminary reports on the ASCE/TCLEE Web page.

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February 2012

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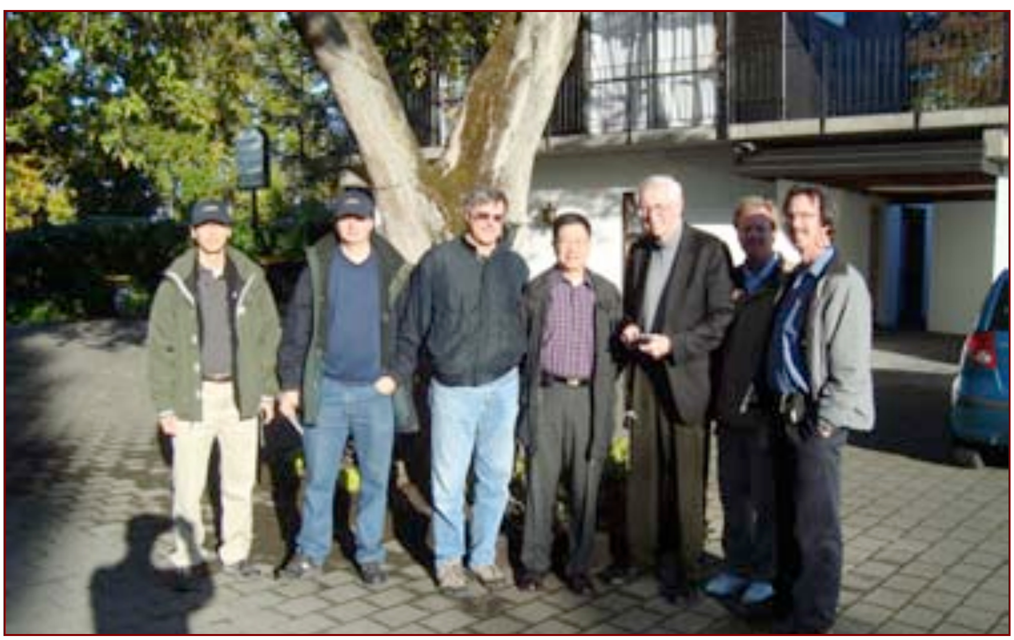

*ASCE Team, from left to right, David Lau, Alexis Kwasinksi, John Eidinger, Alex Tang, Tom O'Rourke, Dave Baska, Craig Davis*

# TCLEE Monograph Series

These publications may be purchased from ASCE, telephone 1-800-548-ASCE (2723), Web http://www.asce.org.

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[www.asce.org/community/disasterreduction/tclee_home.cfm](www.asce.org/community/disasterreduction/tclee_home.cfm)

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As is not uncommon in post-earthquake reconnaissance, incomplete information in the weeks and months after the event can lead to omissions and misunderstandings. We apologize if the findings in this report are incomplete, and the reader is cautioned that it may take months to years of post-earthquake evaluations before a comprehensive understanding of lifeline impacts is available. ASCE/TCLEE will continue to update the lifeline performance information when more information is collected.

The findings and photos presented in this report reflect the collected input from many people and sources; all of them are credited wherever the information or the photo appears in this document. We are thankful to them providing us with permission to use the information and photos given to us. The ASCE TCLEE team members (same as the authors of this monograph) collected data and took photos from October 11 to 17, 2010, and from April 3 to 9, 2011. Information presented for the June 13, 2011 event is based on a follow up investigation by John Eidinger from August 9 and 10, 2011, published information and informal communications with the affected utilities.

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I would like to thank Alex Tang, my co-editor and great friend for his relentless efforts to seek the truth and making this report possible.

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We are much indebt to Professor Tom Wilson of University of Canterbury who arranged transportation for us to visit surface faulting of the October 2010 event and to tour the outskirt of the City of Christchurch. In addition he and his team, Joanne Stevenson, and Sonia Giovinazzi all worked very hard to organize meetings for the TCLEE team weeks prior to our arrival. Their seamless arrangement helped us to carry out a very smooth assessment trip covering all the topics. Tom Wilson also set up information sharing sessions (for both events) on campus for TCLEE team and local lifelines practitioners to discuss observations and recommendations.

Our trips will not be successful and complete without the support from Dave Brunsdon (National Engineering Lifelines Committee), Mark Gordon (AECOM), and Tony Fenwick. Without their kind effort we will not be able to meet with key individuals in various utilities to collect relevant earthquake performance information and to visit sites to document failure modes and good performances. We are very grateful to their effort. We also appreciate Tony Fenwick who volunteered to be the single point of collecting information (such as power point charts, pdf documents, maps, etc.) for the team. We also like to thank Mark Gordon who set up the ftp site for us to download the documents.

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(Univ. Canterbury) and Ian Brown (Ian R Brown Associates) provided observations about liquefaction. John Mackenzie provided invaluable information about structural and nonstructural damage, and design concepts and mitigations taken by Transpower and Orion. Members of the Australian government supported the investigation include Martin Wehner, Adrian Whichello, and Ammar Ahmed. Information collected from other teams PEER (Scott Ashford) and GEER (Ed Kavazajian, Arizona State University, John Allen, Tri/Environmental) are incorporated into this report. Several KiwiRail photos are attributed to Lee Baxter.

Special acknowledgement must be given to John Lamb (photo below). John Lamb was the Project Manager of the 1997 report, "Risk and Realities", that addresses the potential earthquake performance of lifelines in Christchurch.

*John Eidinger, Alex Tang and John Lamb (left to right). This piano was located in a residence in the Port Hills; it jumped off the floor in the February 22 2011 earthquake. It still holds a tune.*

# ENDORSEMENTS

This report was prepared as a volunteer effort by members of the ASCE TCLEE Earthquake Investigation Committee. Nothing in this report should be considered an endorsement of any particular product or company.

While we believe the information contained in this report to reflect what occurred (or did not occur) in the earthquakes of 2010 and 2011 that affected Christchurch, there is no doubt that this report does not contain all possible information, and it may contain inaccuracies.

This report makes mention of major New Zealand corporate and local government entities; some are listed on stock exchanges. While all of these entities shared information with us, the readers should know that none of these entities have endorsed the facts, conclusions or recommendations in this report.

# Table of Contents

# 1.0 Introduction

## 1.1 Summary

A sequence of three large earthquakes impacted the City of Christchurch, New Zealand and surrounding communities. This report describes the impacts of these three earthquakes on the lifelines serving the greater Christchurch metropolitan area.

**September 4 2010 Earthquake**: 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). In central Christchurch, moderate levels of ground shaking and moderate extent of liquefaction. Moderate damage to lifelines.

**February 22 2011 Earthquake**: There were 181 fatalities. More than 500 commercial buildings in the Christchurch central business district were damaged. Estimated costs to rebuild damaged buildings and infrastructure range up to $15 Billion. In central and eastern Christchurch, very high levels of ground shaking, major extent of liquefaction, some landslides and many rock falls. Major damage to lifelines.

**June 13 2011 Earthquake**: There were no fatalities, 46 injuries (2 critical). Preliminary estimates suggest that this event further damaged 100 previously-damaged beyond repair. Estimated costs to rebuild damaged buildings and infrastructure range up to $1 Billion. In eastern and central Christchurch, high levels of ground shaking, moderate extent of liquefaction, a few rock falls. Moderate damage to lifelines.

## 1.2 Overview

Three large earthquakes in 2010-2011 impacted the City of Christchurch and surrounding communities. The first earthquake occurred on September 4, 2010 with a magnitude of 7.1, the second one occurred on February 22, 2011 with a magnitude of 6.3, and the third one on June 13, 2011 with a magnitude of 6.0 (except as noted, we use Moment Magnitude in this report). The epicenter of the 2010 earthquake was approximately 43 km from central Christchurch; the epicenter of the February 22, 2011 event was approximately 6 km southeast from central Christchurch; the epicenter of the June 13, 2011 event was approximately 10 km east-southeast from central Christchurch.

The Christchurch urban area covers some 417 square kilometers on the Canterbury Plains and the northern margin of Banks Peninsula. The Canterbury Plains are a complex of fans deposited by eastward flowing rivers emerging form the foothills of the Southern Alps. Banks Peninsula, a volcanic complex became extinct about 6 million years ago.

European settlement of modem Christchurch began about 1850-1851. The landscape of the Christchurch urban area has been considerably altered by drainage and infilling of hollows since its establishment in the 1850s. Figure 1-1 shows a view of the modern

Christchurch central business district, highlighting the Avon River (foreground), and the Christchurch Cathedral (center-right in this photo).

*Figure 1-1. Christchurch Central Business District (c. 1995)*

The Christchurch City District and the two adjacent Waimakariri and Selwyn Districts were the principal areas adversely affected by the earthquakes, Figure 1-2. The City of Christchurch and the nearby community of Kaiapoi, with combined population of about 400,000 people, were the two urbanized areas that were most strongly affected by the September 4, 2010 4:35 am (local time) $M_w$ 7.1 earthquake. These two communities are located in the province of Canterbury in the South Island of New Zealand. Christchurch is the second largest city in New Zealand. Kaiapoi is located in the Waimakariri District.

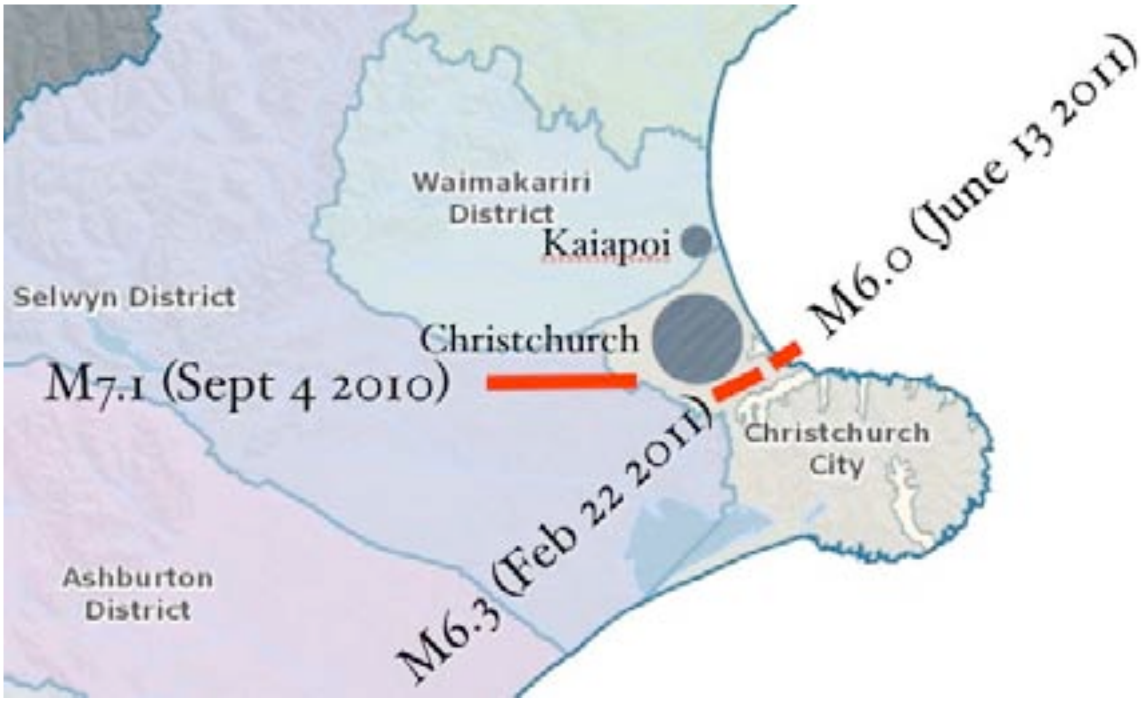


*Figure 1-2. Location of the Earthquakes and Larger Urbanized Areas*

## 1.3 Key Findings

Three large earthquakes in 2010-2011 impacted the City of Christchurch and surrounding By far the vast majority of the damage and impacts to lifelines has been due to liquefaction (all three earthquakes); both due to settlements and lateral spreads. Strong ground shaking played a modest role on the performance of lifeline buildings (mostly in the February 22 2011 event). The effects of rock falls and landslides locally damaged a few lifeline facilities in the February 22 2011 and June 13 2011 events. Surface faulting (September 4 2010 event) damaged a few grade-level roads and railways, but there were essentially no buried utilities at locations exposed to surface faulting.

Substantial damage occurred to water, wastewater and power distribution systems. The sea port was heavily damaged. Levees had heavy damage. Moderate damage occurred to telecommunications, railway and the road / highway bridge networks. Light damage occurred to power transmission systems, gas distribution and liquid fuels. No material damage occurred at the airport. Fire ignitions were few; with no fire spread.

There was serious damage and some collapses of engineered structures in the February 2011 event. This is not surprising, as the most recent building codes in New Zealand require design for PGA = 0.22g, whereas the actual levels of shaking were over PGA = 0.50g in the central business district of Christchurch; and PGA = 0.90g and higher in the Port Hills residential areas.

There are on the order of 1,000 unreinforced masonry (URM) structures in Christchurch, the vast majority of which pre-date modern building codes. A few of the more important structures had some seismic retrofit prior to the earthquakes. Between the three earthquakes, some URMs collapsed (including some that had been retrofitted); and the majority suffered moderate to extensive damage.

Liquefaction-caused settlements and (in some places) lateral spreads also damaged thousands of single family residential wood-stud-on-concrete-slab single family residential structures; none of these structures collapsed or are known to have caused fatalities. Rock falls destroyed several structures and killed people.

## 1.4 Abbreviations

| | |
|---|---|
| ASCE | American Society of Civil Engineers |
| CBD | Central Business District |
| CCC | Christchurch City Council |
| g | acceleration; 32.2 feet/sec/sec = 9.81 m/sec/sec = 1 g |
| M | Magnitude (moment magnitude) |
| MH | Manhole |
| PGA | Peak Ground Acceleration, g |
| PGD | Permanent Ground Displacement (or Deformation), inches |
| PGV | Peak Ground Velocity (measured in inches/second) |
| PVC | Polyvinyl Chloride pipe |
| TCLEE | Technical Council on Lifeline Earthquake Engineering |
| WDC | Waimakariri City Council |

## 1.5 Limitations

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.

## 1.6 Units

This report makes use of both common English and SI units of measure.

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.

# 2.0 Tectonic Setting and Geologic Issues

All three earthquake events occurred on faults that had not been identified before September 2010. The first event occurred on September 4, 2010 resulted in surface rupture, while the second and third events did not have surface rupture.

## *2.1 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. Unless otherwise noted in this report, M refers to Moment Magnitude. Major earthquakes occur rather regularly in New Zealand, including: Moment Magnitude M 8.2 Wairarapa 1855 (near Wellington); M 7.8 Hawke's Bay 1931; M 6.5 Edgecumbe 1987; and 18 other large (M 6.8 to 7.8) notable large magnitude shallow events since 1848.

The Alpine Fault (Figures 2-1, 2-2) is considered highly active (slip rate of 27 mm/year) and capable of producing a M 8 earthquake at any time. The actual fault that broke and caused the Darfield earthquake of September 4 2010 was previously unknown to exist, and is now called the Greendale fault. Figure 2-2 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.

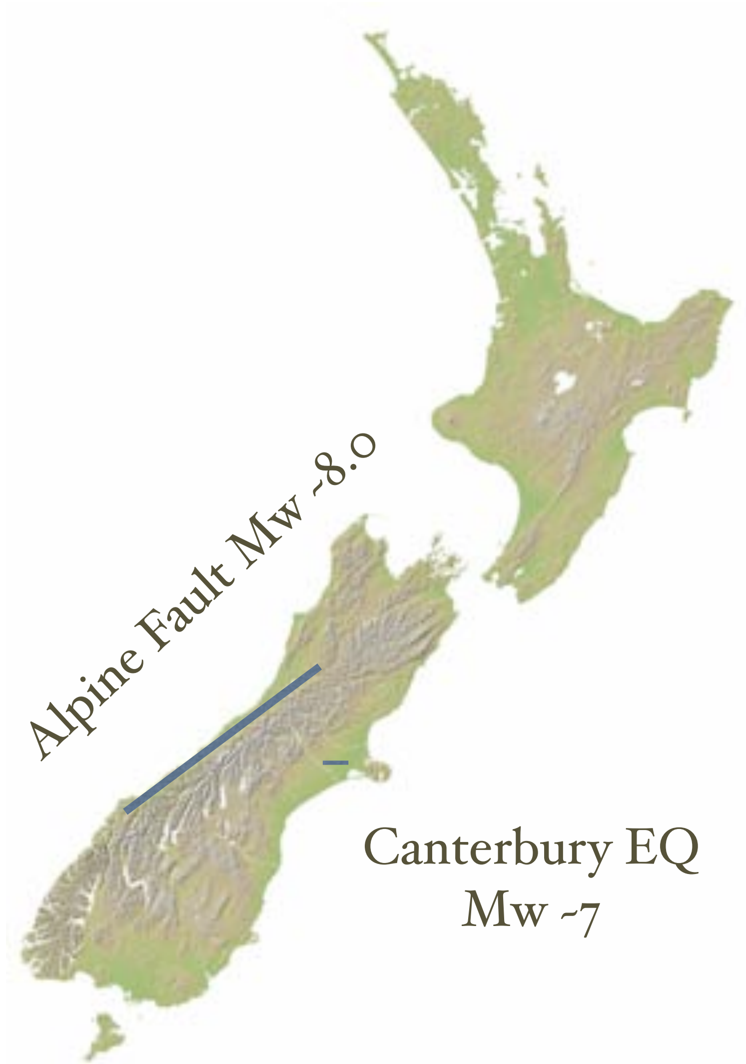


*Figure 2-1. Tectonic Setting*

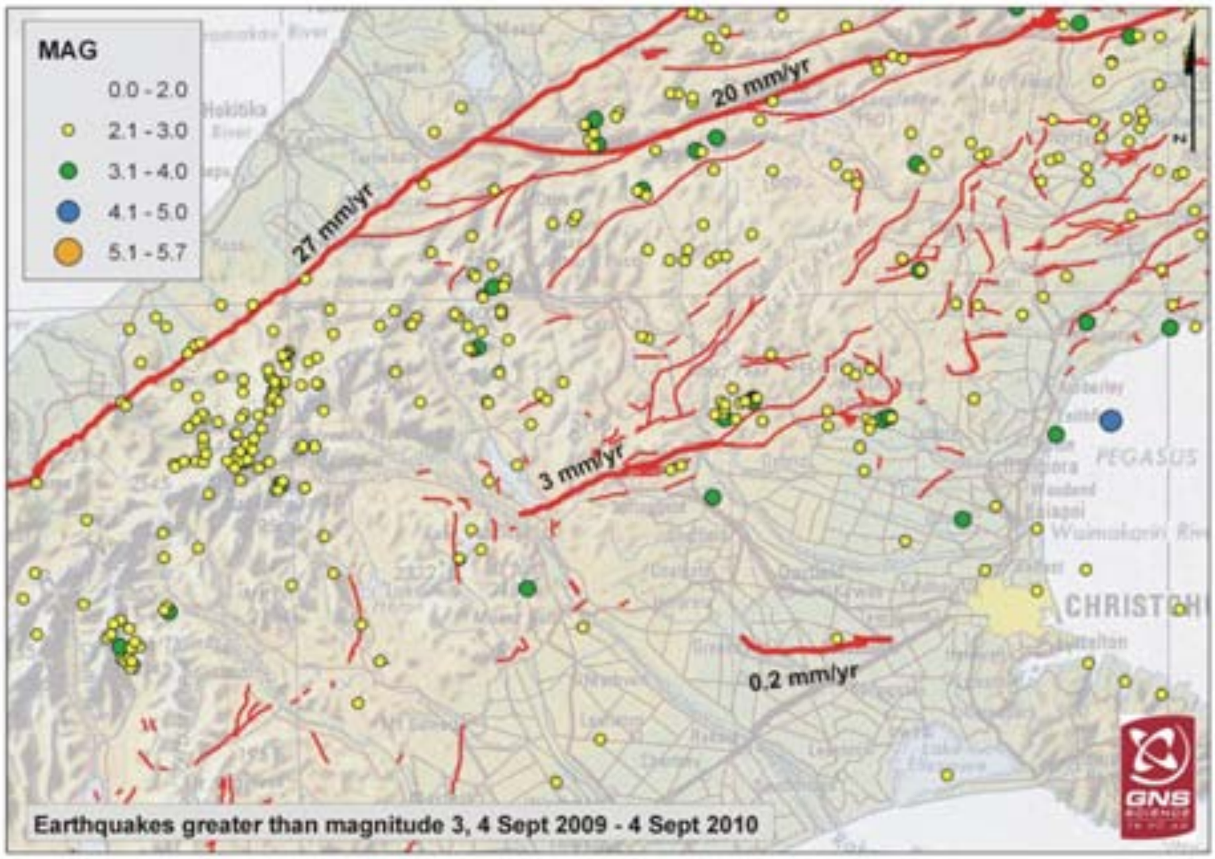


*Figure 2-2. Map of Canterbury Area with Slip Rates of Selected Faults and Earthquake Epicenters, 2009-2010*

Figure 2-3 shows the locations of the main shock (indicated) and aftershocks of the September 4 2010 earthquake. Figure 2-4 shows the February 22 2011 and June 13 2011 earthquakes and their aftershocks through June 20 2011. Figure 2-5 shows the epicenter of the June 13 2011 earthquake.

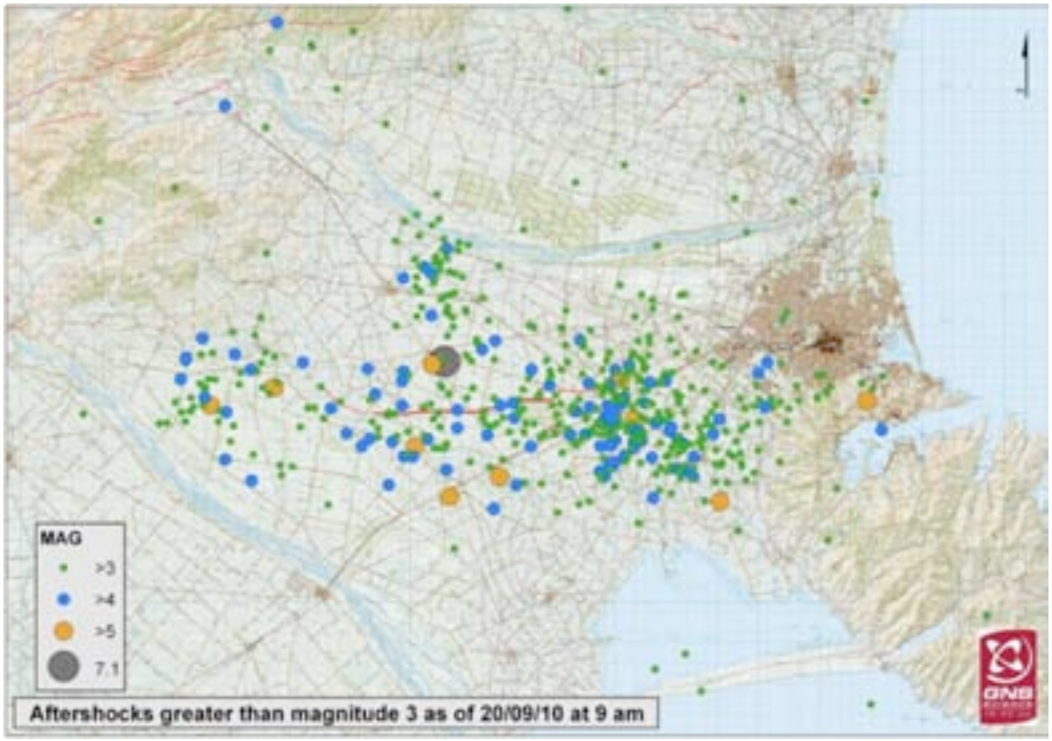


*Figure 2-3. Map of Main Shock and Aftershocks of the September 4 2010 Earthquake*

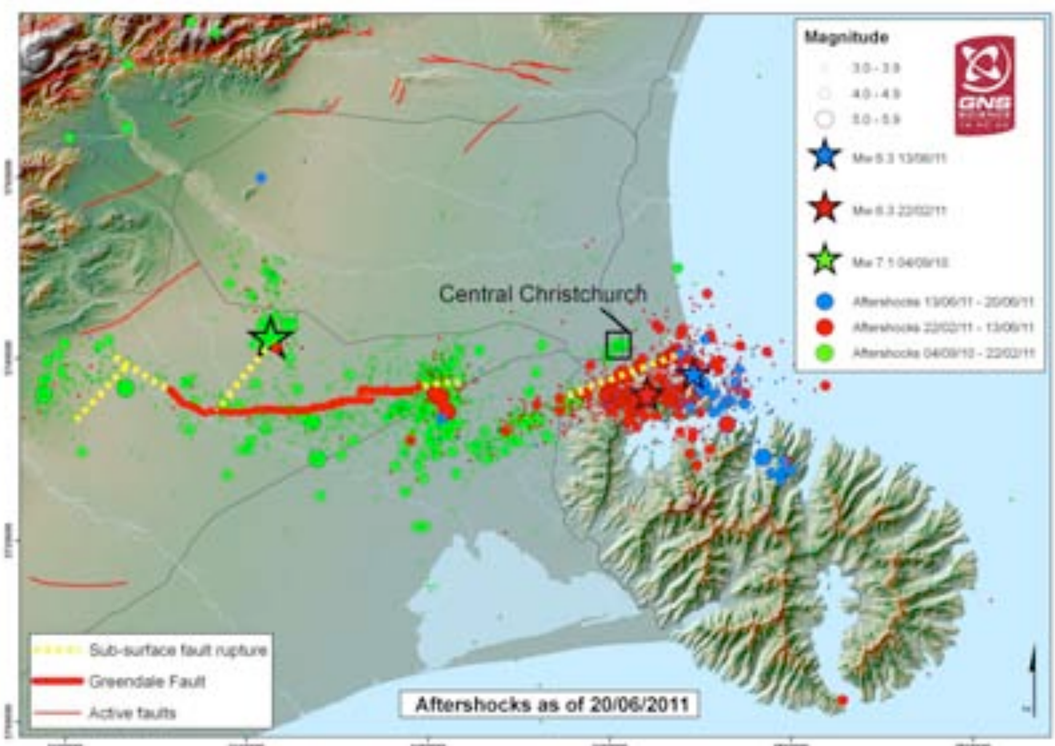


*Figure 2-4. Sept 2010 (Yellow), Feb 22 2011 (Red) and June 13 2011 (Blue) Earthquakes and Aftershocks*

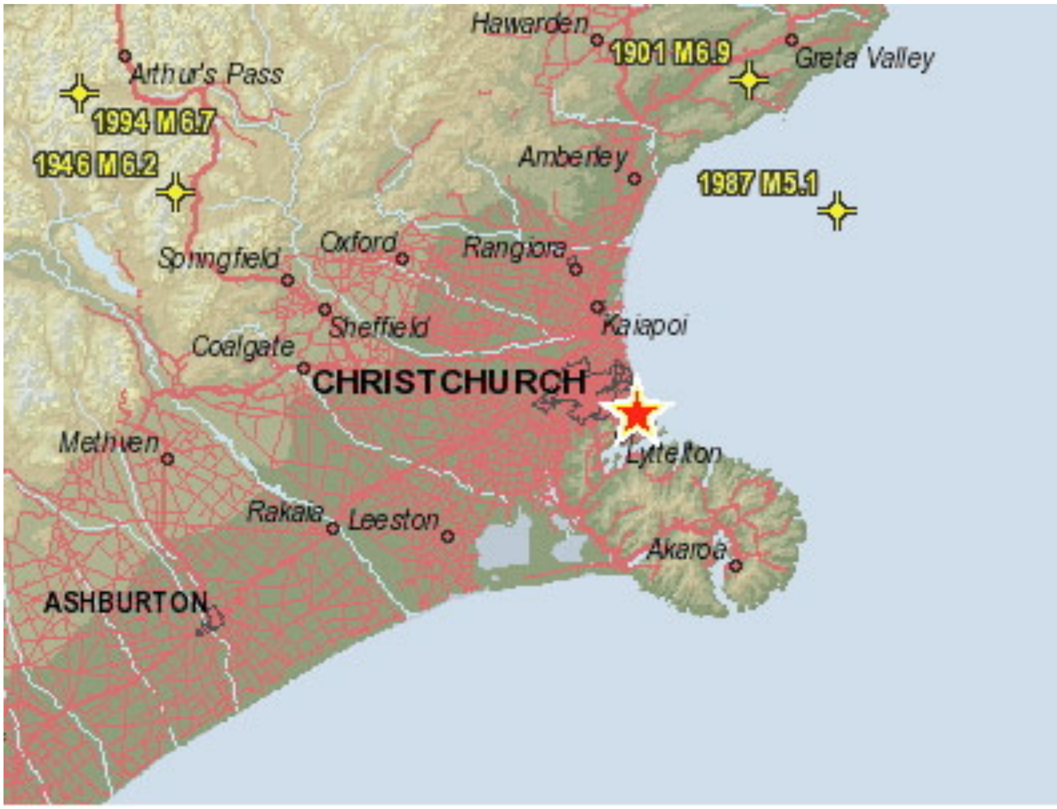


*Figure 2-5. Epicenter of June 13 2011 Earthquake*

A fourth notable earthquake occurred on December 22, 2011 at 1:58 pm local time. Figure 2-6 shows the epicenters of the main shock (M 5.8) and aftershocks (M 4 to M 6) that occurred in the first few hours after the main shock. The earthquakes, being east of the city, produced little damage, but again triggered liquefaction in the eastern part of the city.

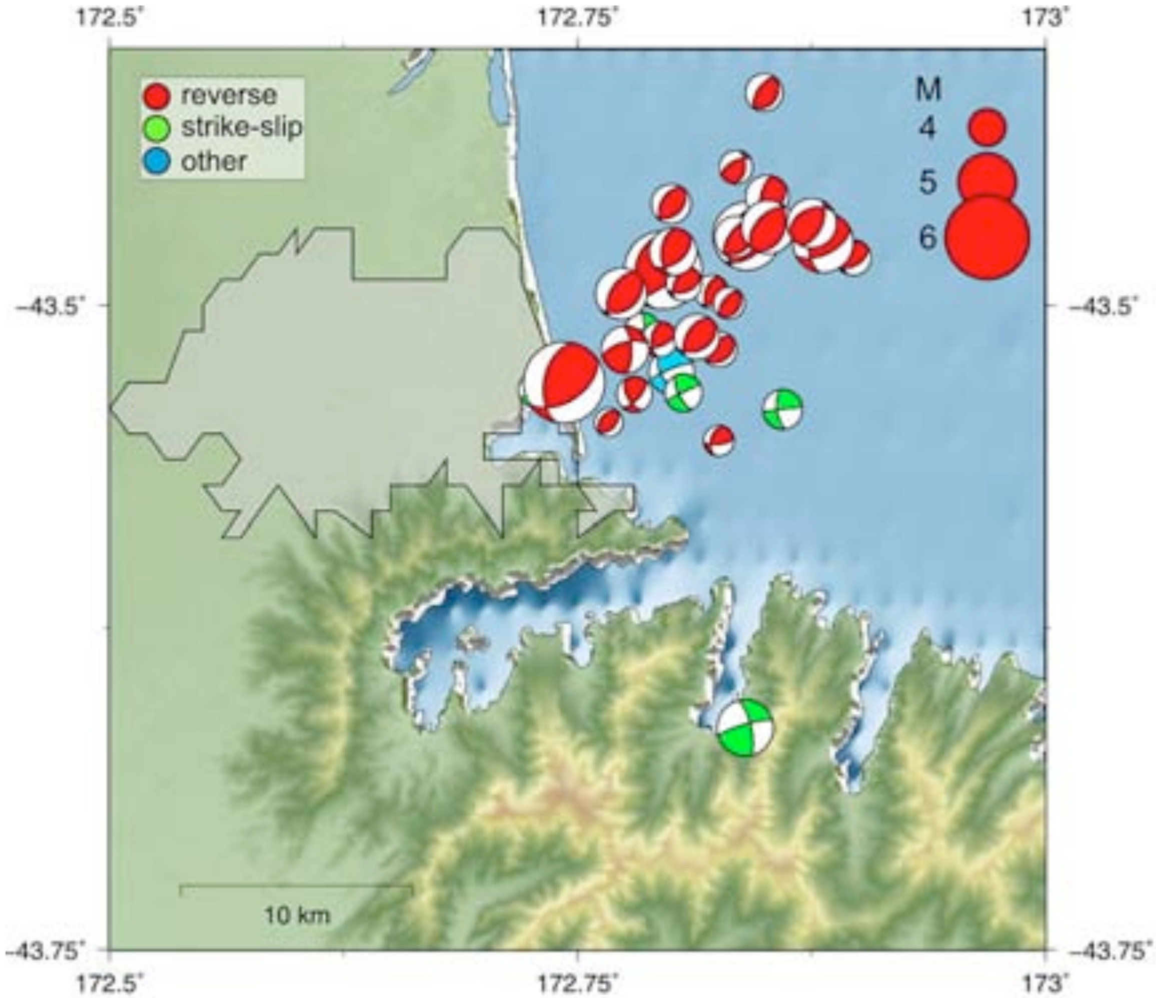


*Figure 2-6. Epicenters of December 22 2011 Earthquake and Aftershocks*

## 2.2 Geologic Setting

Figure 2-7 shows the soil groups for the province of Canterbury (areas in dark grey are un-mapped). The heavy red line indicates the approximate location of rupture for the Septtember 2010 event.

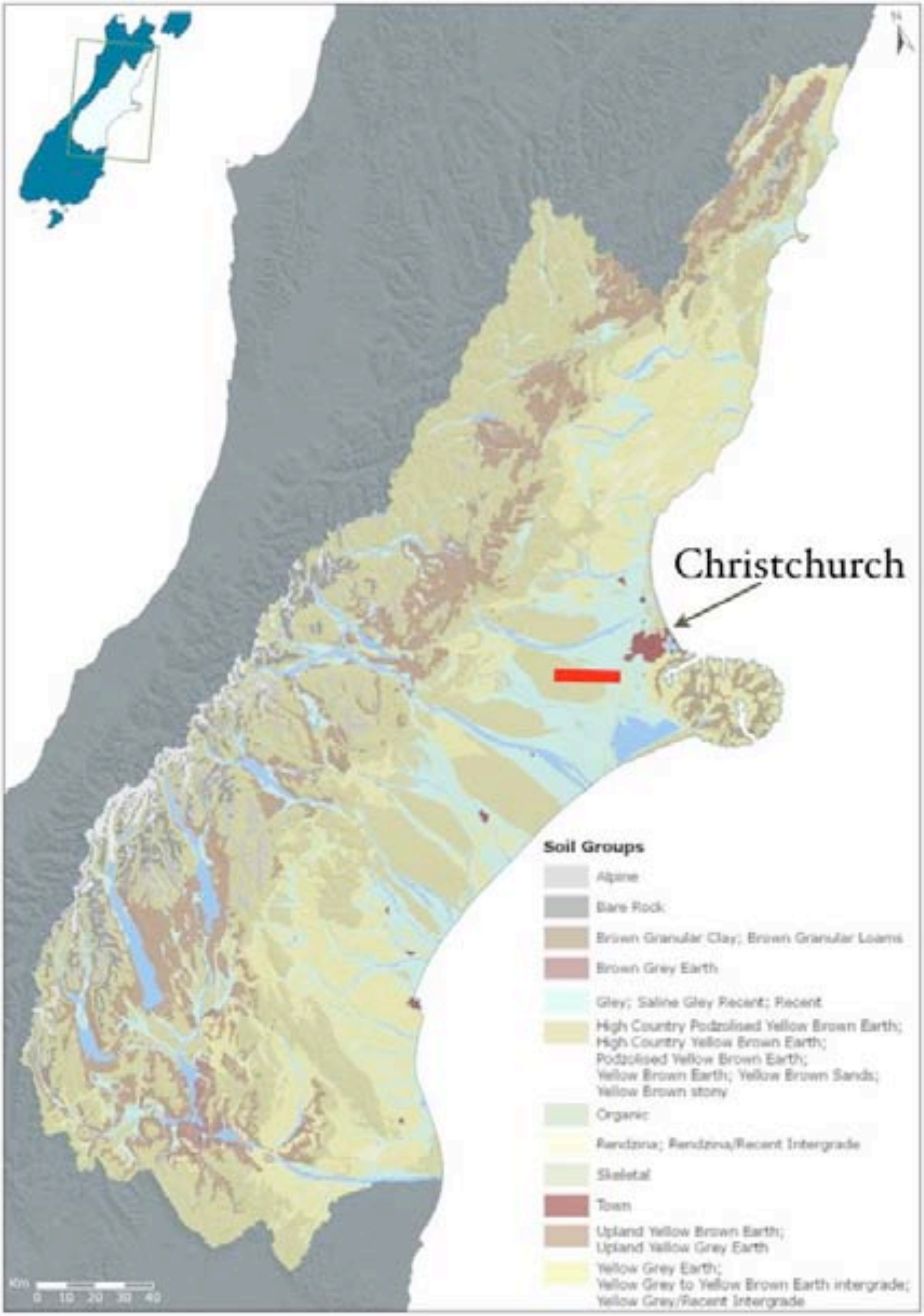


*Figure 2-7. Soil Group Map for Canterbury*

The Canterbury Plains generally consist of alluvial sand, silt and gravel 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 2-8. 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.

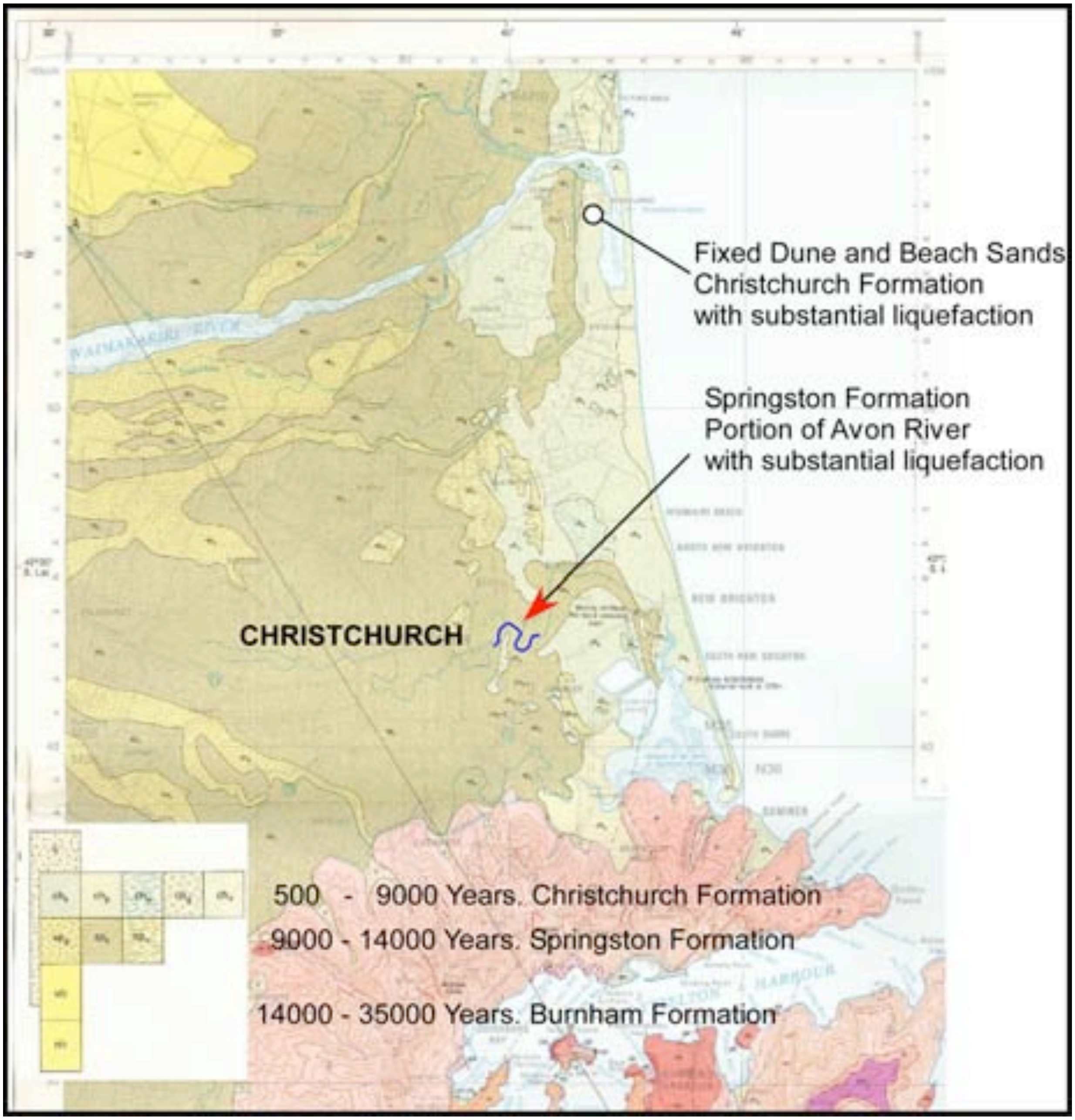


*Figure 2-8. Regional Geologic Map (Adapted from Sewell et al, 1993)*

The geology of Christchurch has been described by Brown and Weeber (1992).

Christchurch is located on Holocene deposits (last 14,000 years) at the Pegassu Bay coast of the Canterbury Plains, and the northern slopes of the adjacent Port Hills of the Banks Peninsula.

Originally the site of Christchurch was mainly swamp lying between beach dune sand, estuaries and lagoons; and gravels, sand and silt of river channel and overbank flood deposits of the coastal Waimakariri River floodplain. The Avon and Heathcote rivers meander through the city to form the main drainage system.

Loess mantles the Port Hills on the northern rim of the Lyttleton Volcano.

## 2.3 Earthquake Sequence

On September 4, 2010 at 4:36 (local time) a M 7.1 earthquake ruptured the Canterbury Plain. The rupture was primarily from strike slip strike-slip faulting, but overall has complicated features of several source types. The fault that ruptures was previously unknown and is now named the Greendale fault. As shown in Figure 2-4 and 2-5, the epicenter was located near the center of the fault rupture, and the rupture propagated away from the epicenter in the east and west directions. As indicated in Figures 2-4 and 2-5, the aftershock sequence from this rupture migrated toward the east over time. Aftershocks started occurring immediately below the City of Christchurch.

On February 22, 2011 at 12:52 PM (local time) a M 6.3 earthquake occurred on a previously unknown blind thrust fault located below the Port Hills, as shown in Figure 2-8. This earthquake epicenter is located south of Christchurch as shown in Figure 2-4. Whether this event is an aftershock of the September 4 2010 event, or a separately triggered event, is perhaps a matter of semantics. This earthquake is characterized as a reverse thrust event with a slight oblique movement. As shown in Figure 2-9, the rupture was oriented toward the Christchurch Central Business District, which sent large energy pulses into the urbanized region. The hypocenter was about 7 km deep. The fault rupture apparently did not reach the ground surface; it stopped approximately 1 km below the ground surface; but recent mapping of the damage to a water reservoir in the Port Hills clearly shows some linear trend of surface deformation; possibly a landslide scarp.

On June 13, 2011, a M 6.0 event occurred on what appears to be an extension of the fault that ruptured on February 22, 2011. The fault mechanism was primarily strike-slip. The earthquake did not rupture the ground surface.

Each of these earthquakes has caused a notable amount of damage to the city of Christchurch and other developed areas in the Canterbury Plains. A number of other aftershocks have also caused measurable damage, but will not be reported herein.

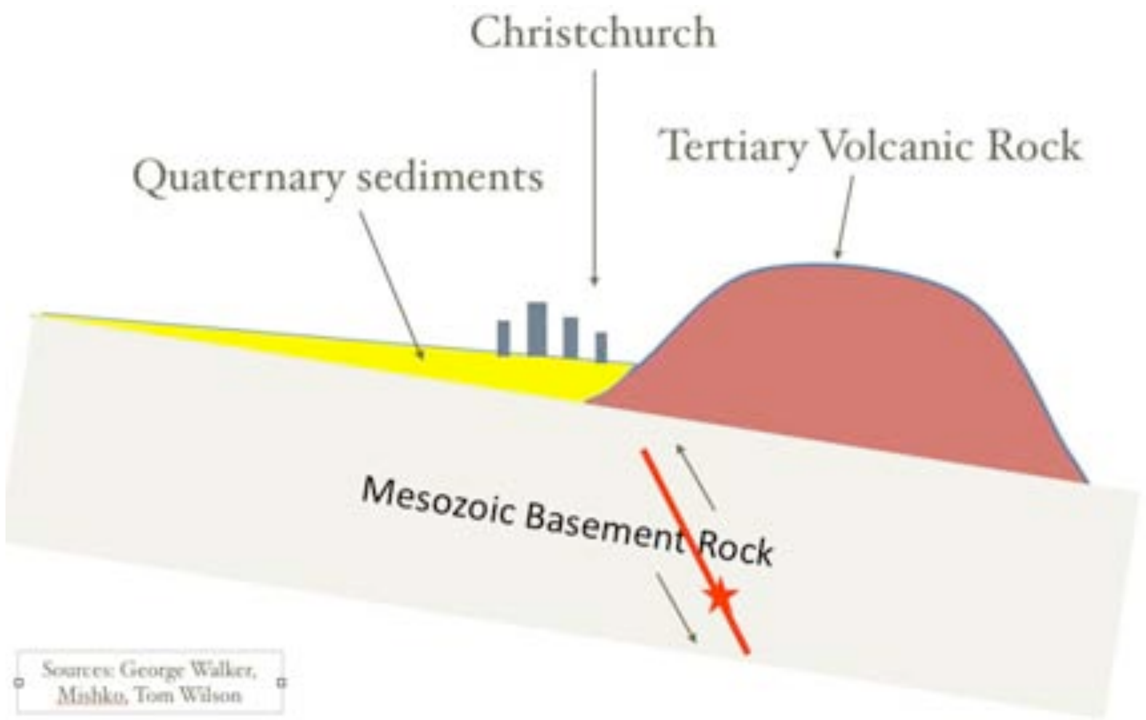


*Figure 2-9. Cross section, February 22, 2011 Fault Rupture (Looking Northeast)*

The earthquake magnitudes reported herein are based on information provided by the United States Geologic Survey using the moment magnitude scale. The GNS in New Zealand are reporting slightly different earthquake magnitudes, Table 2-1. To help distinguish between the three events in this report, we use the **bold** values for each event; it is recognized that with further study, the assigned magnitudes for each event may be varied.

| Earthquake Event | USGS Reported Moment Magnitude | GNS Reported Magnitude |
|---|---|---|
| September 4, 2010 | 7.0 | **7.1** |
| February 22, 2011 | 6.1 | **6.3** |
| June 13, 2011 | **6.0** | 6.3 |
| December 22, 2011 | | 5.8 |

*Table 2-1. Earthquake magnitudes*

## 2.4 Ground Shaking

Figure 2-10 shows a map of the area along with instrumented ground recordings for the September 2010 event.

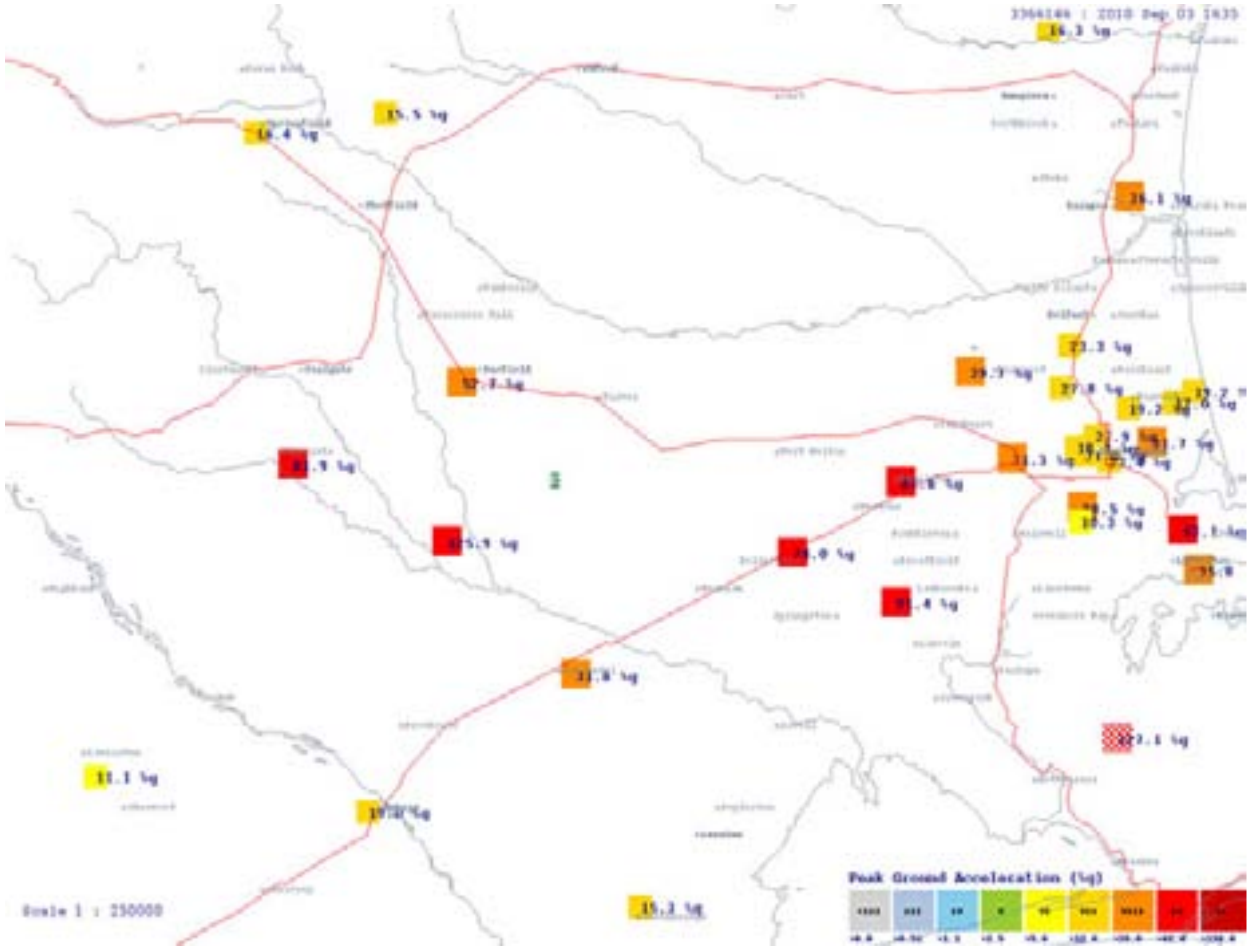


*Figure 2-10. Ground Motion Instruments, September 4 2010 (PGA)*

Ground motions in the urbanized areas on the right side of Figure 2-10 were commonly in the range of horizontal peak ground acceleration (PGA) of between 0.18g 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 0.90g, 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 duration of strong ground shaking for an M 7+ event is short, 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 2-11 shows the ground motions (highest horizontal direction) from the February 22, 2011 event. The motions in the Port Hills area southeast of the central business district were commonly recorded as PGA = 0.9g or higher (hanging wall side of event). In the central business district, recorded ground motions were typically around PGA = 0.5g (footwall).

Figure 2-12 shows a comparison of PGA between the September 2010 (value to the left) and February 2011 earthquakes (value to the right). As seen in Figures 2-11 and 2-12, the PGA values recorded for the M 6.3 earthquake are quite large. As indicated in Figure 2-12, the peak ground shaking recorded at the same sites were generally significantly larger in the smaller magnitude earthquake of February 2011. This is primarily a result of the fault rupture being closer to the recording instruments.

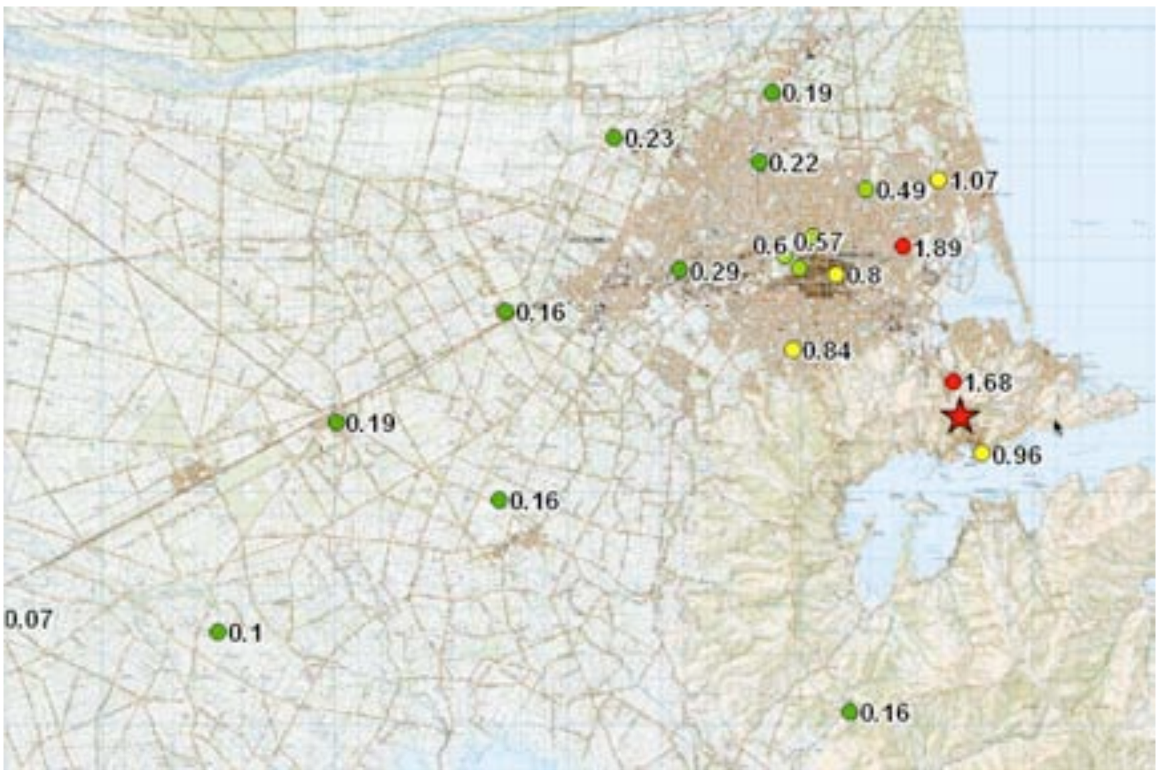


*Figure 2-11. Recorded Ground Motions (PGA), Feb 22 2011*

*Figure 2-12. PGA Comparison between September 4 2010 (left value) and February 2011 event (right value).*

Figures 2-13, 2-14 and 2-15 present the response spectra for recorded strong ground motions (M 7.1 event) in comparison to the design spectra for a 500-yr return interval earthquake at a Class D soft soil site in Christchurch. While a few engineered buildings in the central business district were damaged, none collapsed in the M 7.1 event; a few unreinforced masonry buildings did collapse in the M 7.1 event.

Spectral accelerations for the recorded motion in Figure 2-13 exceed 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 for the M7.1 event. 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 communications). These spectra also reflect strong ground motion pulses from the source rupture directivity. 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.

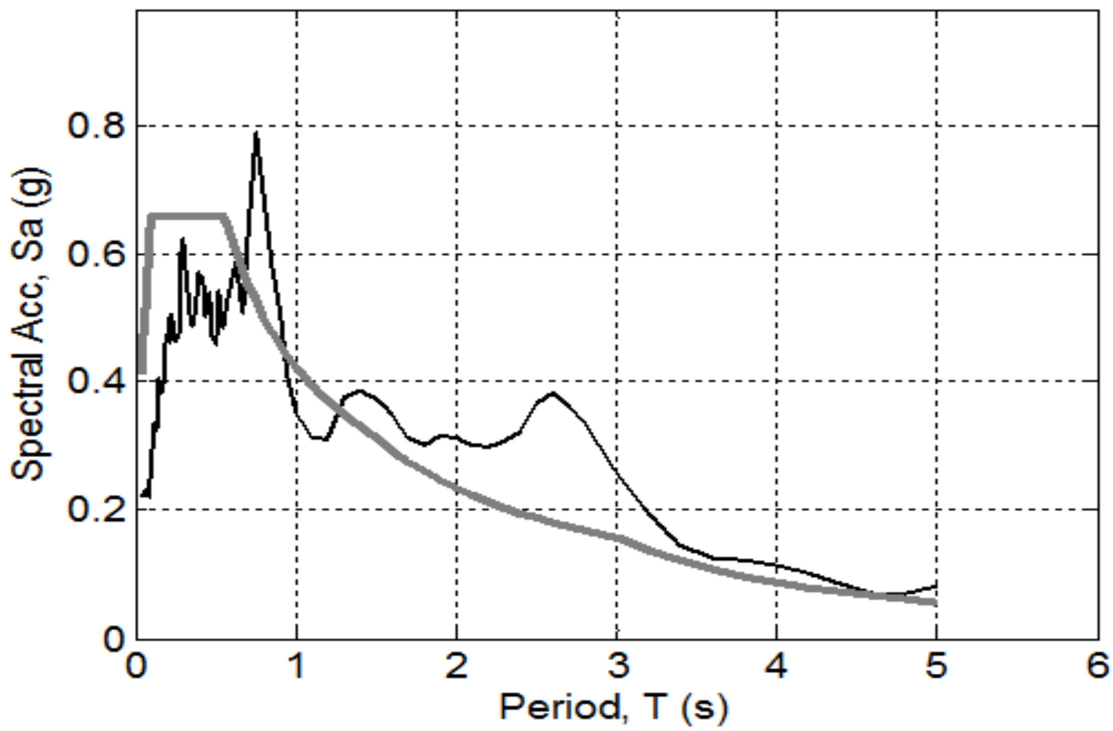


*Figure 2-13. Horizontal Response Spectra (5% Damping), Design (smooth) and Recorded*

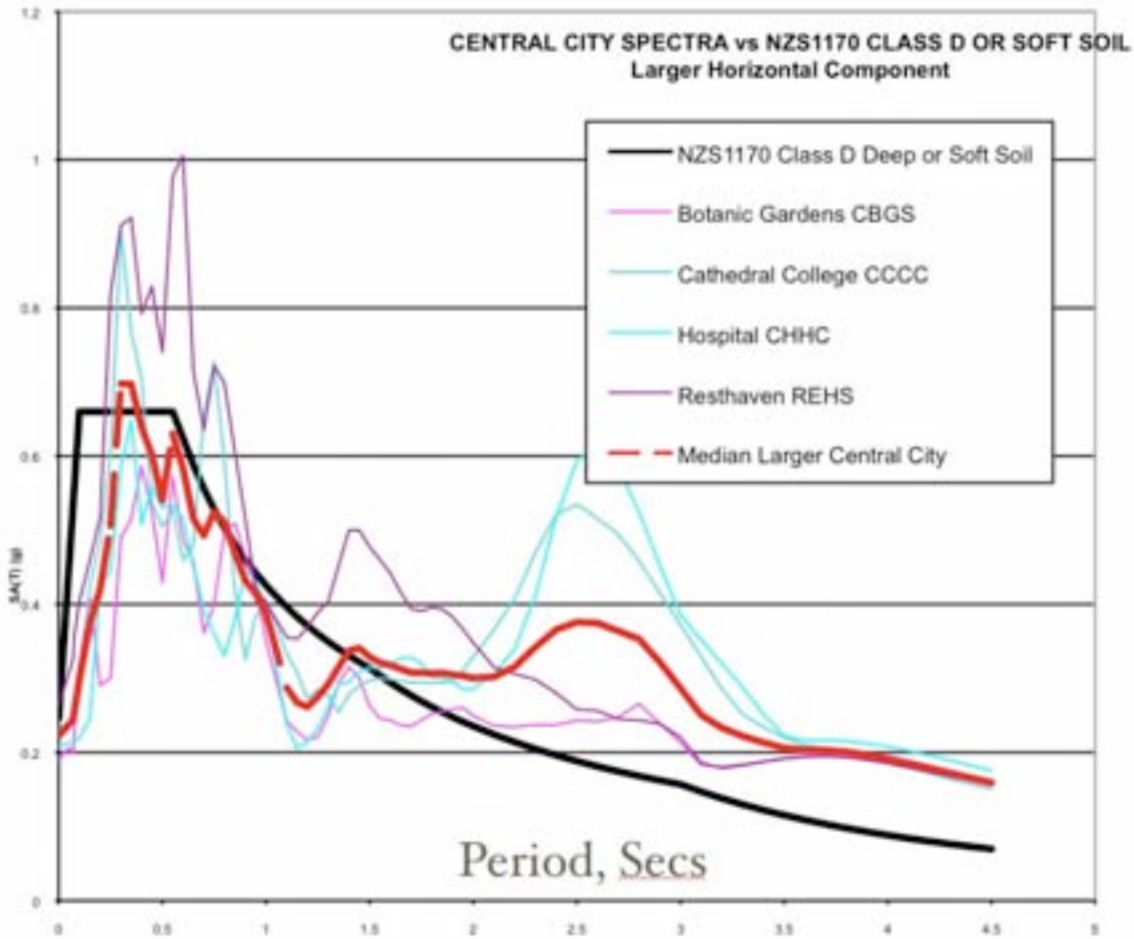


*Figure 2-14. Central City Horizontal Spectra vs. NZS 1170 Class D or Soft Soil*

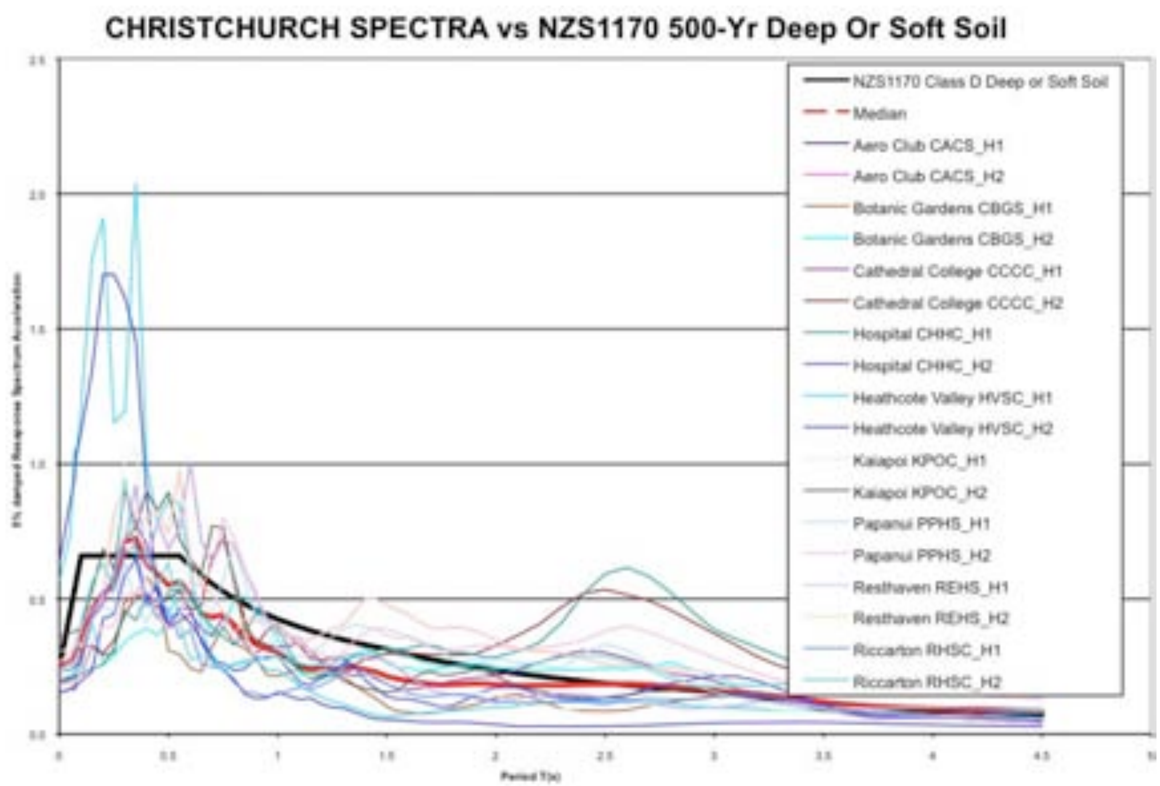


*Figure 2-15. Christchurch Horizontal Spectra vs. NZS 1170 500-Yr Deep or Soft Soil*

Figures 2-16, 2-17 and 2-18 compare the 5% damped response spectra and recorded acceleration time histories at the Christchurch Hospital (labeled CHHC) and Port of Lyttleton site (labeled LPCC). As seen in the spectra plots, the February 2011 earthquake recordings have spectral amplitudes greater than that from the September 2010 earthquake for nearly every period of response.  The time histories show a much longer duration of shaking at a smaller amplitude recorded in September 2010 as compared to that recorded in February 2011. Figure 2-18 is one of many instrumented sites that show similar trends in the recordings.

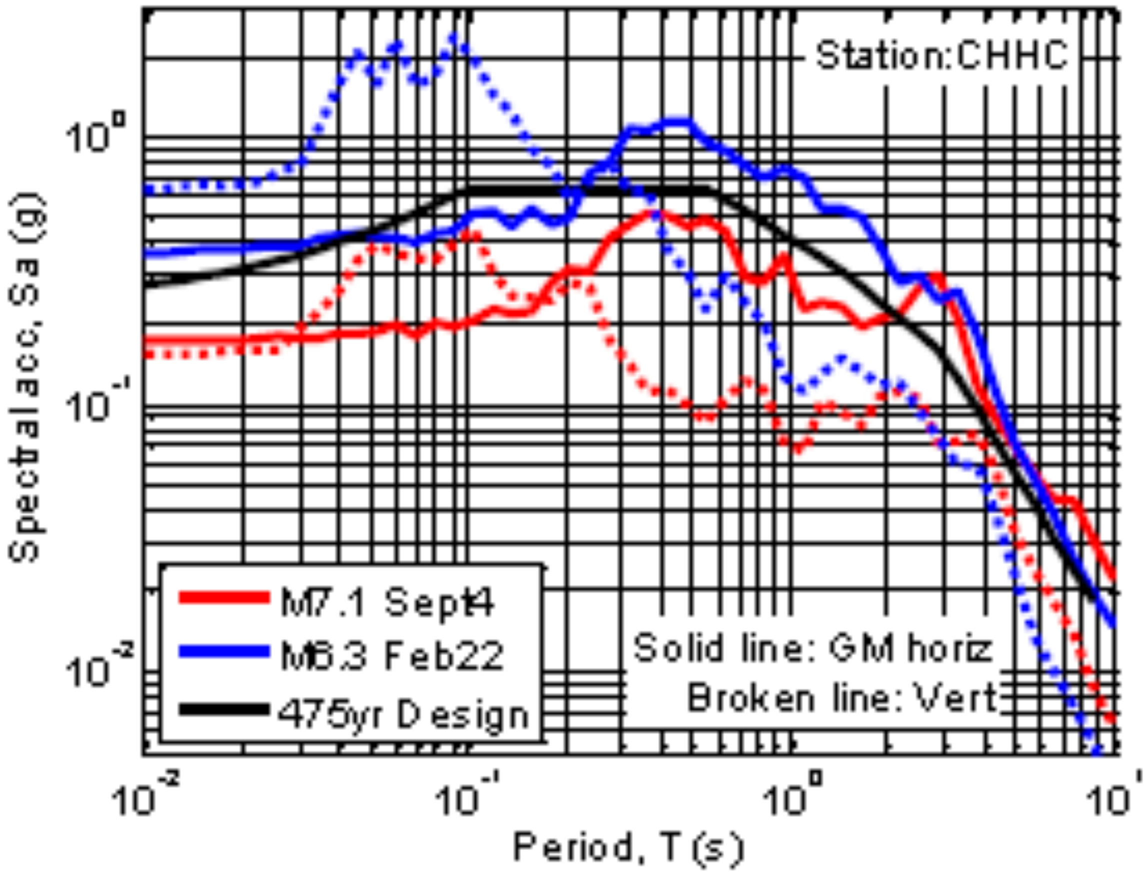


*Figure 2-16. Comparison of Response Spectra between February 2011and September 2010 Earthquakes (source Brendon Bradley, GNS). Soil site, Christchurch Hospital.*

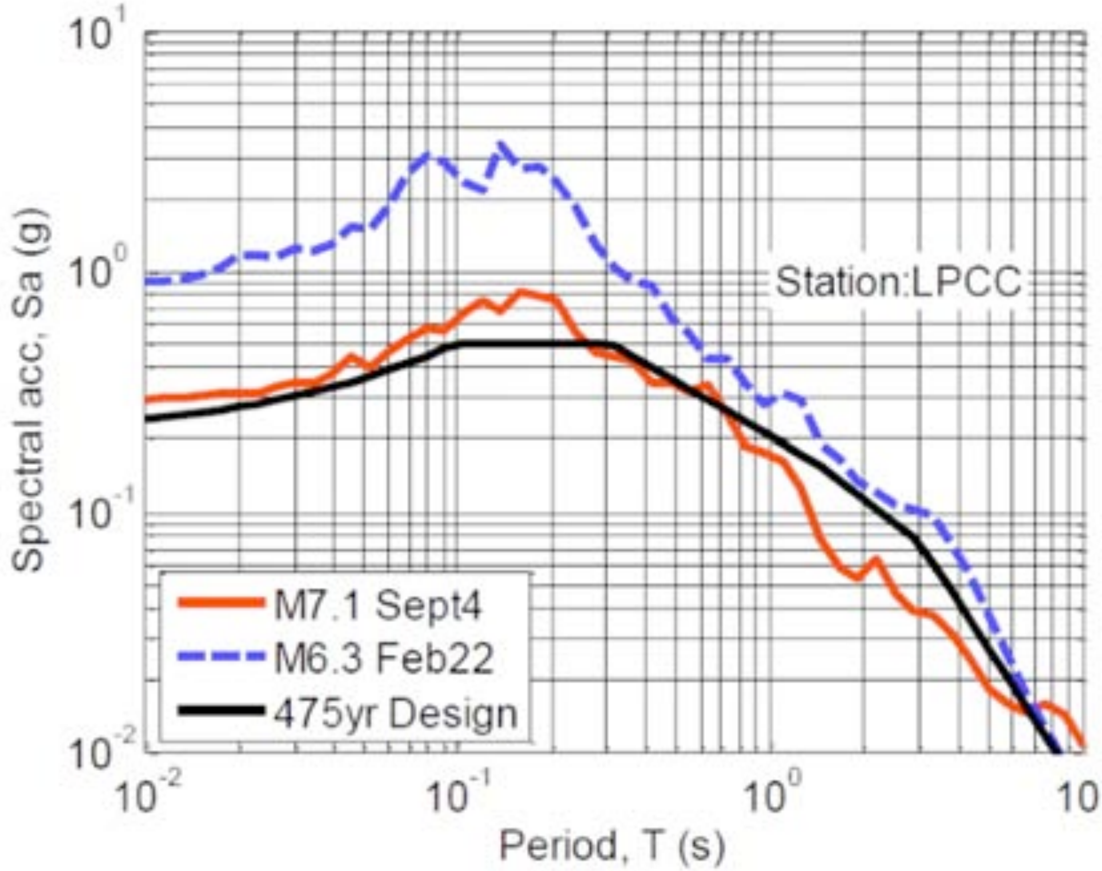


*Figure 2-17. Comparison of Response Spectra between February 2011and September 2010 Earthquakes (source Brendon Bradley, GNS). Rock site, Port of Lyttleton.*

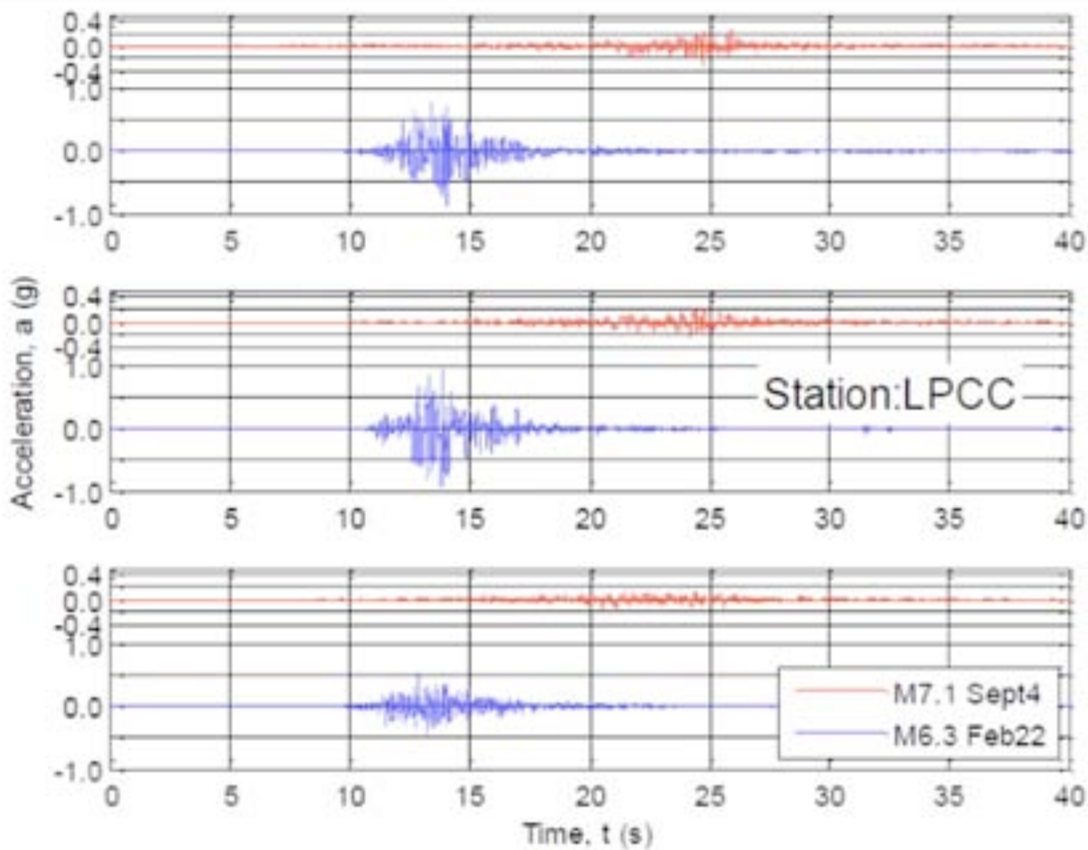


*Figure 2-18. Comparison of Response Spectra and acceleration time history recordings between February 2011 and September 2010 Earthquakes (source Brendon Bradley, GNS)*

Figure 2-19 shows a comparison of time histories recorded during the February 22, 2011 earthquake for a site on rock (Lyttleton Port, top) and another site on soil (Christchurch Hospital, bottom, located on soil, southwest corner of central business district). These time histories show the effect of forced vibration (first 5 seconds of strong ground shaking) of the fault rupture directivity pulse, followed by free vibration of the soils (about 5 cycles of extra strong ground motion at the hospital location) thought to represent waves trapped in the sedimentary basins.

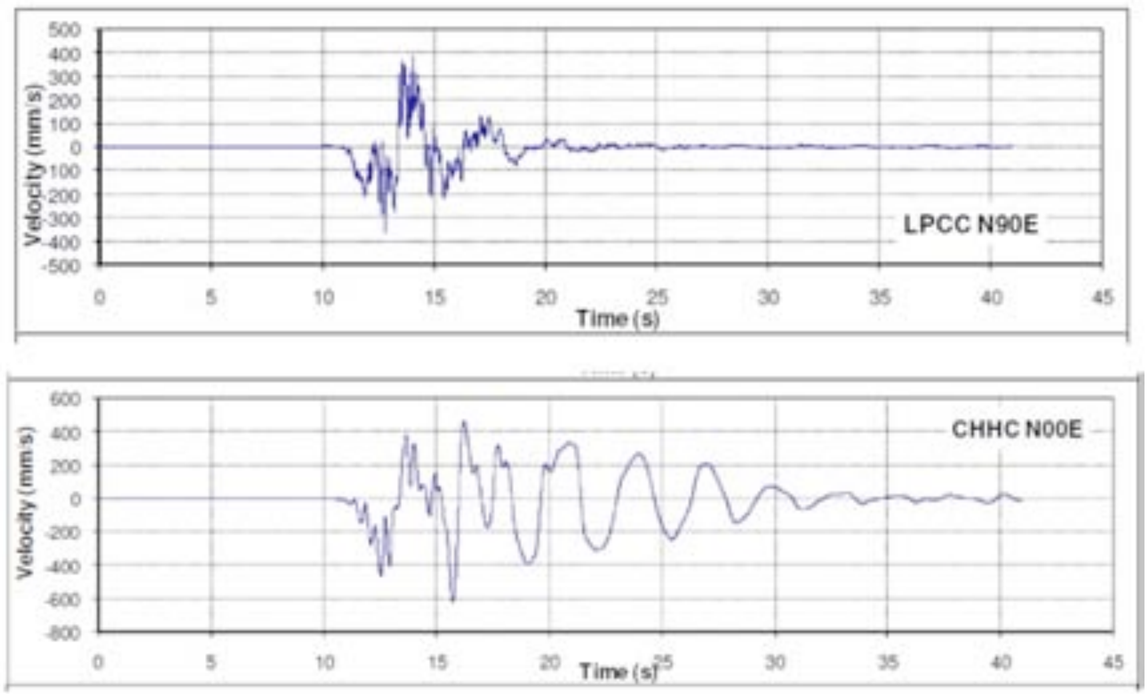


*Figure 2-19. Recorded Ground Motions (PGV), Feb 22 2011*

Figure 2-20 shows the recorded PGA values for the June 2011 event. PGAs in the Port Hills area were on the order of PGA = 0.50g+; motions in eastern Christchurch were on the order of PGA = 0.35g+; motions in the CBD of Christchurch were on the order of PGA = 0.20g.

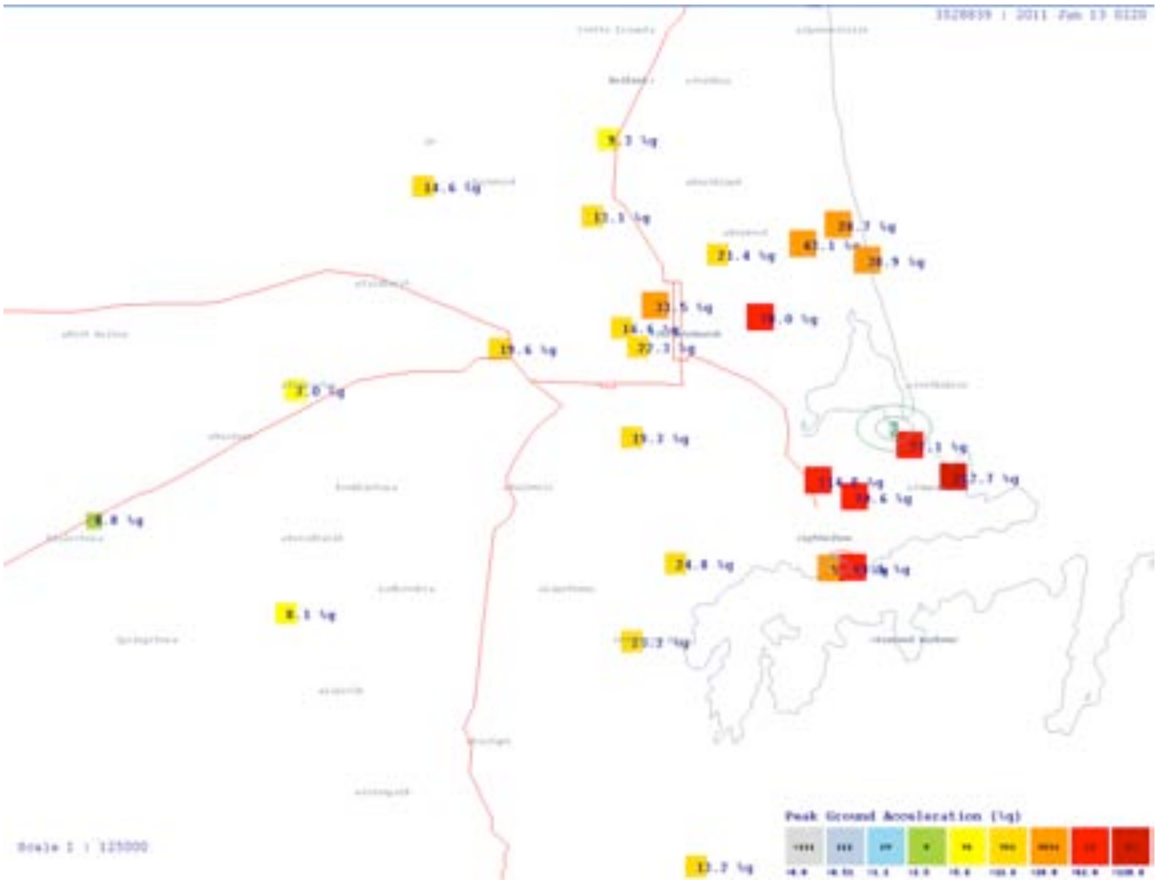


*Figure 2-20. Recorded Ground Motions (PGA), June 13 2011*

Figure 2-21 shows the recorded PGA values for the M 5.8 December 22, 2011 event. PGAs in the eastern suburbs were on the order of PGA = 0.35g to 0.98g; motions in the CBD of Christchurch were on the order of PGA = 0.15g to 0.20g. Figure 2-22 shows the recorded PGA values for the M 6.0 December 22, 2011 aftershock. PGAs in the eastern suburbs were on the order of PGA = 0.34g to 0.66g; motions in the CBD of Christchurch were on the order of PGA = 0.15g to 0.25g.

Some previously-damaged buildings in the CBD collapsed due to the earthquakes on December 22 2011.

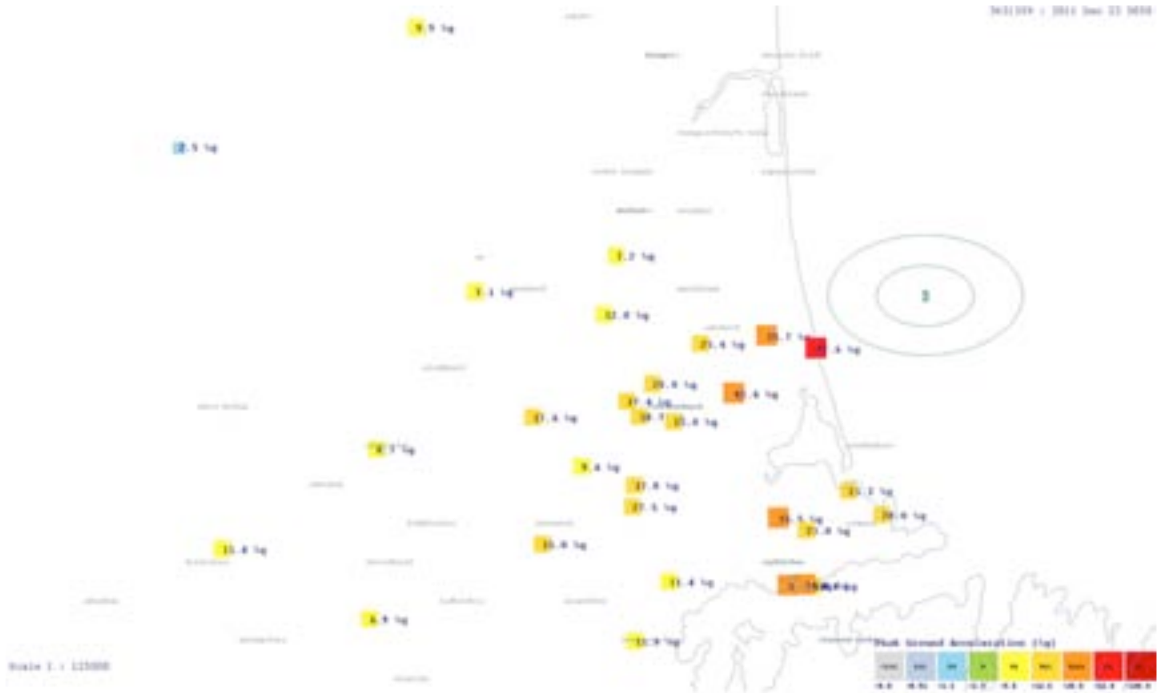

*Figure 2-21. Recorded Ground Motions (PGA), M 5.8 Mainshock, December 22 2011*

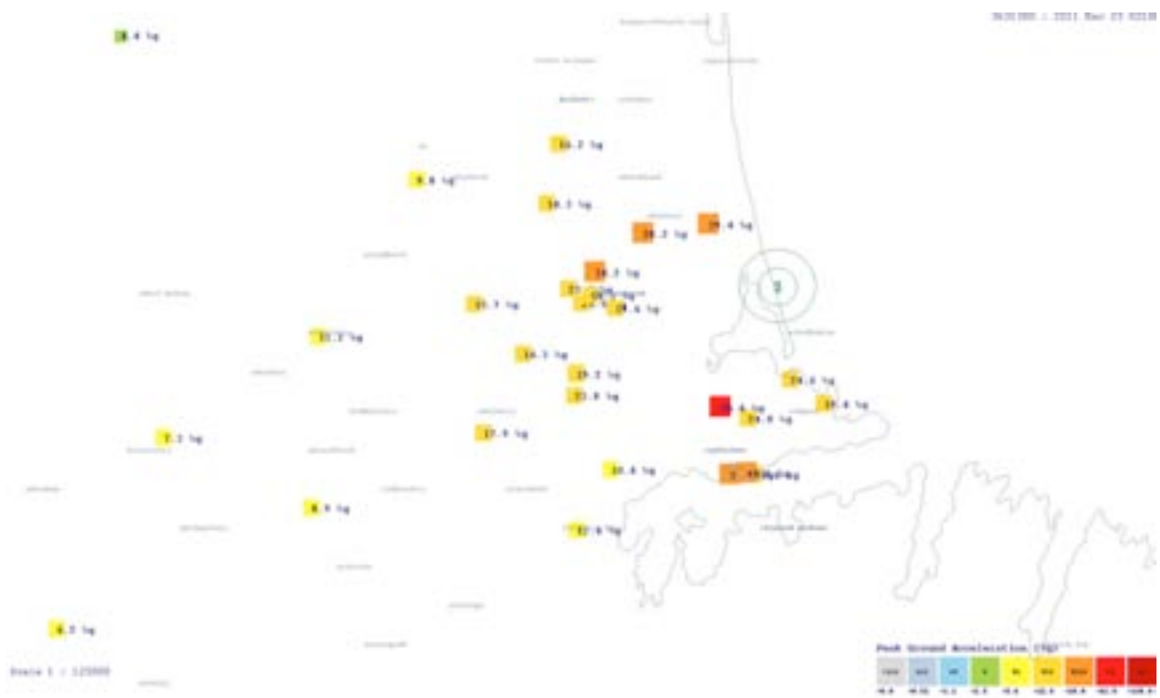

*Figure 2-22. Recorded Ground Motions (PGA), M 6.0 Aftershock, December 22 2011*

## 2.5 Fault Ground Surface Offset

The September 4 2010 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 2-23. 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.

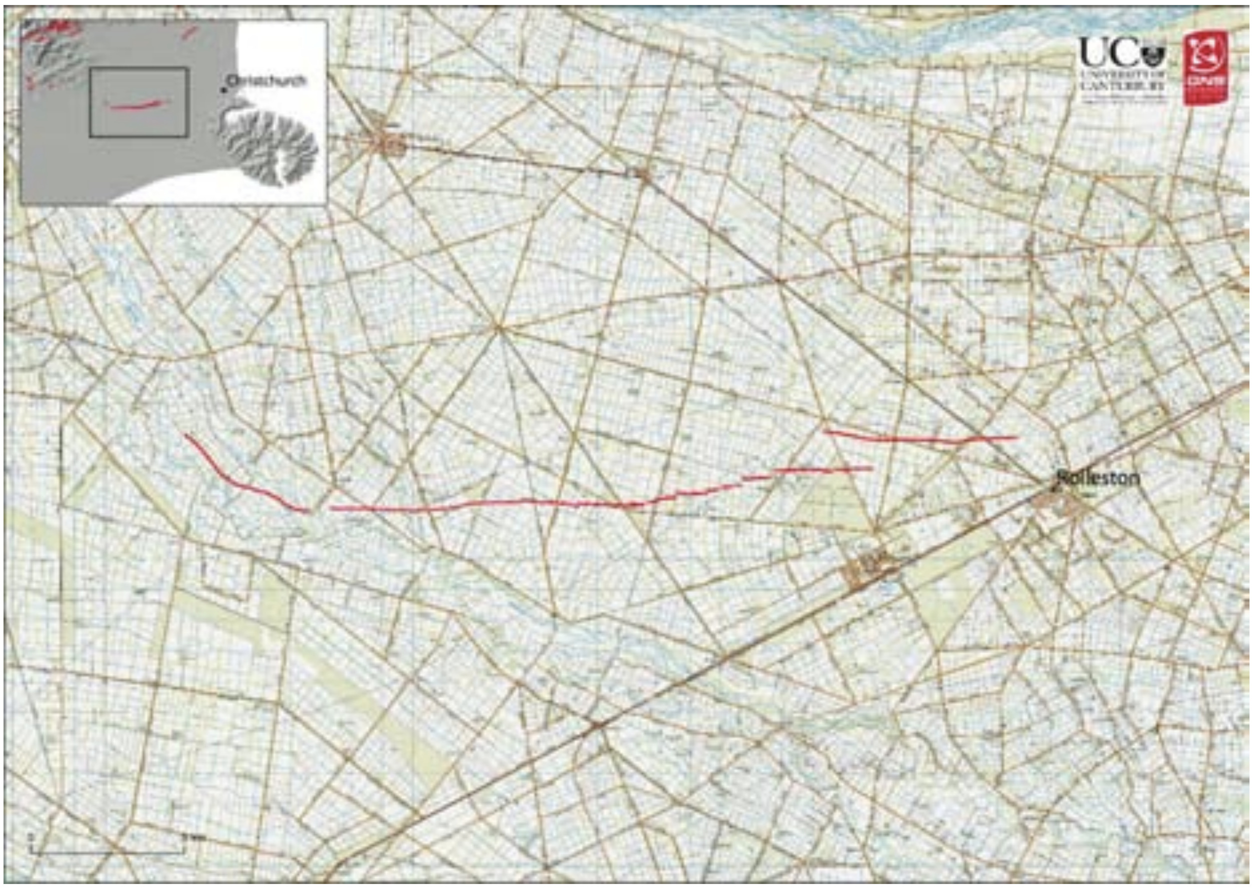


*Figure 2-23. Fault Rupture Map*

These offset amounts are the cumulative amounts as of about September 21, 2010 (Figure 2-24). Almost without doubt the original surface movement was lower than these values, and there was ongoing after slip that results in increasing amounts of total offset; as evidenced by the need to reset train track rails (see Section 12) over the fault, multiple times, in the weeks after the earthquake.

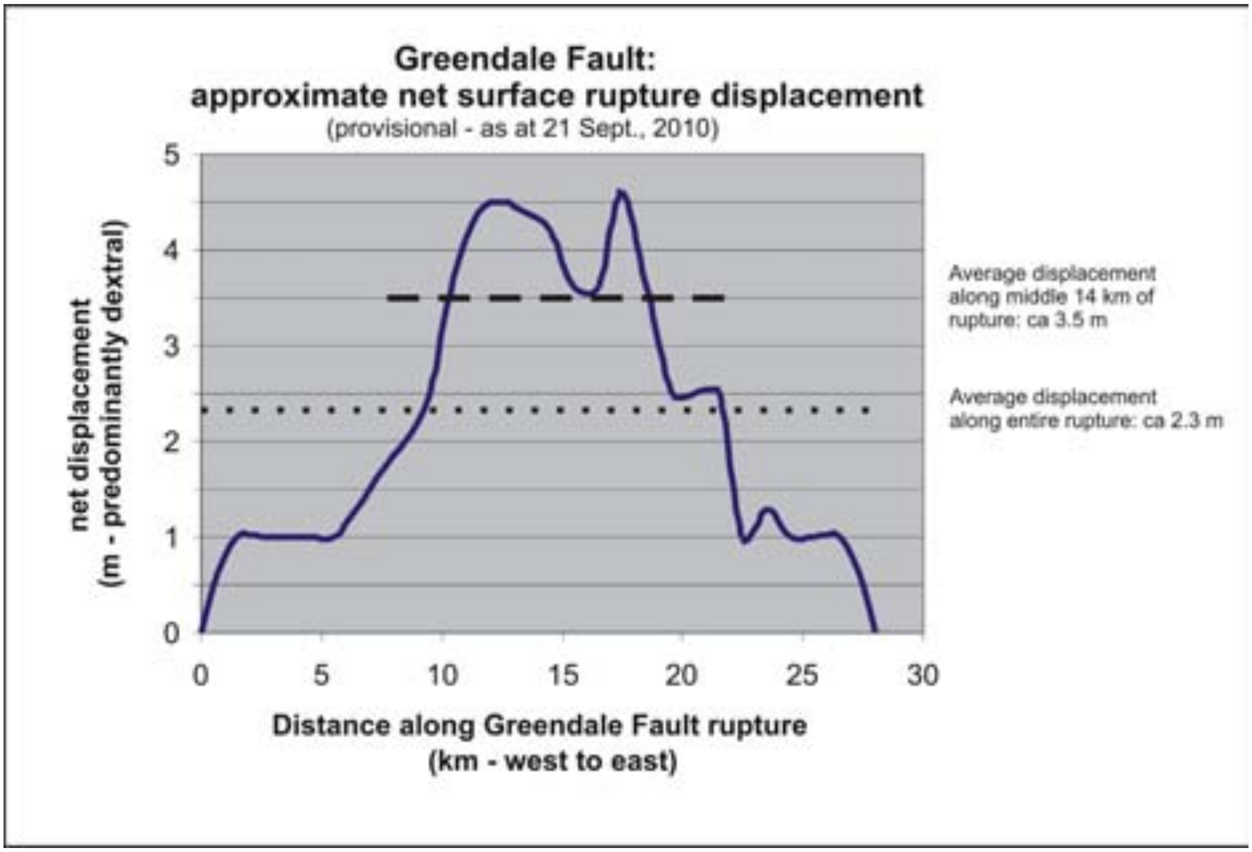


*Figure 2-24. Measured Fault Offset*

Figure 2-25 shows the right lateral offset of a country road. The road was straight prior to the earthquake. Figure 2-26 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 2-25. Fault Offset Through a Road*

*Figure 2-26. Fault Offset Through a Road, West of Rolleston*

Figure 2-27 shows the right lateral offset through a straight hedge. These hedges are used as wind barriers and are believed to have been originally laid out in straight lines.

*Figure 2-27. Right Lateral Fault Offset Through a Hedge*

Figures 2-28 to 2-31 show fault offset patterns that were quite common. While the sense of fault offset was generally right lateral, we observe in these photos that the local zone of deformation were commonly about 10 meters wide, and the azimuth of ground cracking is commonly offset 20 to 30 degrees from the general east-west right lateral sense of movement.

As the fault offset occurred in areas that were primarily farming, there was little (if any) buried infrastructure affected by fault offset.

Figure 2-31 shows one section of the fault offset zone with a Lidar map. Generally, the sense of offset was right lateral, but about 10% of the fault zone also had some vertical offset, commonly about 1 meter rise on the south side of the fault; in a few locations there were small vertical elevation gains on the north side of the fault.

*Figure 2-28. Right Lateral Fault with En-Echelon Cracks*

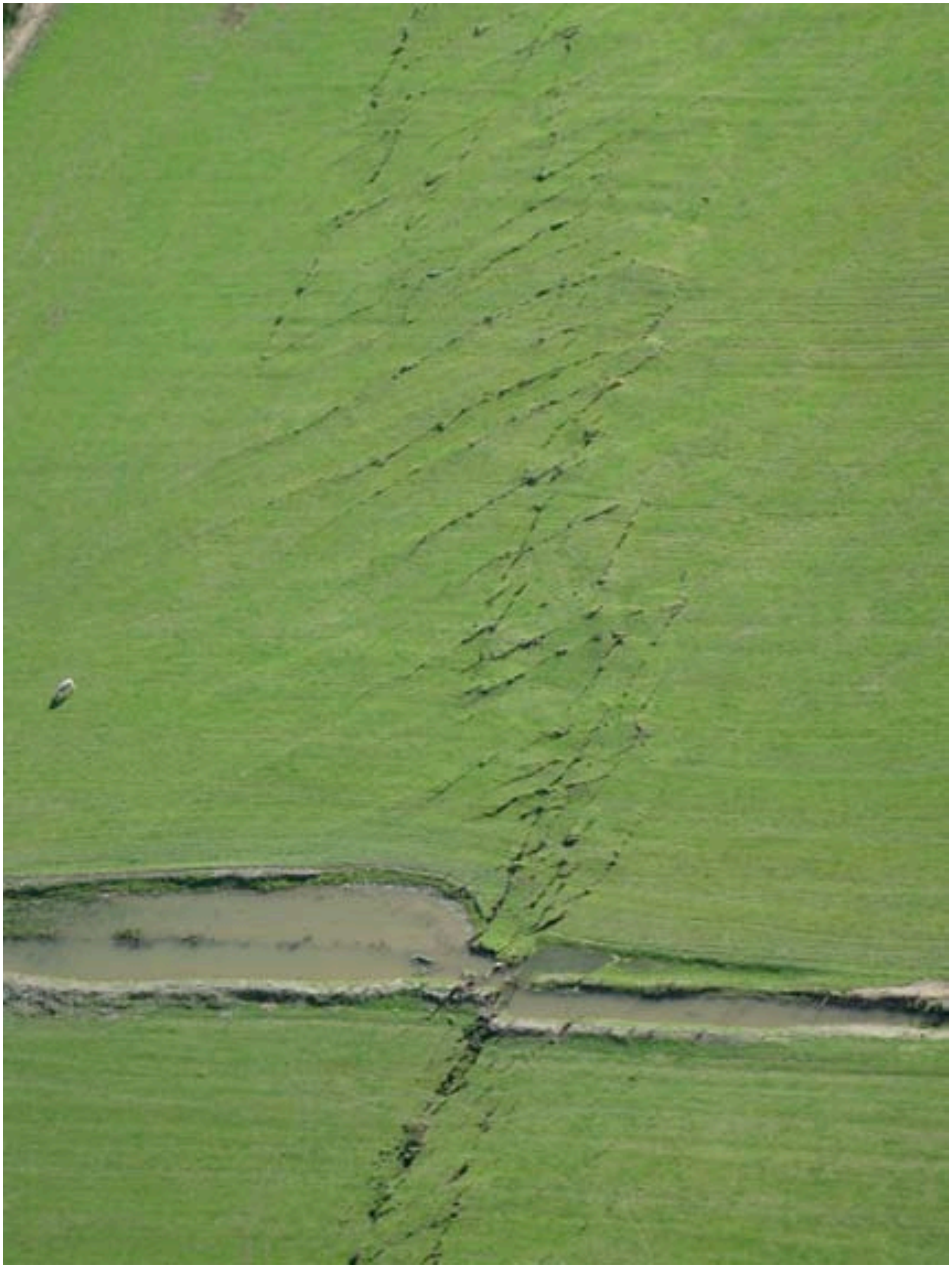

*Figure 2-29. Right Lateral Fault with En-Echelon Cracks (Quigley, Univ. Canterbury)*

*Figure 2-30. Right Lateral Fault with En-Echelon Cracks*

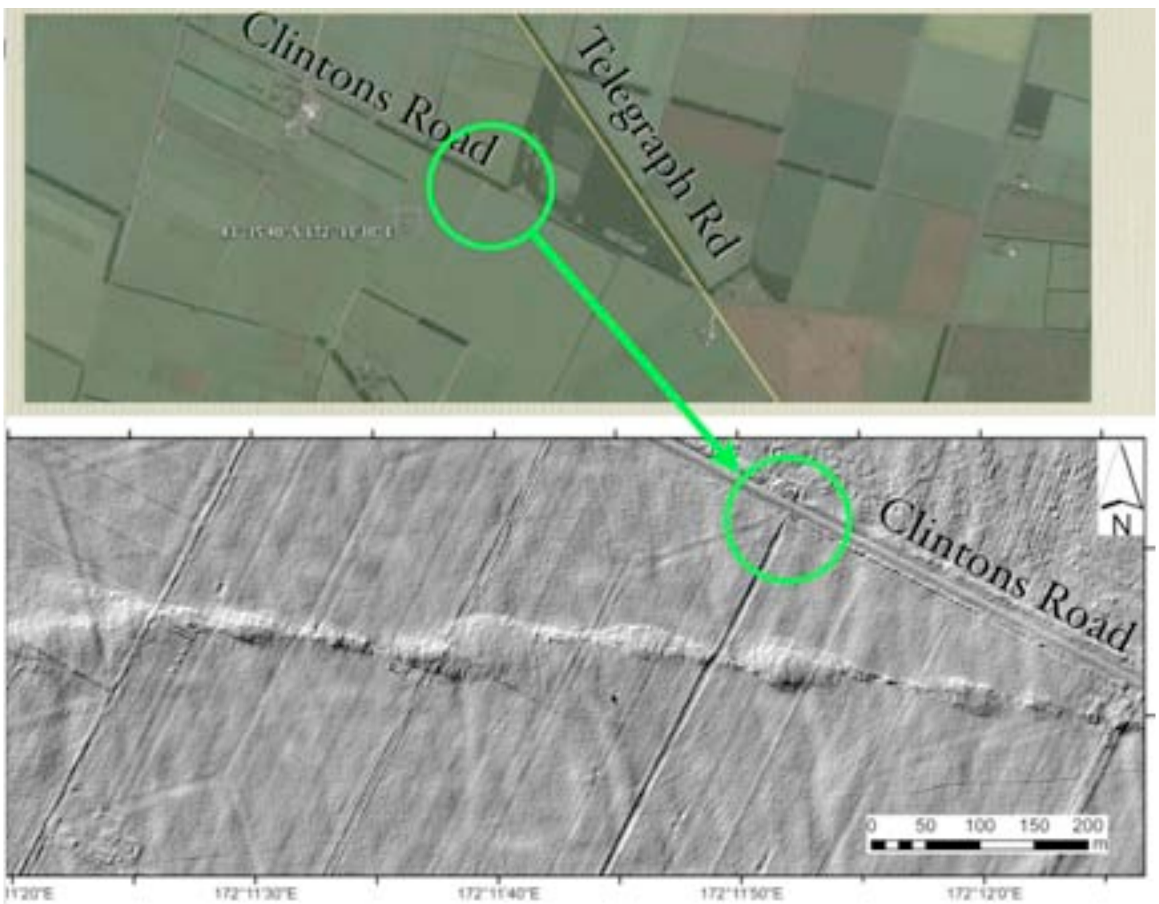


*Figure 2-31. Location Map (Upper) and Lidar Map of Fault Offset Zone (Lower)*

## 2.6 Liquefaction

A regional liquefaction hazard map was prepared in 2004 (Ecan, 2004), Figure 2-32. 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 2-32 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.

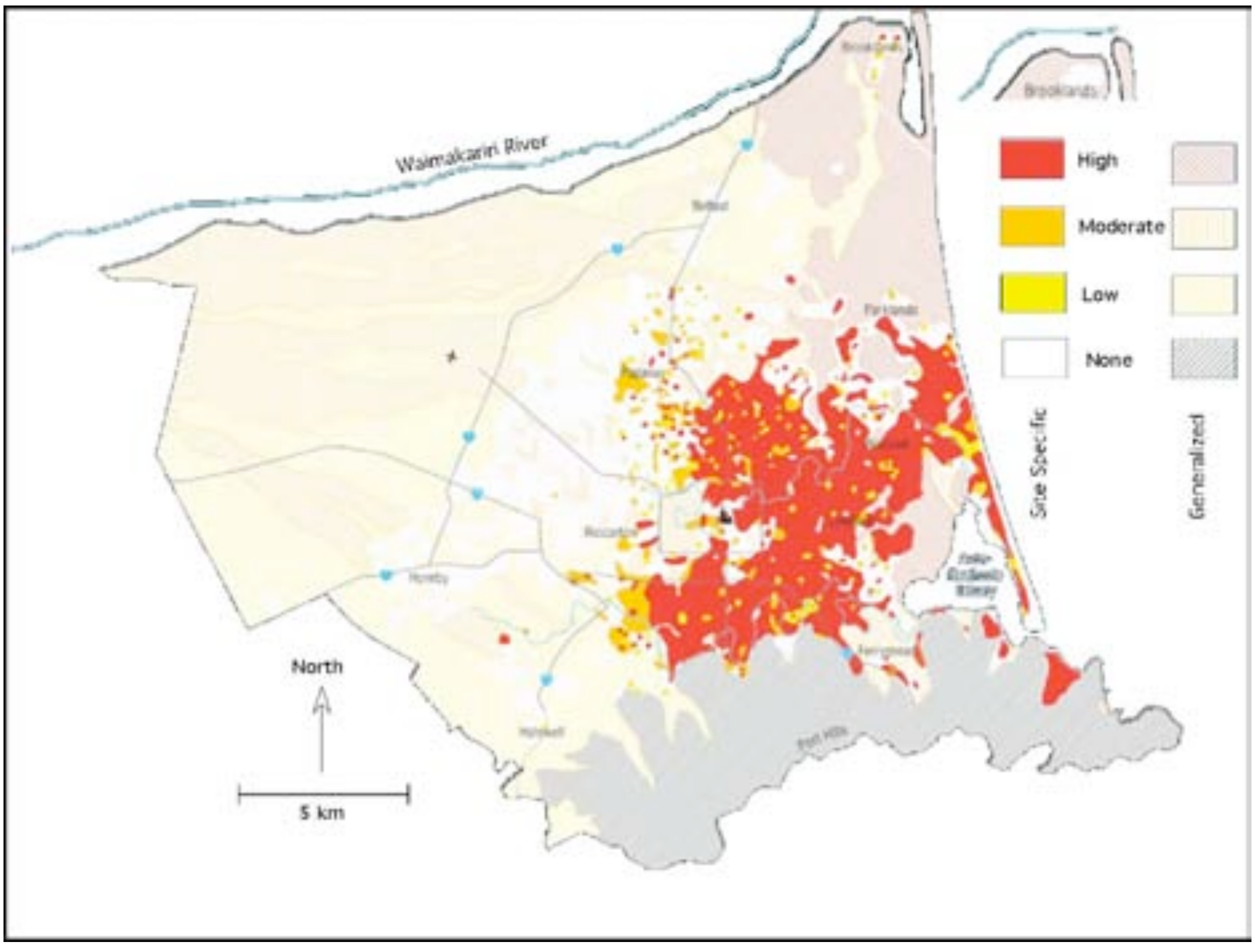


*Figure 2-32. Liquefaction Potential Hazard Map (adapted from Ecan, 2004)*

### 2.6.1 Liquefaction in September 4 2010 Event

Figure 2-33 shows the flooding due to the water ejected due to liquefaction. The "waves" caused by the movement of the vehicles can be clearly seen. The liquefaction induced ground movements also caused water and sewer pipes to break (see Sections 6 and 7), and also damaged artesian ground water wells, which inherently contributed to surface flooding. However, the liquefaction forced great volumes of water from the ground for very long periods of time and ultimately caused the flooding seen in Figure 2-33; this was repeated in the February 2011 earthquake, Figure 2-40.

*Figure 2-33. Flooding due to Liquefaction*

Figure 2-34 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 2-32. Figure 2-34 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 2-8, 2-32, 2-34 are that only a portion (about 5% to 10%) of the Christchurch and Springston Formations (Figure 2-8) or the "red" zones (Figure 2-32) 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) having relatively low shaking amplitudes 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); this was proven to be the case in the February 2011 event. 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.

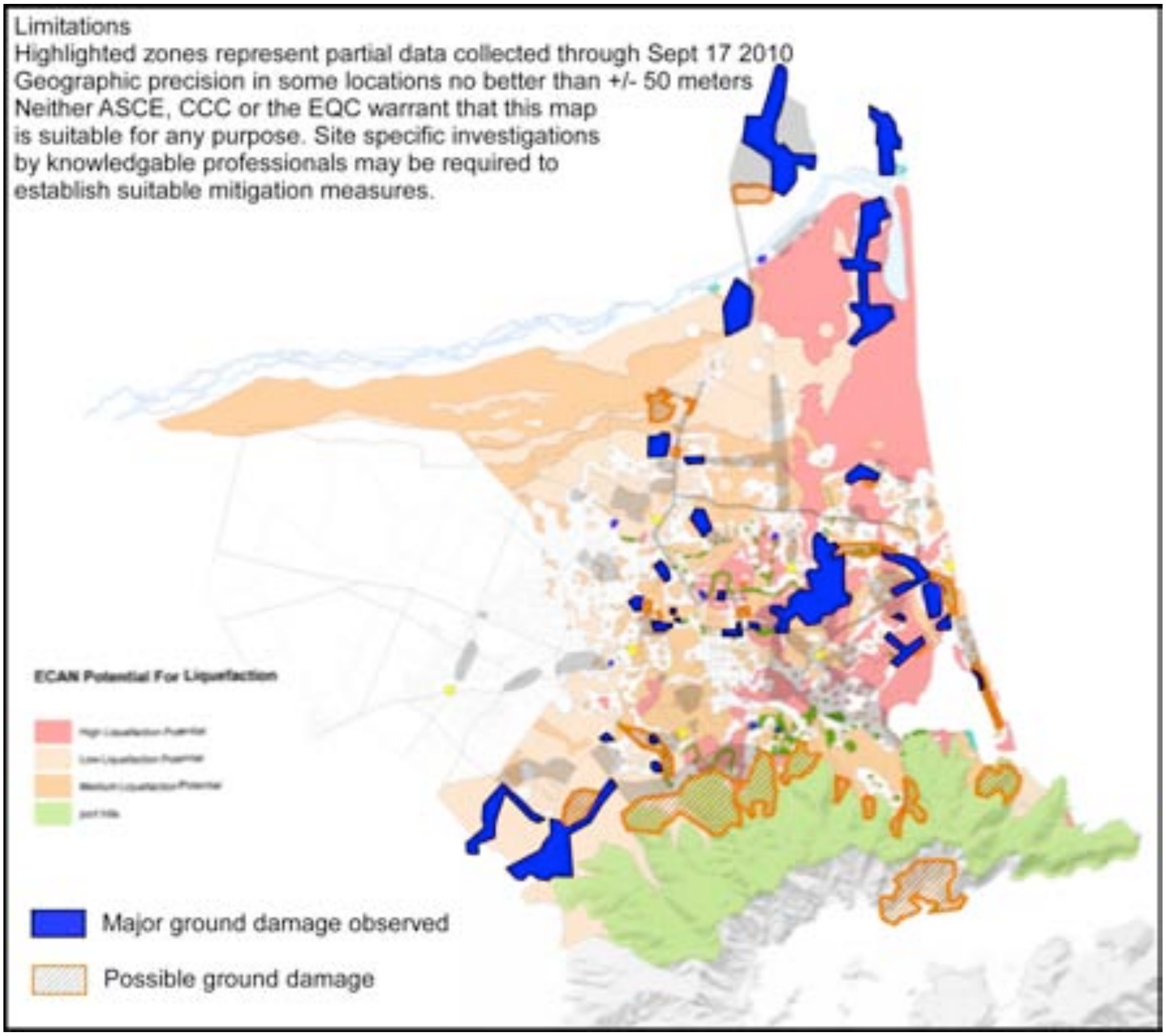


*Figure 2-34. Map Showing Observed Major (Blue) or Possible (Diagonal) Ground Deformation*

Figure 2-35 shows a gasoline (petrol) storage tank that floated. This tank was located in Bexley, an area of Christchurch with widespread liquefaction. Liquefaction is evidenced by the sand boils seen in the foreground of this photo, as well as evidence of sand boils at nearby locations. This gas station was out of service five weeks after the earthquake. Figure 2-36 shows sand boils typically observed in the liquefied areas.

*Figure 2-35. Floated Gas Tank, Bexley*

*Figure 2-36. Sand Boils*

It is evident from Figure 2-34 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 following highlights some of the liquefaction effects on utilities; these will be described in more detail in the individual chapters for each utility. The damaged buried utilities included broken water mains (nearly 500 repairs as of mid-October 2010), broken sewer pipes (at least 400 repairs, and as yet an undetermined number of replacements), about 200 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.

### 2.6.2 Liquefaction in February 22 2011 Event

While the magnitude and duration of the February 22 2011 event were less than the September 4 2010 event, the impact of liquefaction was larger. Figure 2-37 shows a map prepared by Professor Misko Cubrinovski from the University of Canterbury as follows: he drove each street and observed the extent of road and nearby property deformations. Lines in red indicate streets with severe liquefaction, commonly 150 mm (6 inches) of uplifts / lateral spreads or more; magenta shows liquefaction effects only to roads; orange shows low to moderate liquefaction effects; blue shows no liquefaction effects.

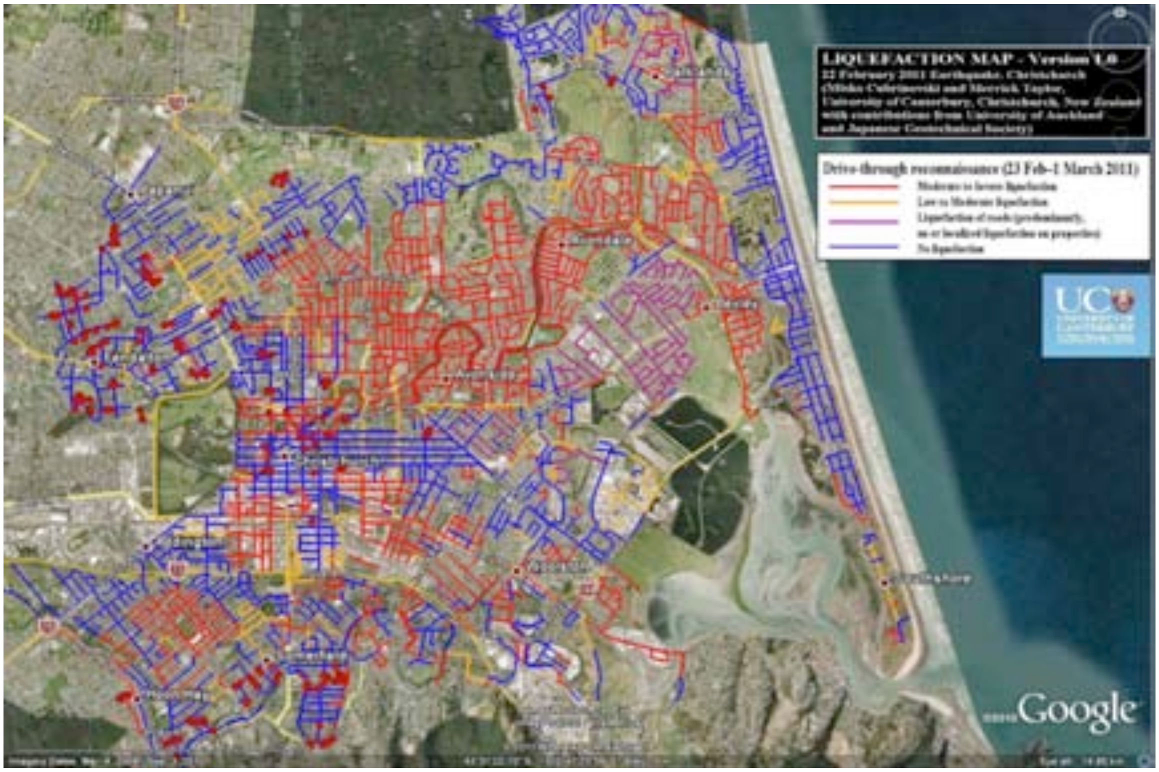


*Figure 2-37. Liquefaction, February 22 2011*

Liquefaction during the February 2011 earthquake extensive flooding of streets and large volumes of sand to be ejected on the ground surface. Liquefaction induced permanent ground deformations in the form of ground settlements and lateral spreading were prominent throughout the city. Figure 2-38 shows liquefaction induced deformations and sand deposits along Palmers Road. Clean up of the sand deposits was still underway in April 2011. Figure 2-39 shows liquefaction induced lateral ground movements causing the sidewalk brick work to deform in the Central Business District. Many of the same features of liquefaction described for the September 2010 earthquake apply to the February 2011 earthquake. However, the effects in February 2011 were generally more extensive, at least in Christchurch.

Comparing Figures 2-34 and 2-37 shows that the total liquefied area in Christchurch somewhat exceeded the areas previously mapped as having the potential for liquefaction. Many of the following chapters describe damages to lifeline infrastructure resulting from the liquefaction induced during the February 2011 earthquake. Damages include extensive water, sewer, and storm drain pipe breaks, lateral movements of bridge abutments, settlement of homes more extensive than explained for the September 2010 earthquake, tilting of buildings, and so on.

An important factor that may have contributed to the extensive liquefaction and resulting surface flooding is the high artesian ground water pressures existent in most parts below Christchurch. The pre-existing relatively shallow groundwater pressures, that exceed the overburden pressures prior to the earthquake, could have made the relatively weak recent sandy soil deposits much more susceptible to liquefaction than would have normally been considered under non-artesian groundwater conditions.

*Figure 2-38. Liquefaction induced ground deformation on Palmers Road, Feb 22 2011*

*Figure 2-39. Liquefaction induced ground deformation in the Central Business District, February 22 2011*

*Figure 2-40. Liquefaction, February 2011*

The June 13, 2011 event again caused liquefaction in some of the areas previously liquefied by the February 2011 earthquake; preliminary indications are that the extent of liquefaction in the June 2011 event was on the order of 15% to 20% of that for the February 2011 event. Effects of this liquefaction included on the order of 10% of the damage to buried lifelines affected by the February 2011 earthquake.

Figure 2-41 shows a graben and lateral spread adjacent to the Avon river in the CBD; as well as the editors of this report. The lateral movement of the banks towards the river resulted in buckling of the girder for the bridge in the background, Figure 2-42.

*Figure 2-41. Liquefaction, Avon River Bank, CBD, February 2011*

*Figure 2-42. Damaged Bridge Girder due to Lateral Spread, CBD, February 2011*

## 2.7 Landslide and Seiche

Much of the Canterbury 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 September 4 2010 earthquake triggered a few rock falls in this area, 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.

In the Port Hills, in the September 4 2010 event, there were no known landslide or rock-fall impacts to man-made structures other than roads. Due to the much more intense levels of shaking in the February 22 2011 event, there were many more rock falls in the Port Hills area, with large boulders falling / rolling into a variety of residential and commercial structures, causing both fatalities as well as substantial property damage. Figure 2-43 shows a road closure with stranded petrol truck, due to rock fall. Figure 2-44 shows rock fall that destroyed a small power substation (lower right of photo); nearby, construction workers and residents of buildings were killed by rock falls.

*Figure 2-43. Rock Fall, Lyttleton Port Area, February 22 2011*

*Figure 2-44. Rock Fall, Sumner Area, February 22 2011*

Figure 2-45 shows cracks at the edge of cliffs at Sumner Head (southeast Christchurch suburb). Many rocks rolled off the steep mountainsides and damaged/destroyed buildings at the foot of the hills. The June 11 2011 event also caused rock falls in this area. Chapter 6 describes some water tanks impacted by rock falls. Figure 2-46 shows extensive rock accumulation on Summit Road.

*Figure 2-45. Cliff Edge Cracks, Sumner Head, February 22 2011*

*Figure 2-46. Rock falls accumulated on Summit Road, February 22 2011*

The rock falls in Redcliff, Figure 2-47, were fatal to a building occupant.

*Figure 2-47. Rock falls in Redcliffs, February 22 2011*

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 within commercial ski areas in the September 4 2010 event (perhaps PGAs on the order of 0.05g± at ski areas); or the subsequent two events.

A number of large icebergs calved into Tasman Lake after the February 22 2011 event; Tasman Lake is located in the Mount Cook National Park; it is formed by the retreat of the Tasman Glacier. Given the distance from the epicenter, local PGAs were likely under 0.01g±. Estimates are that the quantity of icebergs that were calved from the face of the Tasman Glacier was on the order of 30 million tons; larger calving events have occurred in the past. Tour boat operators reported wave heights (seiche) up to 3.5m, lasting for about 30 minutes. The extent of calving due to the wave loading or the inertial loading is unknown.

# 3.0 Seismic Codes and Vulnerability Study

While New Zealand is well known to be seismically active, up to the time of the Christchurch earthquake sequence, the seismic risk for Christchurch was thought to be moderate. There were no known active faults near the city. There was no historical earthquakes near the city. Since the early 1990s, the building code required design for PGA = 0.22g for regular buildings, and somewhat higher for essential structures. A few of the unreinforced masonry structures had undergone some level of seismic upgrade prior to 2010.

The September 4 2010 earthquake produce ground motions in the central business district (CBD) on the order of the seismic design basis of the early 1990s. While there was some damage in the CBD, it was not severe.

The February 22 2011 earthquake produce ground motions in the central business district (CBD) on the order of twice the seismic design basis of the early 1990s. Two recent-vintage engineered structures collapsed. Of the roughly 1,200 buildings in the Central Business District, more than 800 were moderately to heavily damaged; including many modern-designed buildings, as well as many older masonry buildings. Due to concern for ongoing damage due to aftershocks, essentially the entire CBD was cordoned off, meaning that no civilians were allowed in; with the attendant 100% stoppage of economic activity in the CBD. The performance of the buildings in the CBD cannot be considered acceptable with regards to a "resilient city".

## *3.1 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 3-1. 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.

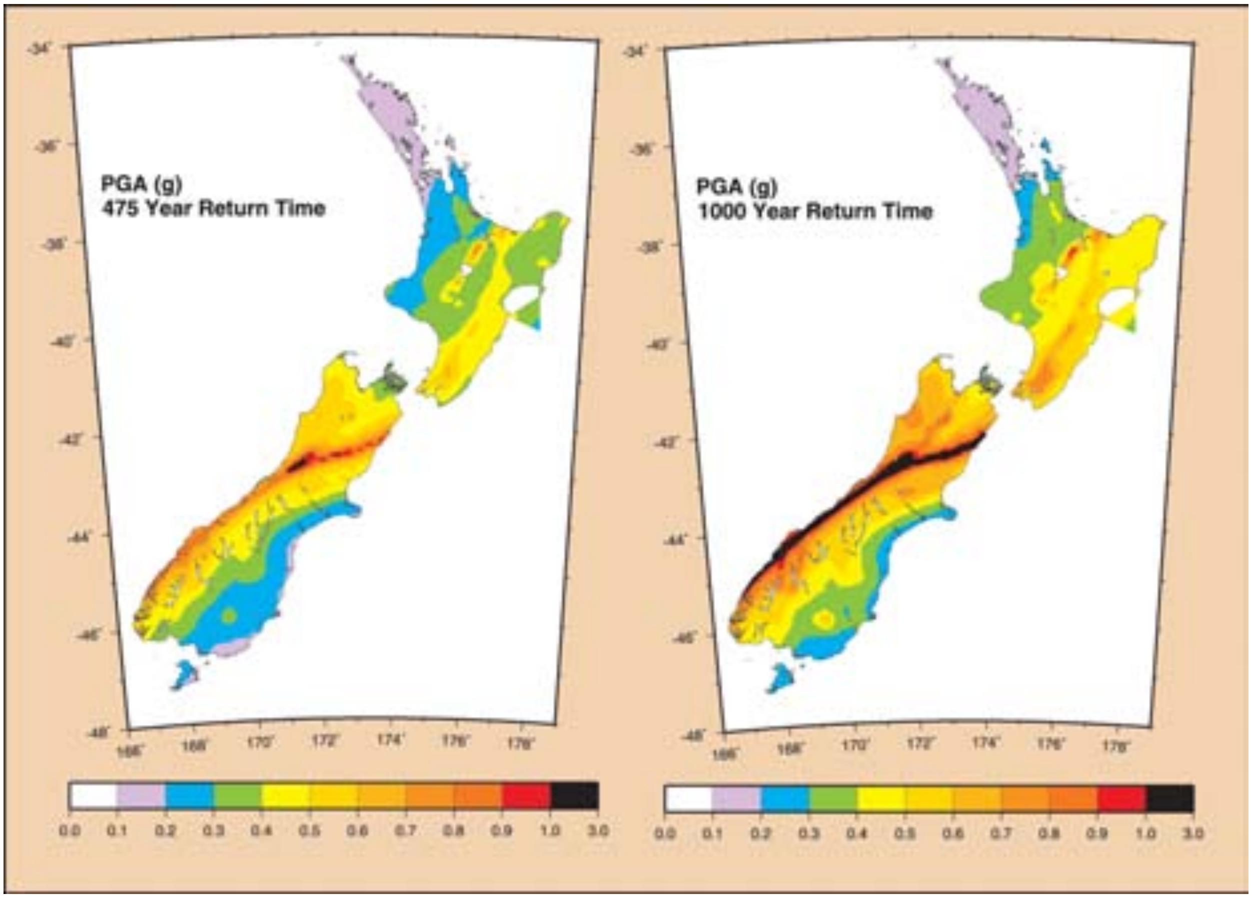


*Figure 3-1. Seismic Hazard Map for New Zealand, Horizontal PGA (g)*

By 2010, new engineered-buildings in Christchurch are designed using modern seismic techniques. The New Zealand codes are similar to 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).

For the September 4 2010 event, 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 were unreinforced masonry. It is our understanding that several of these URM buildings had been seismically retrofitted prior to the 2010 earthquake; the trigger to require retrofit was that if the building could not be shown capable for 1/3 of the then current code (PGA = 0.22g), it would be retrofitted to 2/3 of the then current code, or for about PGA = 0.15g. Even with this provision, most of the smaller URMs remained either completely unretrofitted, or with only partial retrofits (parapets). It is estimated that at the time of the September 2010 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 September 4 2010 earthquake; just the opposite occurred in the February 22 2011 earthquake, where the majority of the URMs suffered moderate to severe damage; one of the retrofitted URMs still had walls collapse (but the majority of the building stood); a portion of the main cathedral (previously retrofitted) collapsed. Some URMs that had moderate damage in the September 4 2010 earthquake sustained additional damage to close then in the February 22 2011 earthquake. One stout URM (lots of walls, small windows, previously used for heavy warehouse loadings) survived both earthquakes and remained open for business after the February and June 2011 earthquakes. Although temporary steel braces were added to provide some lateral support to the main cathedral, the December 22 2011 earthquake shook down large portions of the main east facing walls. By mid-December 2011, the seismically-upgraded URM visitor center (but damaged in the February 2011 event), next to the main cathedral, had been torn down.

## 3.2 1997 Vulnerability Study

In 1997, a vulnerability assessment report for natural hazards, including earthquake was prepared by the Christchurch Engineering Lifelines Group (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 (mostly for inertial loading) ultimately led to a reduced level of damage in the September 4 2010 earthquake, and more rapid restoration of essential services than would have otherwise have occurred. While the liquefaction (and to some extent, landside) hazards had been indentified in the 1997 effort, almost no mitigation actions for these hazards had been taken; with the result that there was substantial damage due to liquefaction in all three earthquakes, and some damage due to landslide in the 2011 earthquakes.

# 4.0 Electric Power

The Electric Power system serving the Christchurch area is provided by three companies: Transpower, Orion and Mainpower. 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 for Christchurch, and buys power from Transpower and delivers it to end user customers, with sub-transmission common voltages of 66 kV, 33 kV, and 11 kV, and distribution based on 400 V to the final residential users. Mainpower is the local power distribution company for communities north of Christchurch, including Kaipoi.

Both Transpower and Orion had implemented some seismic mitigation measures in the decade prior to the September 4 2010 earthquake. These countermeasures, including reinforcement of unreinforced masonry substation (URM) buildings, 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 in the September 4 2010 earthquake.

In the February 22 2011 earthquake, liquefaction was widespread, and led to damage (faulting) for essentially all of the 66 kV buried cables; and about 8% of 11 kV buried cables exposed to much over 50 mm (2 inches) of permanent ground deformations. The failure of these cables resulted in widespread power outages. Repair of buried cables requires considerable time and resources; leading to long term (many months) substantial reduction in sub-transmission capacity in the system. While in the September 4 2010 earthquake, 90% restoration was achieved within a day, for the February 11 2011 90% restoration was met after 10 days. Of the 300 substations in Christchurch, liquefaction failed two substations; rock falls destroyed one substation; strong ground shaking (PGA > 0.5g) failed one seismically-mitigated unreinforced masonry substation building; had the URM buildings not been mitigated, results would have been much, much worse. Strong ground shaking (PGA = 0.5g) damaged a few components at a 220 kV – 66 kV substation.

In the June 13 2011 earthquake, liquefaction occurred in many areas, and led to damage (faulting) for more 11 kV buried cables, resulting in more power outages and setting back the overall long term restoration effort. Between the February 2011 and June 2011 events, more than 120 buried cables were damaged requiring repairs; an unknown number of buried cables sustained some deformations but remain in service; but suggest a higher repair rate for buried cables for years to come.

## *4.1 Transpower Power System Performance*

Figure 4-1 shows the Transpower system serving the Christchurch area. Most power is generated to the south (well outside the strong shaking area for all three earthquake events, and no damage reported) and imported to the Christchurch area. The Islington substation (220 kV – 66 kV) serves the largest portion of the load for Christchurch area; primarily the western part of the City. The Bromley substation (220 kV – 66 kV) serves a portion of the load for Christchurch area, primarily the eastern part of the City. Figure 4-2 highlights several other Transpower substations in the Christchurch area that are discussed in this report. Liquefaction was observed at the 66 kV Papanui substation (September 2010 event) and 220 kV Bromley substation (February 2011 event).

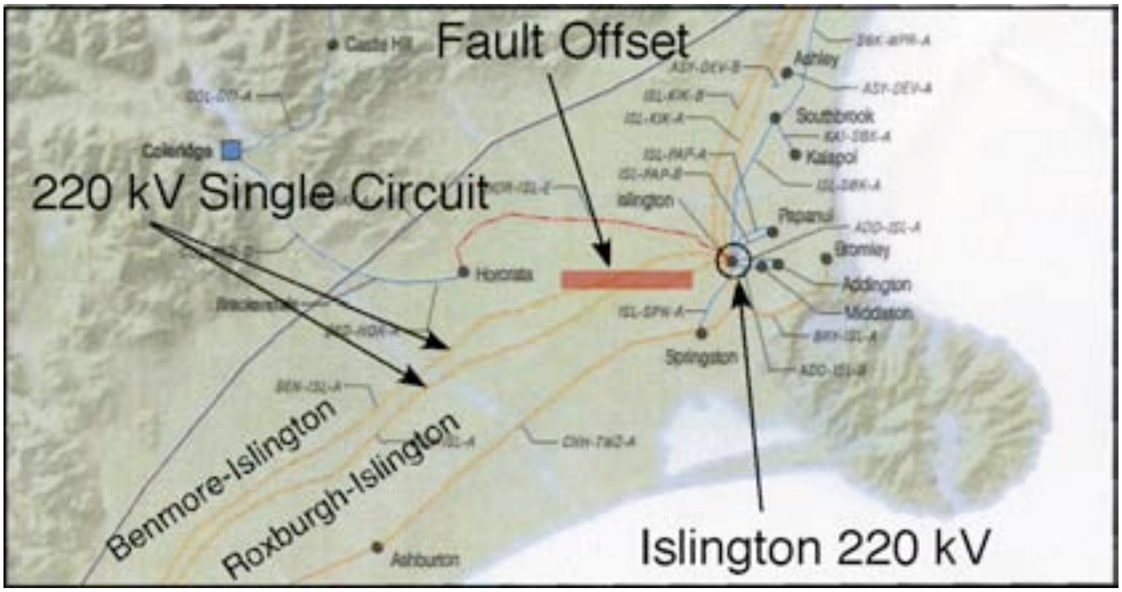


*Figure 4-1. Transpower Regional High Voltage Grid (Red line shows approximate location of faulting for the Sept 2010 event)*

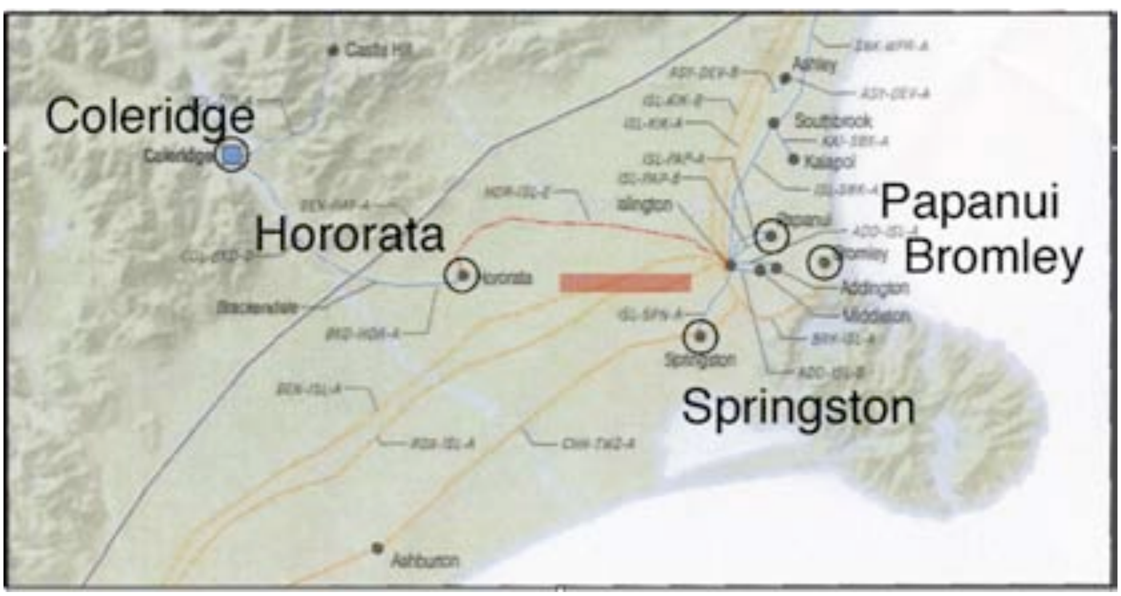


*Figure 4-2. Other Transpower Substations*

Two single-circuit 220 kV overhead transmission lines crossed the rupture zone of the September 2010 event. The fault rupture passed nearby the legs of the steel lattice towers, but not through them (Figures 4-3, 4-4). There was no observed damage to any towers due to inertial shaking in any of the events. Due to the fault offset (September 2010 event), 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 Figures 4-5, 4-6 this sag remains unbalanced 6 weeks after the September 2010 earthquake; Transpower reported that they would adjust the sag during some future outage; Transpower reported this was completed by February 2011. On the Benmore-Islington line, the September 2010 fault offset resulted in high tension loads in a ground wire, which bent the tower extension that supported the ground wire (Figure 4-7); again, this did not led to an outage, but could be repaired during a future outage.

*Figure 4-3. Surface Fault Offset Approaches the Tower in Figures 4-4, 4-5*

*Figure 4-4. Surface Fault Offset Approaches the Tower in Figures 4-3, 4-5*

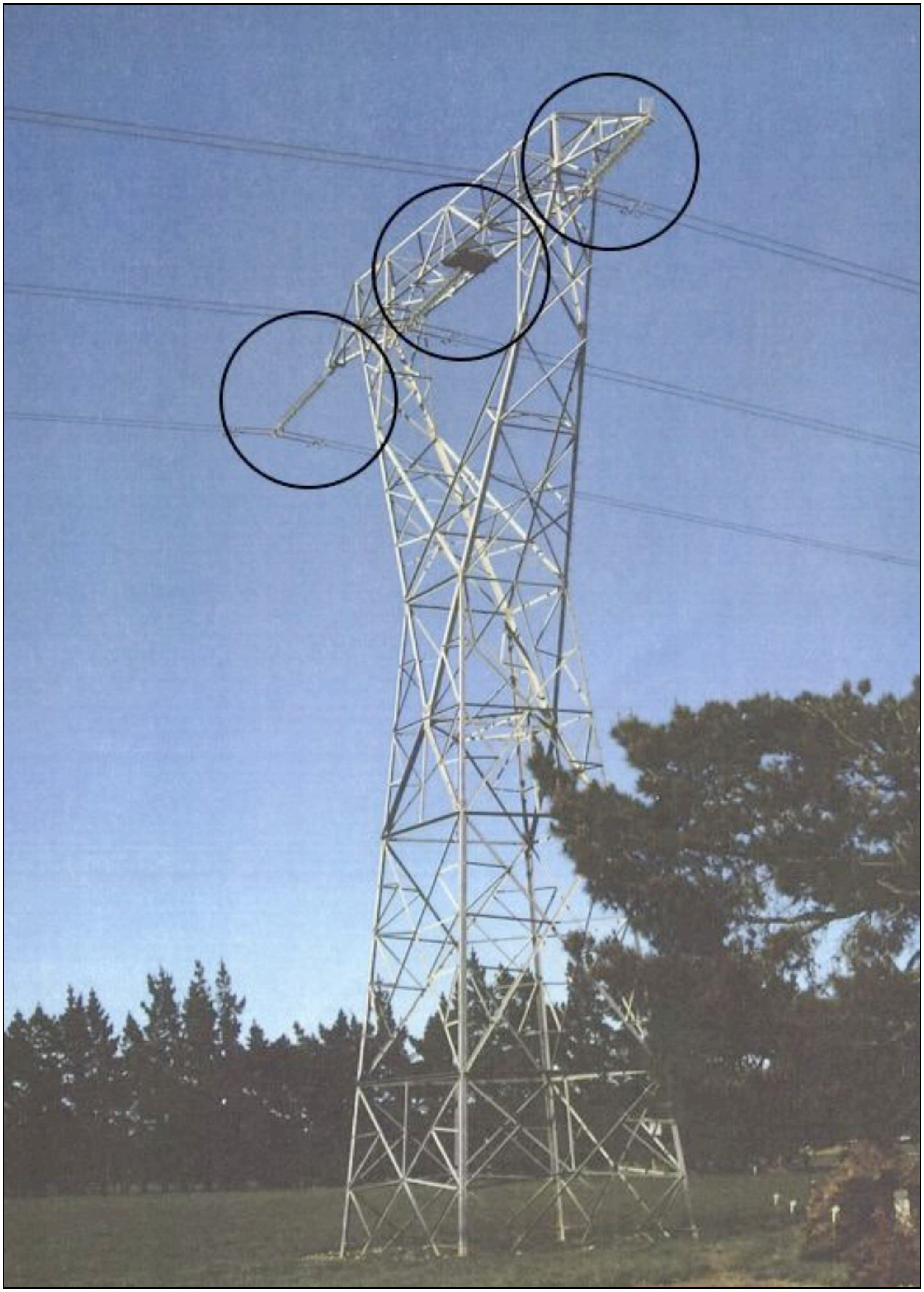

*Figure 4-5. Displaced Insulators on Suspension Tower Adjacent to Fault Offset*

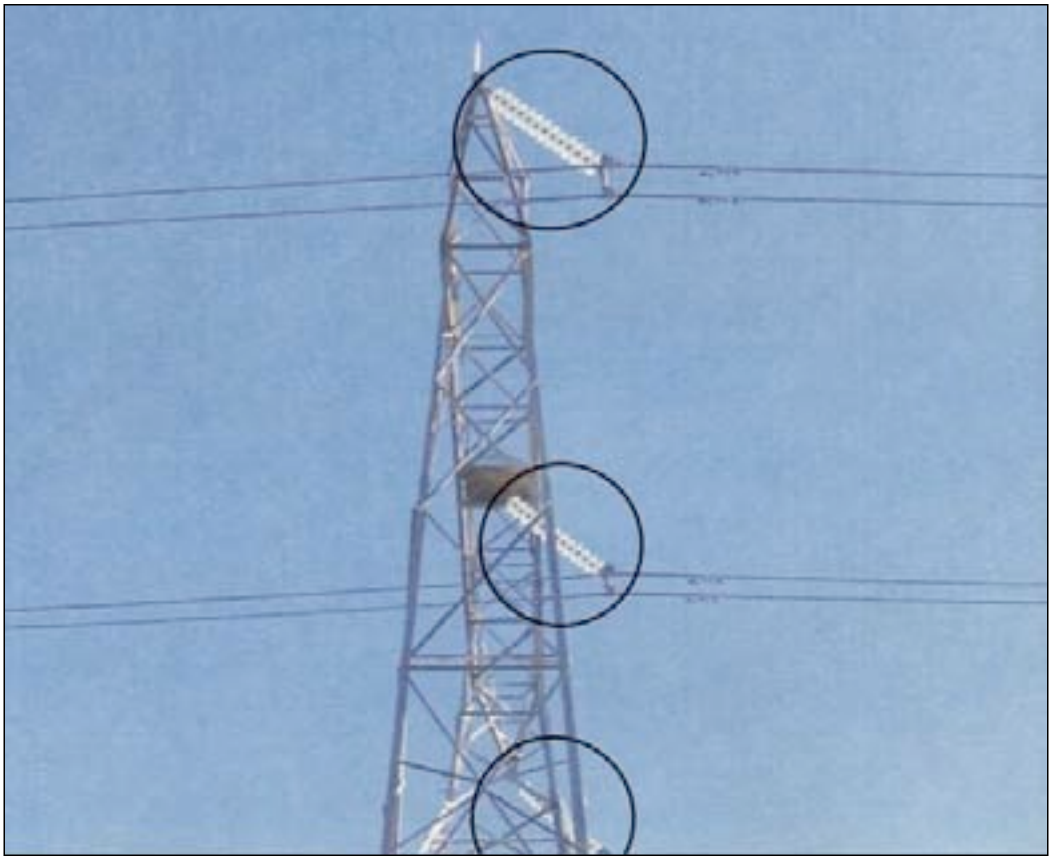

*Figure 4-6. Displaced Insulators on Suspension Tower Adjacent to Fault Offset*

On the Benmore-Islington 220 kV line, the Sept 2010 fault offset resulted in excess ground wire tension that resulted in damage to a tower extension that supported the ground wire, Figure 4-7.

*Figure 4-7. Damaged Tower Extension for Ground Wire*

*Figure 4-8. Angle Tower With Added Guy Wires*

There was a modest number of items damaged at several Transpower substations in the September 2010 event. The cumulative repair cost for damage at Transpower substations (through early October 2010) was 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, Figure 4-11. 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, Figure 4-12. There was a broken window in the relay room. There were two cracks in the control building. Liquefaction did not adversely affect the upgraded transmission tower Figure 4-13.

- Springston: 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 66 kV circuit breaker 438, Figure 4-9. 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 4-14. Three spare (unanchored, in process of relocation) current transformers toppled, Figure 4-15. 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 leaning (Figure 4-8), likely due to liquefaction (but, Transpower staff reported that they could not be completely sure the tower was not leaning before the earthquake). Repair was to install guy wires. Diagonal crack in a wall of the control building next to a door. A small amount of oil sloshed out of the tap changers of transformers T2, T3 and T4. Some 66kV wood bus poles had a slight lean. One disconnect switch (DS 894) was not properly closed. Note: This substation sustained substantial liquefaction and additional damage in the Feb 2011 earthquake.

- Addington – Middleton – Islington 66 kV circuit tripped due to fault protection.

- Addington warehouse: two storage racks partially collapsed (see Figure 17-1, 17-2, 17-3).

- Regional Operations Center. A computer cabinet on a base isolation unit atop a raised floor jumped off its isolator mount (Figure 17-5, 17-6); another unit slid (Figure 17-4). Lighting diffusers in a control room suspended ceiling fell. Tiles in a suspended ceiling fell over a lunch room.

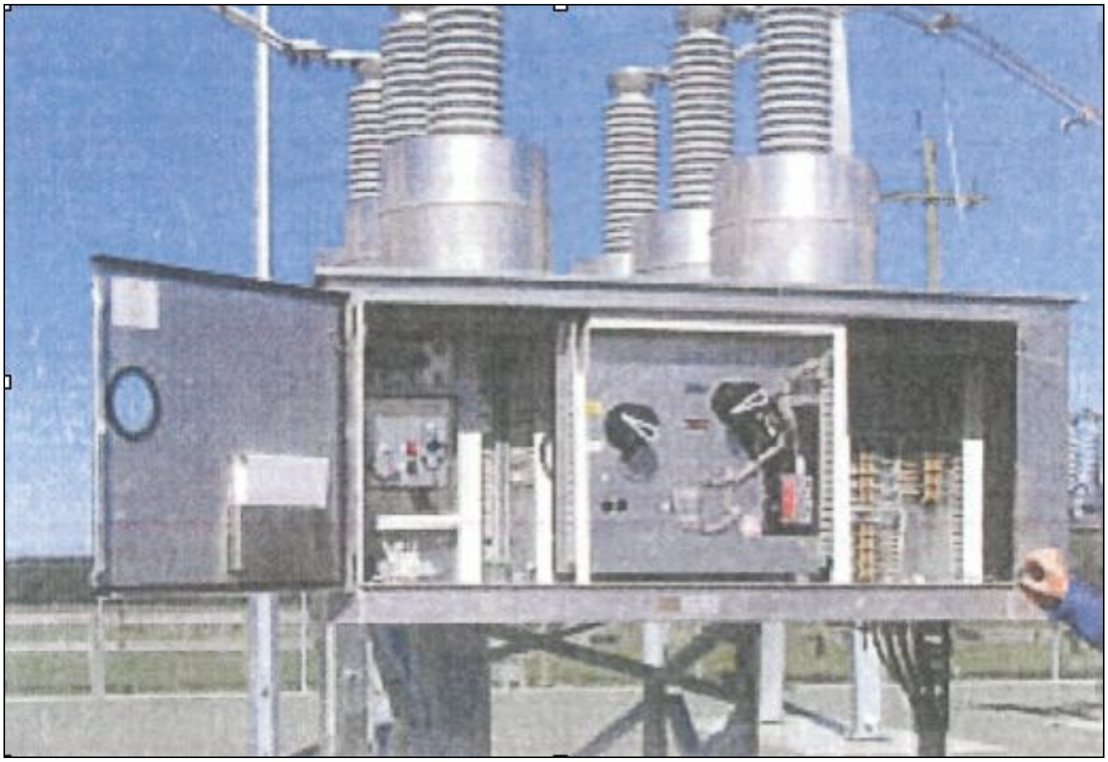

*Figure 4-9. One of Two Cabinet Doors Broke Off, SF6 Circuit Breaker*

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 4-10. 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 4-10. Broken Lightning Arrestor*

*Figure 4-11. Sand Boils, Papanui Substation*

*Figure 4-12. Sand Boil, Settlement and Cracking of Oil Containment, Papanui Substation*

*Figure 4-13. Sand Boil, Upgraded Tower, Papanui Substation*

*Figure 4-14. Hororata Control Building*

*Figure 4-15. Hororata Toppled Current Transformers*

## 4.2 Orion Power System Performance

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 nearly 300 small unreinforced masonry distribution substation buildings, and seismic upgrade of a small bridge supporting two 66 kV pipe-type oil-filled circuits, located in a liquefaction zone. All of these upgraded facilities remained serviceable immediately after the September 2010 earthquake; although the 66 kV circuits in the liquefaction zone were damaged and will need ultimately need to be replaced or bypassed; in the February 2011 earthquake, additional liquefaction failed these 66 kV cables.

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 4-16 shows the customer outages at selected times; the Magnitude 5.1 aftershock of early September 8 2010 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 4-16 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.

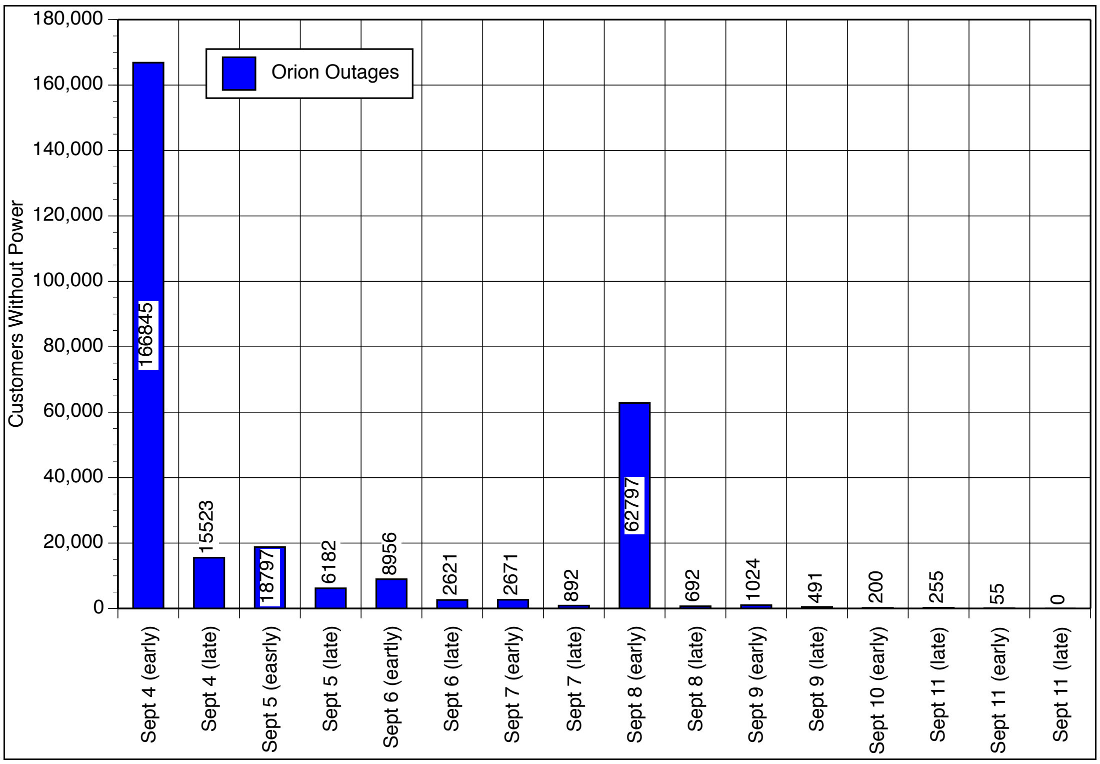


*Figure 4-16. Customer Outages, Orion System*

Figure 4-17 shows the main transmission lines of the Orion system. The circle shows the damage location on the Bromley-Dallington double circuit 66 kV lines (but they remained operable) due to settlement and lateral spread.

Figure 4-18 shows the damage trends for buried circuits due to the February 22 2011 earthquake. In the areas highlighted by the red circle (major liquefaction), the 66 kV buried circuits were abandoned as the buried cables were damaged at multiple locations. In the areas highlighted by the yellow circles (moderate liquefaction), the 66 kV buried circuits were repaired at six locations (Eidinger, 2012).

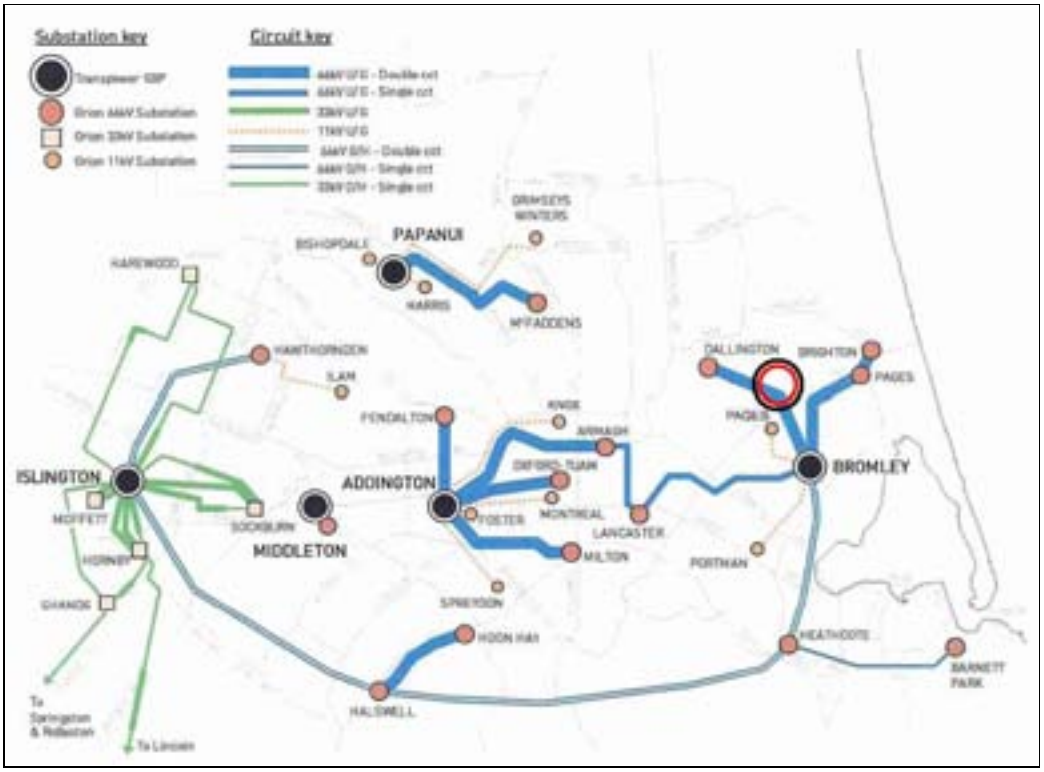


*Figure 4-17. Orion System (Damage Location to 66 kV Circled, September 2010)*

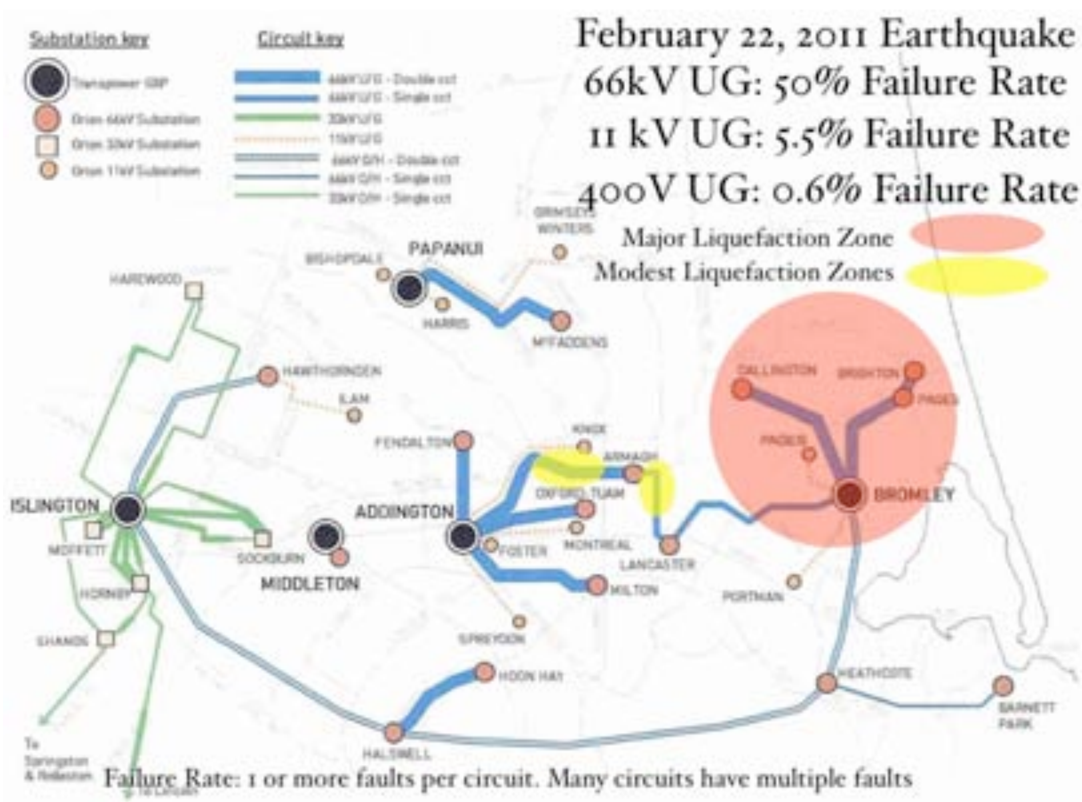


*Figure 4-18. Orion System (Damage 66 kV Circuits, February 2011)*

Figure 4-19 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 4-20 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 4-19. Orion URM Upgraded Small Substation*

*Figure 4-20. Orion URM Non-Upgraded Former Small Substation*

Figure 4-21 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. The cables remained functional after the September 2010 earthquake, but failed in the February 2011 earthquake. As part of a temporary measure after the September 2010 earthquake, Orion braced the bridge on which the cables are located. There were several other 11 kV buried cables that were completely broken in the September 2010; we believe all of the broken cables were in the areas with lateral spreads and/or settlements. In the February 2011 and June 2011 earthquakes, there were many more failures (at least 120) of buried 66 kV and 11 kV cables.

*Figure 4-21. 66 kV Cables*

Figure 4-22 shows one of many tilted low voltage power poles, located at Avonside and Robson Ave. These wood poles commonly are buried 6 to 7 feet into the ground (~2 meters). The locations with observed tilted poles correspond essentially one-to-one with the areas with observed liquefaction. According to Orion, none of the poles toppled.


*Figure 4-22. Titled Power Pole*

## 4.3 Transpower Performance – 22 February 2011

The February 22 2011 earthquake had modest impact to the Transpower system: the Bromley substation had liquefaction and some component damage; and one 66 kV tower suffered a rock fall through the tower, but the tower remained standing.

Figure 4-23 shows the response spectra (5% damping) recovered at a site close to the Bromley substation. Ground motions were about PGA = 0.5g.

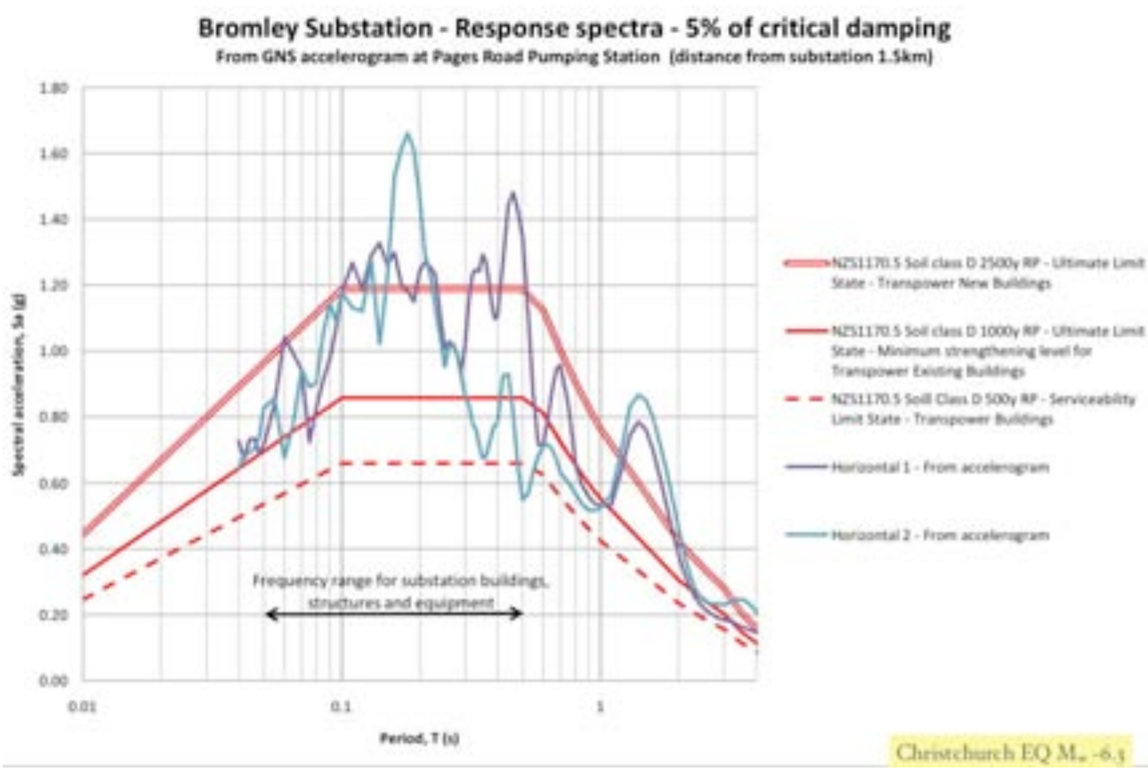


*Figure 4-23. Horizontal Response Spectra (5% Damping) Near Bromley Substation*

The control building at Bromley substation is a two-story reinforced concrete building. The building suffered no observable damage. Within the building, there was a variety of damage:

- Some tiles from a suspended ceiling dislodged and fell. These had no adverse impact on equipment.
- Cabinets, table top equipment all performed well. Transpower had previously seismically-restrained all the equipment (including desk-top computer monitors, shelving, etc.) using angles, hold down clips, etc.
- A new battery rack had been installed. The battery rack, on the second floor, was seismically anchored; however, the batteries within the rack did not have spacers, and they slid several inches during the earthquake. Figure 4-24 shows scratch marks caused by the sliding movement of the batteries. Transpower reported that the batteries remained functional, all the same.


*Figure 4-24. Sliding of Batteries in Battery Rack at Bromley Substation*

The control building contains low voltage switchgear. The circuit breaker (#37) for one position had been put into its "not-in-service" position prior to the earthquake. During the earthquake, its heavy eccentric mass caused it to partially topple (Figure 4-25). Figure 4-26 shows that the steel support frame for this breaker cracked; anchorage to the concrete floor for all units showed distress (concrete spalling). Transpower responded by installing supplementary bracing for all breakers; with the long term plan to replace all the breakers with modern equipment.


*Figure 4-25. Toppled Circuit Breaker at Bromley Substation*

*Figure 4-26. Cracked Steel Frame for Circuit Breaker 37, Bromley Substation*

There was a lot of liquefaction around, and some within the 220 kV and 66 kV yards at the Bromley substation, Figures 4-27 and 4-28.

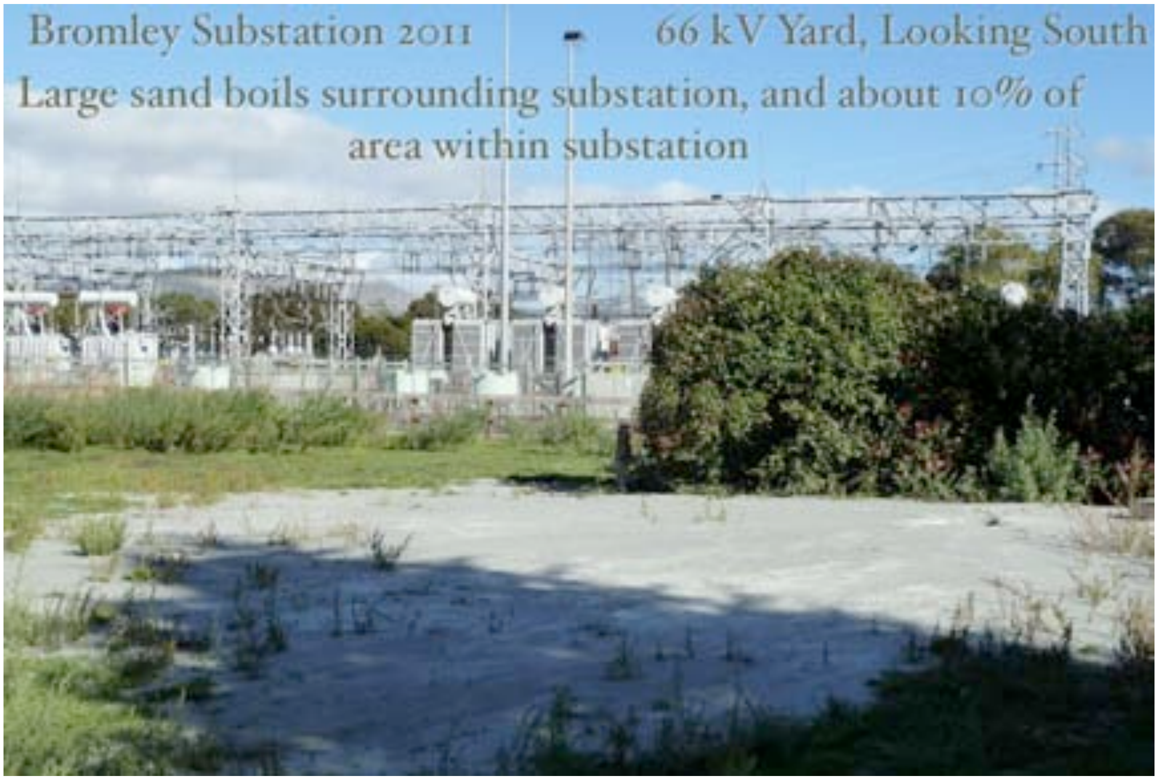


*Figure 4-27. Liquefaction Outside the 66 kV Yard, Bromley Substation*

The liquefaction seen in Figure 4-28 is within a part of the yard using rigid bus. With the settlements and the rigid bus, it was reported that several of the center-break 220 kV disconnect switches were partially out of alignment (but with no contact burns), requiring manual effort to re-set them into proper alignment.

Candlestick-type breakers (ABB type LTB245, installed since 2002), performed well, as did adjacent 220 kV current transformers.

One bushing on a 66 kV transformer failed (Figure 4-29), possibly due to insufficient slack. All transformers at the yard were anchored; a few bolted anchors showed signs of slippage, but less than an inch.


*Figure 4-28. Sand Volcano, ~ 1 Foot Deep, inside the 220 kV Yard, Bromley Substation*

*Figure 4-29. Broken Transformer Bushing, 66 kV, Bromley Substation*

One of six identical voltage transformers broke (Figure 4-30). This component was tied into the rigid bus using a short vertical riser cable; it is possible that relative movement (combination vertical, horizontal shaking and possibly differential settlement) allowed the cable to become tight, putting a high "yanking" load on the component below.


*Figure 4-30. Broken Voltage Transformer, 220 kV, Bromley Substation*

One of the disconnect switches (Figure 4-31) showed a 1 cm displacement in one of its contacts.

*Figure 4-31. A disconnect switch with a 1cm offset in its contact.*

Figure 4-32 shows a 66 kV transmission tower that suffered damage due to a boulder that rolled down the hill (Port Hills area). Fortunately, the boulder decided to "miss" the four main support legs. Similar damage with the boulder going through the tower and hitting only secondary members, with the tower remaining standing, has been observed to transmission towers in the 2008 M 8.0 Wenchuan, China earthquake.

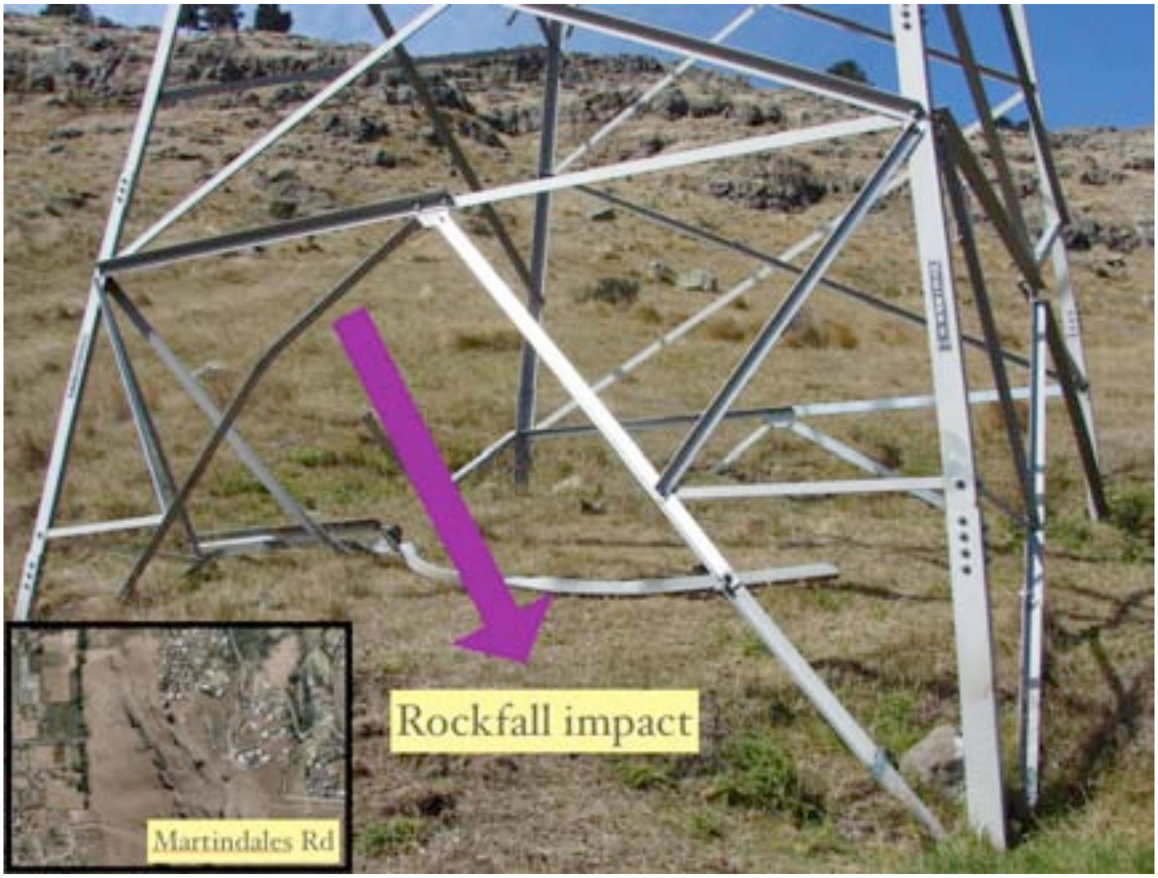


*Figure 4-32. Damaged 66 kV Transmission Tower*

Many 220 kV towers were in zones with liquefaction (Figures 4-33, 4-34). While evidence of sand boils (commonly 4" to 12" deep) were observed on a variety of towers, it was reported that some (all?) of the 220 kV towers had been upgraded by tying-together their four foundations; there was no lateral spreading observed at these locations; the tower members appeared to remain elastic. On an adjacent 66 kV tower that did not have the foundations tied together, the liquefaction allowed relative movement of a leg, with attendant buckling of secondary members; but the tower remained in service.

*Figure 4-33. Liquefaction at 220 kV Transmission Tower*

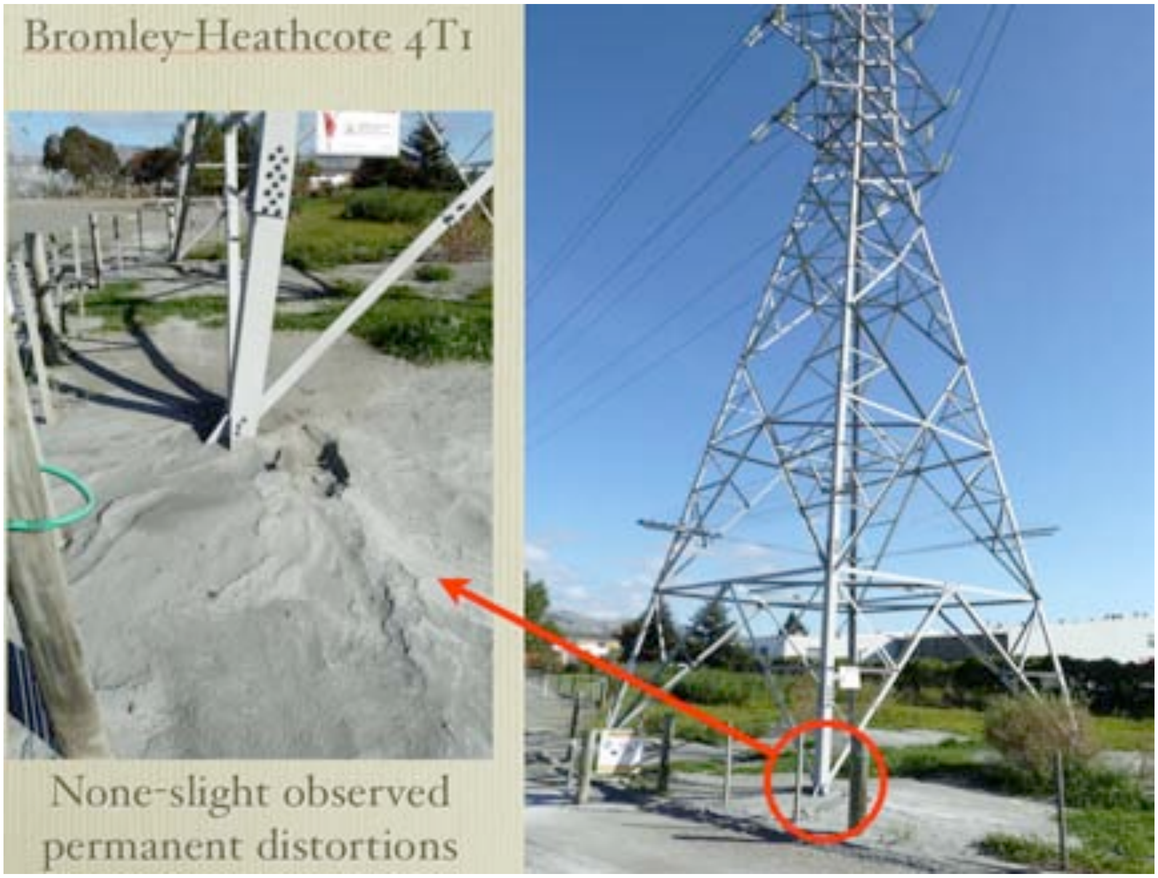


*Figure 4-34. Liquefaction at 66 kV Transmission Tower*

## 4.4 Orion Power System Performance – 22 February 2011

As of early April 2011, the estimated power outages due to the February 2011 earthquake was still unknown, as not all power had yet been restored. The estimated customer-minutes of outages was 629,000,000, or more than 6 times worse than the September 4 2010 earthquake. It took Orion 10 days to restore power to 90% of its customers, which was about 10 times worse than in the September 2010 event.

The reasons for the poorer performance in the February 2011 event include:

- Serious damage to 4 substations. This caused some local outages and substantial effort to rebuild.
- Damage to both main Orion headquarters buildings. This hampered emergency response.
- Widespread damage to buried 66 kV and 11 kV cables. This was the most costly and time-consuming type of damage, and the primary reason for long power outages. System wide, 50% of 66 kV cables, 5.5% of 11 kV cables, and 0.6% of 440 V cables experienced damage (percentages are higher in liquefaction zones).

> Damage to cables affected in particular Dallington and Brighton substations because all of the 66 kV cables serving these substations failed.

In Sumner (eastern Christchurch at the base of the Port Hills), there was a considerable amount of rock falls. One of the small distribution substation was directly impacted, resulting in the total loss of the substation, see Figures 4-35 and 4-36. This URM facility had been seismically upgraded prior to the earthquake, but evidently earthquake-triggered avalanche landslide was not considered as a hazard. Figure 4-37 shows the damaged switchgear within this substation.

*Figure 4-35. Substation in Summer damaged by a large boulder that fall in its back.*

*Figure 4-36. Substation Impacted by Rock Fall (Sumner Redcliffs Area) Feb 22 2011*

*Figure 4-37. Damaged Switchgear Within Avalanche-Impacted Substation*

Figures 4-38 (September 2010) and 4-39 to 4-41 (February 2011) show the effects of liquefaction at the Brighton substation. While there are sand boils apparent in the 2010 event, facility remained functional. In the February 2011 event, the liquefaction was more severe, resulting in a loss of bearing capacity and several feet of settlement and tilting of the building. The water seen in Figure 4-39 is just a couple of inches deep; under the water are a few feet of silts and sands. Figures 4-40 and 4-41 show the transformer building and adjacent radiators after the water drained and the soils were dug out. While the door held leak tight, the tilting of the foundation led to complete functional failure, requiring a brand new substation to be built. Similar liquefaction-induced foundation failures and tilting of the building occurred at the New Brighton substation.


*Figure 4-38. Liquefaction at Brighton Substation, September 4 2010*


*Figure 4-39. Liquefaction at Brighton Substation, Feb 22 2011*


*Figure 4-40. Liquefaction at Brighton Substation, Feb 22 2011*

*Figure 4-41. Liquefaction at New Brighton Substation, Feb 22 2011*

A transformer and circuit breaker (Figure 4-42) were rapidly installed (about five days in a design-build effort) on site in order to restore service until the substation could be rebuilt. A new provisional 66 kV line running from Bromley Substation was also necessary to restore service. This line is shown in Figure 4-43 in the vicinity of Bromley Substation. This temporary installation settled about 50 mm in the June 2011 earthquake, but remained functional.

*Figure 4-42. Temporary transformer installed after the Feb 22 2011 earthquake in order to restore service to the New Brighton Substation area.*

*Figure 4-43. A temporary 66 kV line installed after the Feb 22 2011 and running from Bromley Substation (seen on the background behind the white gates on the left) and the temporary transformer shown in Figure 4-44.*

*Figure 4-44. Pages Substation endings for the two 66 kV lines to New Brighton Substation.*

*Figure 4-45. Pages Substation endings for the two 66 kV lines to Bromley Substation. A damaged bushing is observed on the left*

*Figure 4-46. Pages Substation transformer building.*

Figure 4-47 shows one of the successfully-upgraded substation buildings in the Feb 2011 earthquake. Note the failure of the adjacent unreinforced masonry structure. One upgraded substation still failed due to inertial overload, Figure 4-48; ground motions at this site were likely well over PGA = 0.5g. This is the only URM substation (of 268) failure due to inertial overload in this event. Given that better than 99% of the similarly-upgraded URMs did withstand the inertial loadings, one might consider this an overall success, in that the cost savings of doing relatively modest URM upgrades were real; while the post-earthquake response needed to resolve one damaged (and normally unoccupied) URM was not too high. The building of the substation in Figure 4-48 was later demolished and the substation was replaced by the pad-mounted transformer in Figure 4-49.

*Figure 4-47. Success of Upgraded URM Substation, Feb 22 2011*

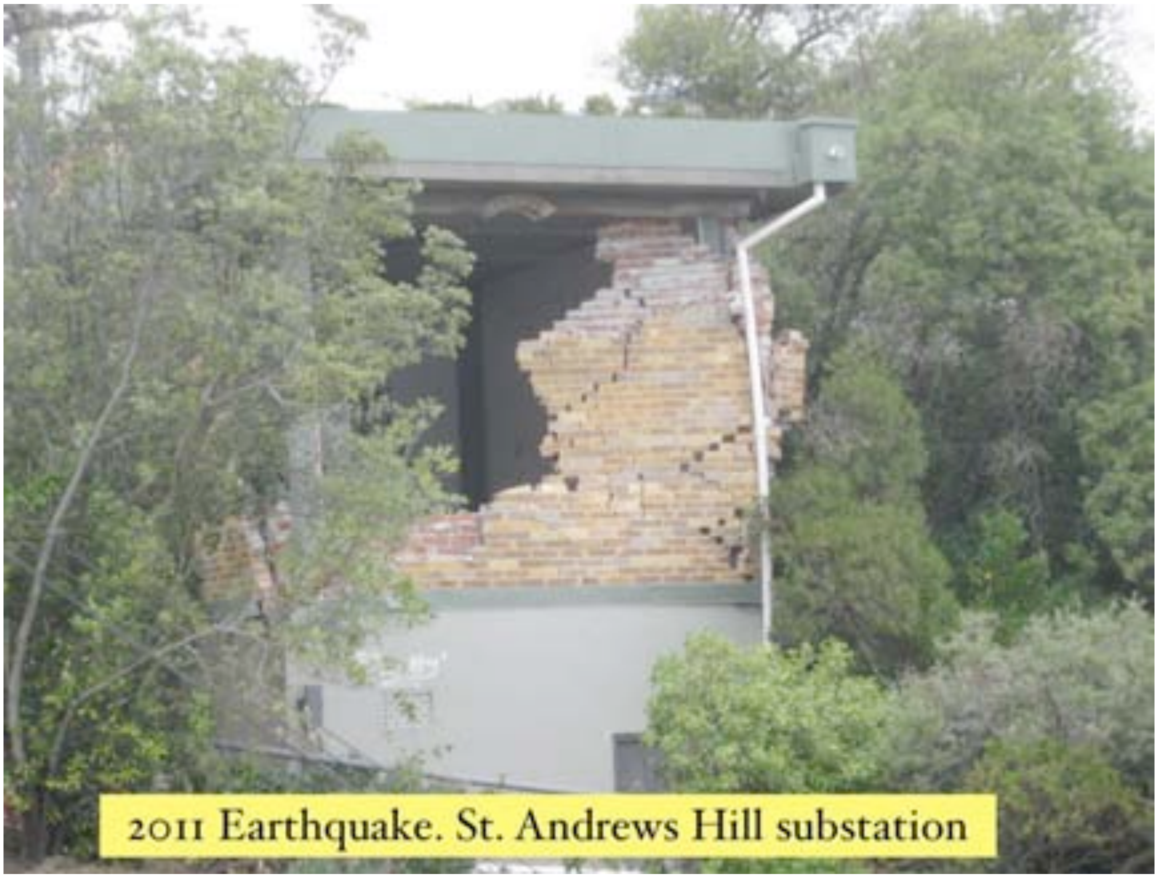


*Figure 4-48. Failure of Upgraded URM Substation, Feb 22 2011*

*Figure 4-49. The pad-mounted transformer that replaced the one inside the substation in Figure 4-47.*

While the damage to a few substations was important, the bulk of the power outages in the Orion system were due to failed buried 66 kV and 11 kV cables. The Addington to Armagh (Figure 4-17) twin 66 kV oil-filled pipe-type cables failed, likely due to settlements and lateral spreads of the nearby Avon river in the CBD. The 66 kV Armagh to Lancaster cable (direct burial XLPE-type with thermal backfill) failed at three locations in a zone exposed to moderate liquefaction displacements (Figure 4-18). The 66 kV Armagh to Addington cable (direct burial oil-type with thermal backfill) failed at three locations in a zone exposed to moderate liquefaction displacements (Figure 4-18).

About 15% of the 11 kV cables failed, or 330 km of 2,200 km. Through August 31, 2011, about 1,000 buried cable faults had been identified; more than Orion would normally identify in a decade; Orion forecasted in might take 3 to 5 years to find all the faults. Typical 11 kV cables are direct burial, PILC or XLPE. Of the 11 kV cables with faults, about 86% are along streets mapped (Figure 2-37) as having severe liquefaction effects, 8% in streets mapped as having moderate liquefaction effects, and 6% in streets as having no / minor liquefaction effects.

There were very few failed 400 V distribution-type cables.

Figure 4-50 shows damage to a direct burial 11 kV cable. Figure 4-51 shows damage to two 66 kV pipe-type oil-filled cables in direct burial with thermal backfill. The lack of reinforcement allowed permanent ground deformations at this site to concentrate movement at a discontinuity of the thermal backfill; leading to high curvature and failure. Figure 4-52 shows damage to three 66 kV XLPE cables.

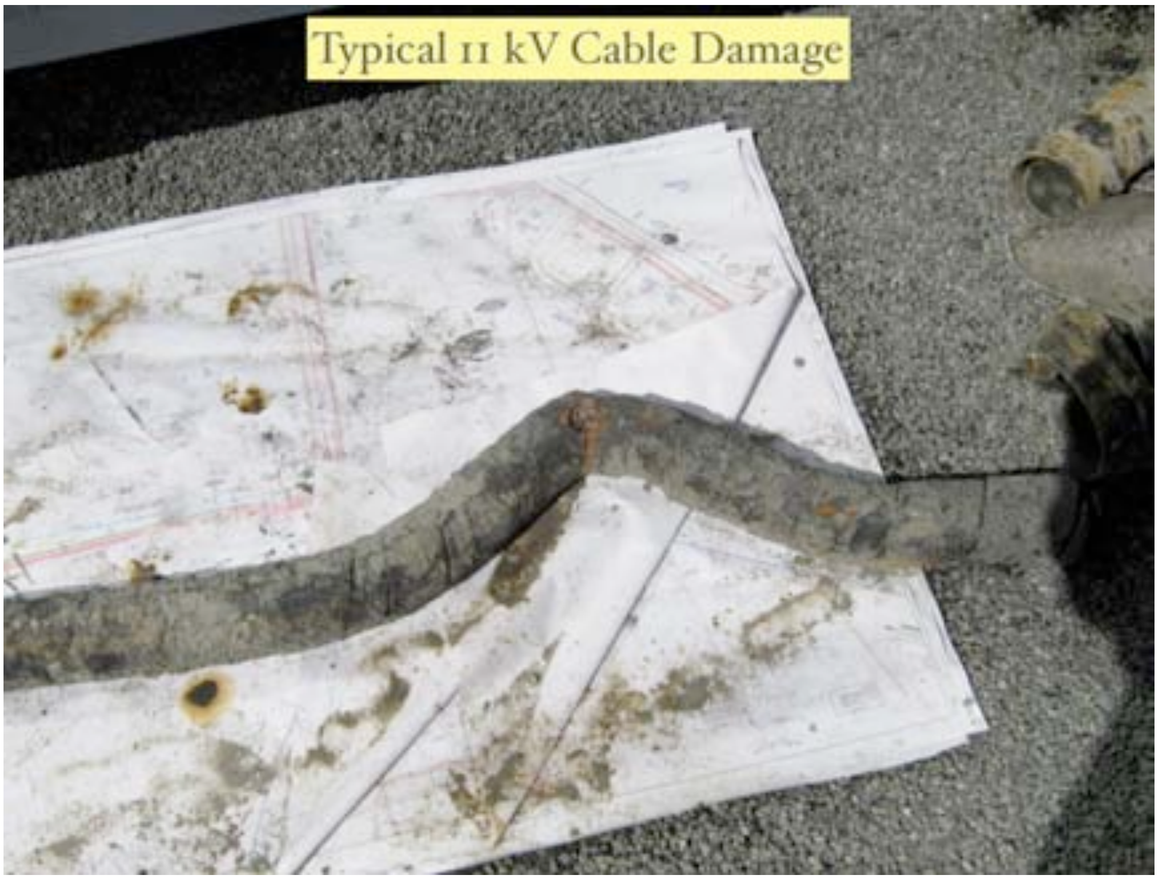


*Figure 4-50. Failure of Typical 11 kV Buried Cable, Feb 22 2011*

*Figure 4-51. Failure of Two 66 kV Buried Oil-Filled Cables, Feb 22 2011*

*Figure 4-52. Failure of Three 66 kV Buried XLPE Cables, Feb 22 2011*

Figure 4-53 shows the cross section of the damaged 66 kV oil-filled pipe-type cable. Figure 4-54 shows the cross section of a damaged 66 kV XLPE-type cable.

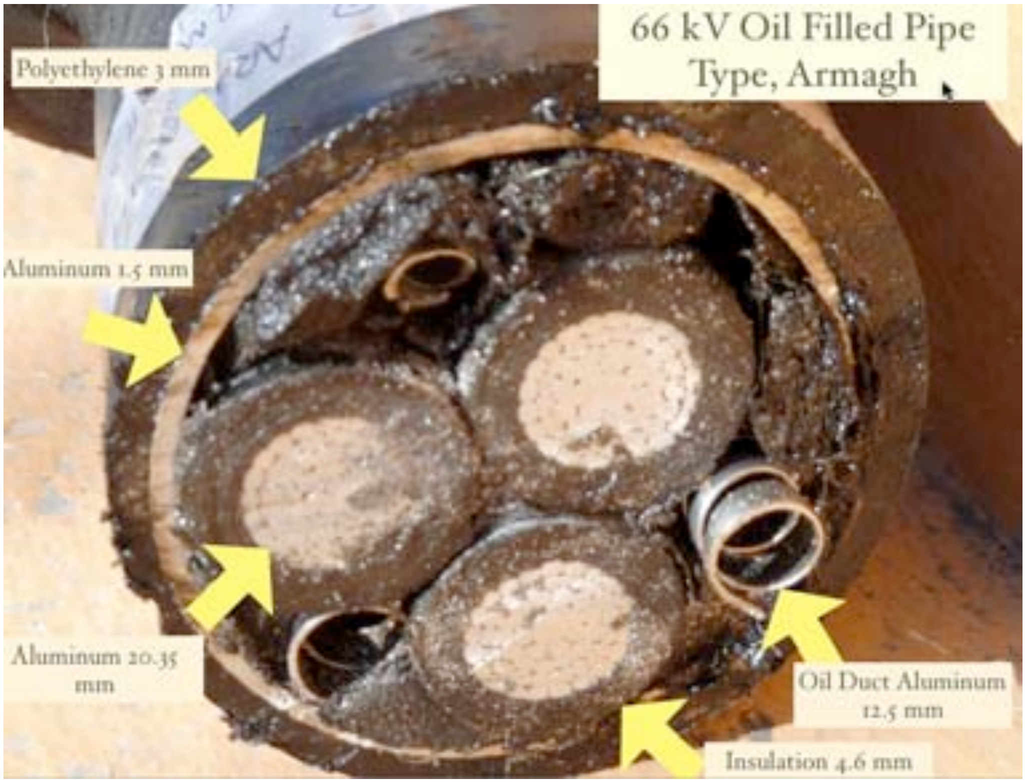


*Figure 4-53. Cross Section of 66 kV Buried Oil-Filled Cable*

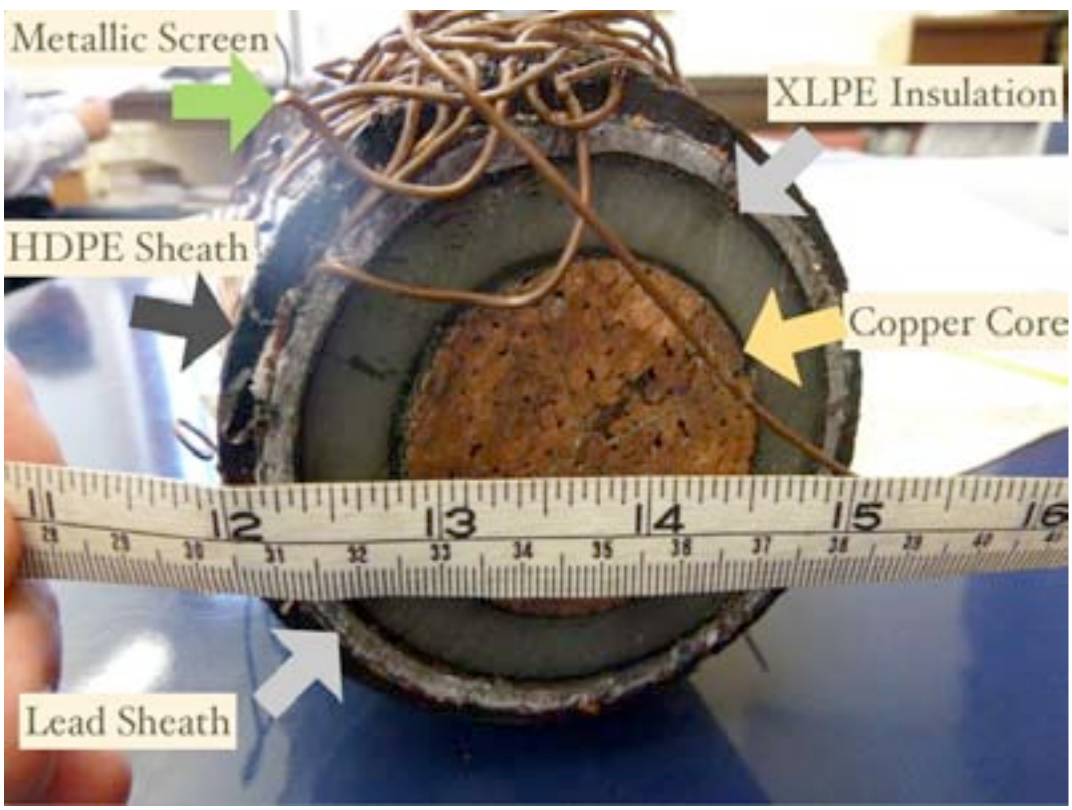


*Figure 4-54. Cross Section of 66 kV Buried XLPE Cable (Scale is inches / cm)*

*Figure 4-55. Cross Section of 11 kV Buried Cable*

Figure 4-56 shows the oil tank for the Dallington No. 2 cable. The tilted tank is evidence of the liquefaction at the Bromley substation site; but more importantly, the tank pressure gage reads 0 psi (0 kPa), reflecting that the pipe-type cable has failed.

*Figure 4-56. Oil Tank at Bromley Substation for Dallington No. 2 66 kV Cable.*

## 4.5 Orion System Performance – June 2011

The Orion system suffered additional damage in the June 2011 event. Relative to the February 2011 event, the June 2011 event was much less damaging. Through August 2011, the repair cost for the June 2011 event was about $3 million; $40 million for the February 2011 event; and $4 million for the September 2010 event.

## 4.6 Mainpower System Performance – September 4 2010

Mainpower is the electric distribution system operator for Kaiapoi and nearby Pines Beach. Both these areas suffered extensive liquefaction effects in the Sept 4 2010 earthquake.

Figure 4-57 shows a location along Beswick Street. The electrified lamp post has dropped about 1.8 m (6 feet), and yet the light is still illuminated. This type of installation uses relatively short lengths of low voltage buried cable, demonstrating that, at least in this case, that the flexible cable was able to sustain the differential settlements.


*Figure 4-57. Electrified Lamp – September 4 2010 – 1.8 meter movement*

Figure 4-58 shows a damaged buried cable (11 kV) in Kaiapoi, located opposite the police station on Williams Street. There were several other damaged buried cables in the Mainpower system.

Figure 4-59 shows the pulled cable to a house meter box in Kaiapoi. Along this street, ground settlements and lateral spreads were commonly on the order of 150 mm to 300 mm. While the houses were racked, none collapsed.

*Figure 4-58. Damaged Buried Cable– Sept 4 2010 – Mainpower*

*Figure 4-59. Damaged Cable to House Electric Meter – Kaiapoi – Sept 2010*

Figure 4-60 shows a damaged distribution cable in Kaiapoi. Figure 4-61 shows the buckling of power and other cables out of a cable tray that crosses a small creek in Kaiapoi; the banks of the creek showed a lateral spread.

*Figure 4-60. Damaged Distribution Cable – Kaiapoi – Sept 2010*

*Figure 4-61. Buckled Distribution Cables – Kaiapoi – Sept 2010*

Figure 4-62 shows a temporary generator in use in Kaiapoi after the September 2010 earthquake. These were being use to supply power to parts of the community that had severed distribution buried power cables. Similar generators were also used in Christchurch after the February 2011 earthquake, for the same reasons.


*Figure 4-62. Temporary Generation – Kaiapoi – September 2010*

Figure 4-63 shows the power restoration of the Orion distribution system after the February 2011 earthquake. The vertical axis is MW (peak hour). Peak load for Orion is typically in the wintertime (space heating), around 650 MW; or 400 MW in the summer time. As of 42 days after the February 2011 earthquake, power demand had returned to about 85% of normal for that time of year.

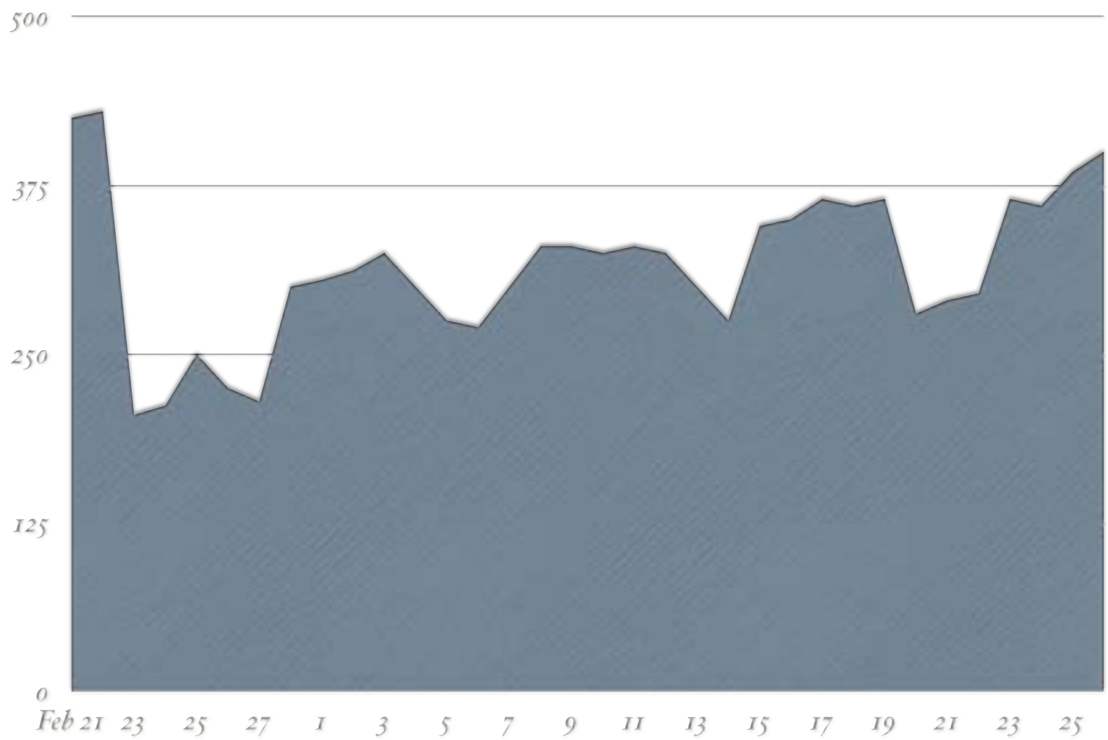


*Figure 4-63. Power Restoration – Orion – February and March 2011*

## 4.7 Acknowledgements

Many people from Transpower, Orion and Mainpower contributed to the findings. John O'Donnell and Shane Watson and Roger Sutton (Orion) provided detailed information for the performance of the Orion system for all three events. Kim Glover, Wayne Youngman, Peter Greenway, Ian Burgwin, Andrew Renton, and Christophe Tudo-Bornarel (Transpower) provided information for the Transpower system. Greg O'Sullivan (Mainpower) provided detailed information for the performance of the Mainpower system in the September 2010 event. John Mackenzie described the damage and seismic mitigation actions taken by Transpower and Orion, both before and after these earthquakes; he also led site visits to several substations.

# 5.0 Telecommunication

In 1978, the divestiture of the New Zealand Post Office created Telecom, a state owned enterprise. In 1990 the business was bought by Bell Atlantic and Ameritech that own telecommunications businesses in the US. In 1993 Bell Atlantic and Ameritech reduced their ownership of Telecom. In 1993 Bell South created Vodafone providing cellular service to compete with Telecom in New Zealand. By 1998 the presence of US ownership in these two companies was close to nil.

Still, with the influence of the US presence for two decades, the telecommunication network in the Christchurch area in general is similar to that of North America. However, the network elements consist of different vintages of equipment including the network cabling materials.

Wireless services in New Zealand have gained huge momentum due to the rapid increase of demand. Hence, deployment of wireless networks by competing service providers render good coverage in densely populated areas. In order to capture market share, the speed of cell site deployment (aka Base Transceiver Station (BTS[1]) has priority over many perceived non-critical or low probability issues, such as earthquakes. For example, installation of BTS on roofs of commercial buildings is common, but without careful detailing, these types of installations might not be ideal from an earthquake point of view.

During the TCLEE post earthquake lifeline performance visit, with the help of Dave Brunsdon, National Engineering Lifelines Co-coordinator and Tony Fenwick, Infrastructure and Policy, we had the opportunity to meet the two major service providers of Christchurch and its vicinity to collect post earthquake performance information. Many lessons were learned from both service providers as to the steps they had taken to reduce damage, as well as lifeline interdependence. We observed that there remain lots of opportunities for both engineers and policy makers to explore and establish economically viable plans to reduce future earthquake damage and to improve performance.

For both the September 4 2010 and February 22 2011 events, there were a variety of damage-points in the nodes and links of the telecommunication networks; however, in both earthquakes, the loss of offsite electric power and limited duration of emergency backup battery power dominated the post earthquake performance of telecommunication services. Contributing causes to the service outages was damage to underground facilities mainly due to liquefaction ground failures due as settlement and lateral spreading.

## *5.1 System Performance – Earthquake of September 4 2010*

It has been widely reported in newspapers that the Telcos performed "very well" in the September 2010 earthquake. Without doubt, several actions taken by the Telcos prior to the earthquake reduced the amount of damage to their infrastructure, and reduced the

[1] In this chapter BTS will be used.

length of service interruptions. However, there were still a number of issues that occurred in the September 2010 earthquake that resulted in widespread service outages. Therefore, one cannot say the service providers passed this earthquake with "flying colors", if one is to adopt a policy of having essentially continuous communication service over the entire affected area. The problem is not that they were not prepared, but more that their preparations were not complete.

Both the September 2010 and February 2011 earthquakes identified several weak links in the systems, as will be discussed in the next sections. Had the duration of strong ground shaking of the September 2010 earthquake been longer, or the epicenter been closer to Christchurch, there would be more damage and the service disruptions would have been much longer and more widespread[2]. In such case, other lifeline service providers such as power and water that used cellular services as their primary dispatch tool for repair and maintenance crew would have a much longer recovery period.

Due to the widespread loss of commercial power (see Chapter 4), there were many battery related problems in the Telecom systems. These problems stem from three problems: insufficient reserve power; age of the batteries; and inability to rapidly deploy a sufficient number of emergency generators to re-charge the batteries. The logistics of mobilizing large numbers of power generators was tested, and the need for improvement was recognized. There were a few minor equipment problems but there was no equipment building damage. However, the telecommunication service outage, service brownout, and congestion lasted a couple of days after the Sept 2010 earthquake. Brownout means normal maintenance and upgrade service efforts were stopped and service will be focused on outages; that is restoring service to customers without service only. By the 13th of September 2010, 9 days after the earthquake, some customers were still having problem with broadband services in Christchurch[3].

Since most utilities use cellular service as their primary communication tool for normal and emergency operations, the service providers prioritized service to power company in order to help themselves.

Emergency procedures will be improved from lessons learned.

## 5.2 Cellular System (Mobile System)

Both service providers had experienced similar set backs without major failures of BTS in both networks. The common failure modes that caused service disruption were:

- Ran out of battery power,

[2] According to Telecom, service restoration was done more effectively after the February 2011 earthquake than the September 2010 earthquake, reflecting the lessons learned from the September 2010 earthuqake.

[3] According to Telecom records, service was entirely restored 7 days after the earthquake.

- Antenna tower out of plumb or loosened guide wires, and
- Minor circuit congestion.

Due to power outage many BTSs were not operating, which created pockets of uncovered areas. In addition, repeated speed dialing caused circuit congestions that further impaired the network.

In many BTSs, both service providers decided to conserve battery power by switching from 3G (uses more power) to 2G (uses less power) service. In some cases, this strategy was success in that it provided sufficient time to bring in power generators to maintain BTS operation.

Contractors offering support were turned down due to difficulties in managing additional resources. The unclear scale and severity of damage was the main reason in making this decision.

### 5.2.1 Telecom New Zealand

Chorus is one of the four divisions of Telecom New Zealand (TNZ will be referred to as Telecom in this chapter). Chorus is New Zealand's largest telecommunications utility provider. They maintain and build the TNZ's local access network. That network is made up of local telephone exchanges, cabinets, copper and fibre cables. It connects around 1.8 million New Zealand homes and businesses throughout the country. Chorus were responsible for repairing damage to the access network to any of Telecom's impacted network elements, as well as providing power and building restoration services to any impacted Telecom exchanges. Therefore Chorus played an important role in the post earthquake emergency and recovery effort.

Chorus had good working relationships with their contractors and the power company, which resulted in minimal delay in their recovery effort. Civil Defense support such as allowing access to secured zones and logistics was helpful in restoring downed sites.

Since Telecom owns a vast network of cellular, landline, and emergency call services, Chorus had to handle more cases of glitches. Section 5.2 will focus on cellular network and its services.

Chorus' main focus was to ensure power to and connectivity of the cellular network's base transceiver stations. Offsite (Orion) power outages were the main cause of downed sites; although there were also sites with antenna towers out of plumb due to ground settlement or liquefaction. Under normal (non-earthquake) conditions, urban sites without an on-site power generator usually have 2 hours of battery reserve power, while remote sites have 5 hours of battery reserve power. About 500 sites (sites without power generator) were impacted by Orion power outages. Power restoration started within 2 hours after the main September 4 2010 earthquake. It was difficult to access priority of generator deployment initially. A number of small power generators were available locally. Within a day after the earthquake, 60 more power generators were shipped in from other Telecom facilities within the South Island and then from facilities in North Island.

At Kaiapoi Exchange the antenna tower of the cellular network had a 1° to 2° slant from vertical due to ground slumping, Figure 5-1. Operation was not affected. The fix will be determined later. The antenna tower at Gailbraith Mobile site had 5° lean, Figure 5-2. Again, operations were not affected. Two cable guided antenna towers had slack guide cables, most likely the anchor points were affected by ground deformation. The towers were not in danger of collapsing and the sites remained operational.

The most difficult part of restoring cellular service was access to leased buildings that were not accessible due to safety concerns.

Although there was traffic congestion on the network, the network remained stable.

*Figure 5-1. Kaiapoi Exchange Antenna tower slant about 1° to 2° (Courtesy Telecom New Zealand)*

*Figure 5-2. Antenna tower base at Gailbraith Exchange rotated 5° (Courtesy Telecom New Zealand)*

### 5.2.2 Telecom Emergency Response

The "War Room" in Telecom House was set up to handle the emergency situation and manage resource allocation within about an hour after the September 2010 earthquake. The building is in the Central Business District (CBD) of Christchurch that was secured by Civil Defense. Telecom exercises its Crisis Management capability periodically, and this is one reason that Telecom was able to rapidly respond to the impacts caused by the earthquake.

The decision was made to relocate Call Centre services to another Telecom site. There was some minor damage to the facility, and the relocation helped to allow the local staff time off to handle family commitments as a result of the earthquake. The 111 ICAP Emergency call service in Wellington continued to operate in tandem with the Christchurch-based service, as per normal. The 111 Emergency Service Operation is the same as the 911 PSAP (Public Safety Answering Point) in North America.

Special skilled employees needed for the restoration effort were brought in from outside of the earthquake impacted area to supplement locally-available contractors. Employees not involved in the post earthquake recovery effort were allowed "special leave", which was lasted about a week.

Daily interface with Civil Defense was one of the main efforts to provide quick access to the secured zones to performance recovery services to sites within the secured zones.

About 1200 employees were affected. Upon returning to work they had to attend a health and safety briefing to ensure some basic awareness in a post earthquake situation was known. Reviews with the staff after strong aftershocks were also performed to instill confidence. The Telecom Human Resources response team provided staff support throughout both the September 2010 and February 2011 earthquakes.

In order to speed up restoration and recovery prioritization decision, future network information from Network Operation Centre in Hamilton will be structured.

### 5.2.3 Vodafone

Vodafone has a larger market share of the mobile service in New Zealand with Telecom the strong contender. As Vodafone was established as the mobile service company, their strength is in the cellular services. This earthquake tested their processes and procedures in service recovery and mobilizing resource to cope with the service interruptions.

Vodafone has both contractors and staff to perform maintenance and emergency services. Vodafone has good relationship with contractors that work on various projects and maintenance.

Within hours after the Sept 4 2010 main shock that hit Christchurch, 98 Vodafone sites (BTS, Technology Centre, and micro-sites) were identified with power failure and were on battery power.  63 sites were progressively going down with battery power running out in the morning of September 4, while 35 sites were at risk with the same fate. By about 9 a.m. September 4, 30 2G BTSs were down due to loss of power, and 59 2G BTSs were operational, Figure 5-3. That is, about 34% of the 2G BTSs within the greater area of Christchurch were out of operation.

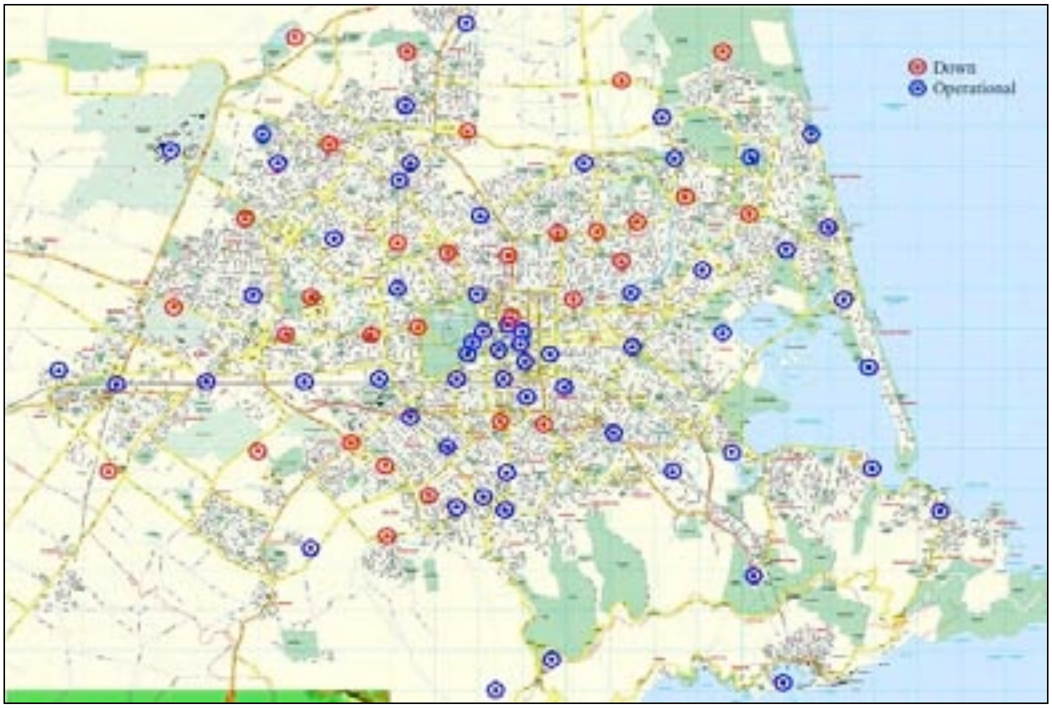


*Figure 5-3. Locations of BTS out of power (Courtesy of Vodafone New Zealand)*

Generators of various sizes were deployed to maintain or restore service where sites were in power outage areas. Figure 5-4 shows one of the remote sites receiving a larger size generator in case of prolonged power outage. Note that the building has a quick connect box on the outside to facilitate fast hook up.

For 3G sites that are co-located with 2G services, 3G service was switched off in order to conserve battery power, particularly critical transmission hubs. In addition, a countrywide brownout was put in place to ensure network stability.

The impact was about 60% mobile traffic congestion, but the system remained stable. By about 10 am September 4, 16 sites had generators deployed by Downer EDI, contractor of Vodafone; 40 portable generators and 4 trailer generator sets were being brought in from Otago, Auckland and Wellington. Plans for 30 generator sites of the access and transmission offices were established in case of long duration power outage. By the evening of September 6 2010, two 3G and one 2G sites were down with one site running on generator. An 1100 kilowatt power generator was deployed to CTP as a backup to the generator on site.

At the Round Top site, the battery failed prematurely. It ran for only 15 minutes after power failure.

*Figure 5-4. Power generator installed at this Vodafone remote site (Courtesy of Vodafone New Zealand)*

Due to reduced capacity resulted from downed sites, voice traffic was prioritized over data traffic.

It was reported that one BTS site at Lyttleton Port had its antenna tower knocked out of plumb due to ground settlement.

All sites were running normally by September 13 2010, 9 days after the earthquake. Remedial works were needed for 6 sites after completing inspection of the last 16 sites of a total of 127 sites.

### 5.2.4 Vodafone Emergency Response

Two hours after the main shock of Sept 4 2010, at 7:30 AM the Emergency Management Team (EMT) was initiated. It was reported back to the CTO (Chief Technology Officer) that all Christchurch staffs were accounted for.

All resources movements were tracked from CTP. In order to ensure good response from all staff in the Christchurch area, Vodafone initiated three activities:

- Structural engineers were deployed to inspect employees' houses. This was funded by Vodafone, and
- Relief teams were brought in from Auckland to help employees for health and safety issues, and

- Care packages and additional leave for local (Christchurch) employees impacted by the earthquake.

A refueling plan was put in place in case of extended power outage. Key staff were put on standby to work 24/7 for the first 7 days after the earthquake.

A helicopter was used to investigate and inspect possible transmission faults in remote areas. Excellent support from contractors was experienced.

In addition, Civil Defense support was critical in logistics and access to secured areas to perform recovery activities.

Vodafone was also equipped with Cellsite On Wheels (COW). If a BTS collapsed, the COW could be moved to the vicinity of the damaged BTS in order to restore the cell quickly, Figure 5-5. The COW is a self-contained unit with all the necessary equipment to operate as a BTS. Note the telescopic pole for mounting antennas when deployed in the field. The capacity of the COW may have a lower capacity than the original BTS it replaces, but it provided coverage.

*Figure 5-5. Vodafone Cellsite On Wheels (COW).*

## 5.3 Landline System

The landline system is mainly owned by Telecom. Although Vodafone also provides home phone and Internet services, the majority of the landlines were leased from Telecom. The interconnection links used between the Central Offices are cables and wireless. Both copper and optical fiber cables are used, while wireless depends mainly on microwave. Interconnections between BTSs and Mobile Exchange Offices use the same methods.

In the poor soil areas of the earthquake impacted zones, underground cabling systems sustained damage due to water leaks and stretched cables.

### 5.3.1 Telecom

The landline system is also the responsibility of Chorus. Telecom network links have different vintages of cables, including both paper insulated copper cables and optical fiber cables. A plan was initiated to slowly replace copper cables by optical fiber cables to increase the broadband speed and capacity.

Telecom sustained heavy cable faults and some broken cable as a result of the earthquake. The aerial system had damage reported, but still performed well, except for a number of tilted utility posts in the poor soil areas. There were some non-structural damage at a few Telecom buildings, but the network operation was not impacted. Network traffic was heavy but congestion was minimal and did not affect the network. The most requests after the earthquake were relocation services of landline phones. This was mainly due to houses damaged in this earthquake. Also it was difficult to keep up with the demolition of condemned buildings to disconnect the cable. Most Central Offices are equipped with power generators. One generator failed to start automatically due to damage of the transfer switch (thought to be caused by high vibrations). It was started manually after the fault report was received.

The Call Center at Christchurch was given a yellow sticker due to ceiling and window damage, which was repaired within 24 hours and a green sticker was then posted allowing Telecom employees to enter the facility. The Kaiapoi Exchange concrete slab slumped about 100 mm, but the equipment was not affected and remained operational, Figure 5-1. The Halswell Exchange concrete slab base cracked, the fuel tank for the power generator and the manhole were raised due to liquefaction, Figures 5-6 and 5-7. The Hororate Building is a wood building on piles; it moved sideways about 100 mm and was lifted back without affecting the equipment operation and there was no cable damage due to the building lateral movement.

*Figure 5-6. Halswell Exchange, the underground fuel tank was raised due to liquefaction (Courtesy of Telecom New Zealand)*

*Figure 5-7. The manhole outside Halswell Exchange was also raised due to liquefaction (Courtesy of Telecom New Zealand)*

Roadside cabinets of the DSL (Digital Subscriber Lines) circuit had minimum battery backup, but all these cabinets had quick external power connection on the outside.

Cable fault level was back to normal within a week after the earthquake. However, underground cable upgrades in Christchurch and the vicinity were still on going as of October 2010, Figures 5-8 and 5-9. The underground cable repair shown in Figure 5-8 was located in Christchurch where significant liquefaction occurred. The cable repair shown in Figure 5-9 was located at the intersection of Charles St and Jones St in Kaiapoi. It is on the west side of Charles St, the coordinates are 43.3838°S, and 172.6603°W. This location is very close to the riverbank and liquefaction occurred in this area. In both cases the plastic conduits are used for routing optical fiber cables. Telecom is aware that more cable faults will be showing up.

*Figure 5-8. In Christchurch, contractor was routing optical fiber cable to repair cable damage in this area.*

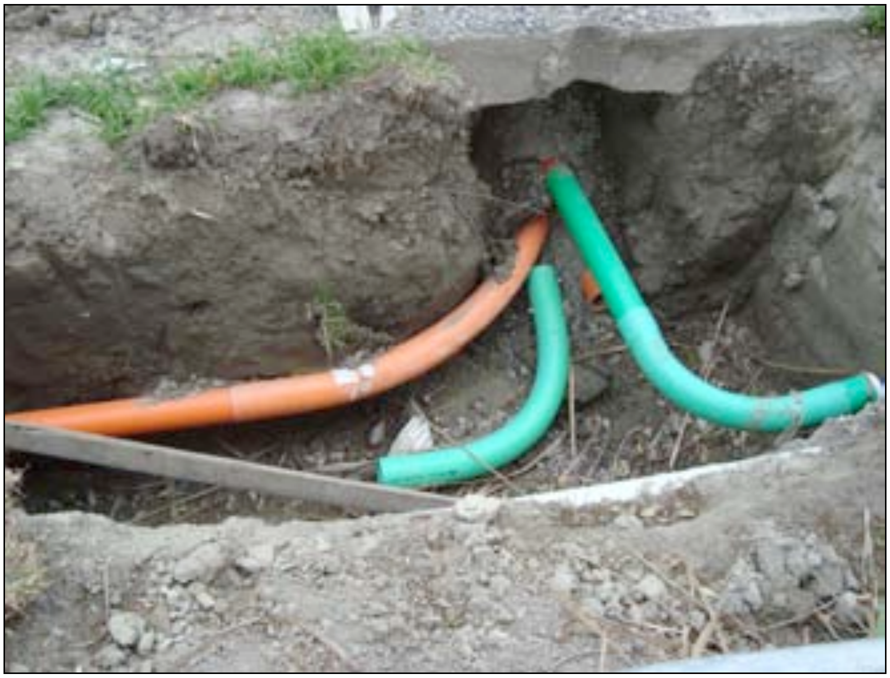

*Figure 5-9. Under ground telecommunication cables repair, plastic ducts were used in this area northeast of Christchurch.*

### 5.3.2 Vodafone

Vodafone had 4,000 customers with fixed line services went down due to Telecom cable faults and damage. This is a contracted wholesale service from Telecom. By the 13th of September 2010 Chorus reported to Vodafone that 13 out of 109 affected cables still need to be fixed. This affected Internet services to Vodafone customers.

## 5.4 Major Observations and Recommendations

Landline services will soon be replaced by wireless services in the near future. This is definitely the case in voice service from recent surveys in North America where cellular voice subscribers are rapidly increasing, while the number of landline voice subscribers remains flat or is decreasing.

When cellular service was initially deployed in early 1980s, the cell network was not considered an essential service. But, with the change in usage over time, it is now a good time to change and ensure a more earthquake-resilient cell network.

The September 2010 earthquake reinforced again the importance of reliable power supply and a more robust network control management.

Telecommunications service providers in New Zealand have been steadily enhancing seismic performance of their systems and were making a lot of right decisions to mitigate earthquake damage. While the overall telecom system performance shows the result, however with the setbacks that actually occurred, it is apparent that improvements are still needed.

We had the opportunity to tour a key Vodafone switching facility. From what we saw at this recently-constructed facility, it is apparent that there have been serious effort to build new infrastructure with the intent to ensure a resilient network in an earthquake environment. The building was constructed to survive an extreme event. The equipment inside was either anchored to the floors or a combination of anchors and overhead braces to prevent toppling, Figures 5-10 and 5-11. A robust overhead steel structural frame work was used to secure cable racks and light fixtures to prevent shaking damage, Figure 5-12. The backup power generator for the equipment was properly installed. The starter battery mount was anchored to the floor and the batteries were retained with a steel bar to prevent shaking damage, Figure 5-13.


*Figure 5-10. Equipment anchoring, Vodafone.*

*Figure 5-11. Overhead bracing of tall and slender equipment, Vodafone.*

*Figure 5-12. Cable rack structural frame securing the cable racks and light fixtures, Vodafone.*

*Figure 5-13. Starter battery mount for the backup power generator, Vodafone*

However, we observed a few items that require improvement. Figure 5-14 shows a piece of test equipment sitting on an open shelf without being tied down, and Figure 5-15 shows a cart with casters (the casters may have locking device) and not secured to the wall. The equipment mounted on the wall with a power adaptor plugged in the wall socket (Figure 5-16) should be hard wired or a device used to prevent the plug from being accidentally unplugged.

*Figure 5-14. Test equipment shown was not secured to the shelf.*

*Figure 5-15. The cart shown was not secured to wall or to the floor. The wheels may be locked but the cart can topple or the equipment on it may fall.*

*Figure 5-16. Power connection not protected from accidentally unplugged*

Strategically located storage facilities for resources during emergency should be developed. Emergency required materials such as mobile power generators, fuel, Cellsite On Wheels (COW), Switching On Wheels (SOW) and spares should be available for at least 75 % to 80% of the calculated damage for the area the storage facility was planned cover. Agreement with heavy equipment rental company should be put in place for post disaster deployment.

Alternate routes to access remote sites should be developed in case the primary route was not available after the disaster.

Other considerations such as economic impact to businesses, cost effectiveness (including impact to the business bottom line) of the improvements, the cost of recovery (including the capacity and resource availability), and life safety should be part of the overall equation when developing the above recommendations.

## *5.5 Earthquake of February 22 2011*

Due to extensive liquefaction and lateral spreading causing wide spread building damage in Central Business District (CBD) of Christchurch resulted in more problems with the cell sites and exchanges. Although there was no significant equipment damage, the reserve power supply continued to be the major problem area of the networks. The September 2010 earthquake did not help, as the batteries in many cases experienced degradation of capacity. Also the post September 2010 event plans to replace aging batteries have not started.

The service providers learned new lessons in this second event. The closing of the CBD with restrictions of access created additional emergency protocol changes to handles problems within the equipment buildings. Service providers with redundant critical operations and emergency centers can easily handle the cordon situation.

### 5.5.1 Overview

Due to extensive building damages within Christchurch CBD, many cell sites installed in the impacted buildings experienced problems that were unique depending on the degree of structural damage. The service providers had to readjust the routing of their networks to bypass CBD to maintain service, to monitor network congestion, and to provide circuits to the district where most of the businesses had relocated. Duration of service interruption varies with locations and service providers. Some areas had longer service interruption with some service providers, while some areas had shorter service interruption with the same service providers.

While in the cordon area, about 50% of public phones still had dial tone, indicating that the End Offices they are connected to were still functioning once power was restored.

The overall performance of telecommunication was reasonably good. From the information collected, all the service providers had about the same problems, and these are discussed in the following sections.

### 5.5.2 Chorus

Chorus is the major service provider of landlines, wireless, and Internet data services. The following information was collected through a meeting with local Chorus management team.

Asset checking and restoration efforts were set up within four hours after the earthquake. The earthquake on September 2010 had effectively allowed a smooth execution of the plans. As part of the emergency response plan, the primary emergency operation center, called ‘war room’, was relocated out side of the cordon area immediately. Good communication access and procedures are the factors contributing to the effective response.

Christchurch Call Centre activities were transferred to other national sites. All local staffs not involved in the emergency process were placed on “special leave” for about a week after the earthquake.

Similar to after the September 2010 Earthquake, contractors were deployed to provide additional resources to help local emergency response groups. Special skilled staffs were brought in from other parts of the country to support specific tasks.

Similar to after the September 2010 Darfield Earthquake, contractors were deployed to provide additional resources to help local emergency response groups. Special skilled staffs were brought in from other parts of the country to support specific tasks. However, this event demanded more resources than the September 2010 earthquake. There will be many lessons and changes to emergency response plans to deal with future larger events of natural disaster.

***Operations***

Emergency call (111) centre in Christchurch CBD was migrated to an alternative site, although this site was functioning. The move was to ensure easy access to the operation since access to the cordoned area was a challenge.

Core network was severely congested particularly in the middle of the day. The main reason was the cable faults were about 4 times that of the September 2010 earthquake.

Requests of relocating service was much higher than the September 2010 earthquake, mainly due to the CBD being cordoned off.

There was no damage to the 7-story Christchurch Telephone Exchange, but it was within the cordoned area, so relocating 1,500 Call Centre staff became a challenge. Some of them were collocated with Telephone Exchange. This is also Telecom's third priority site nationally and a significant network hub for South Island and Christchurch. The building lost power and was restored within a week, as Orion had to clear other customer connections first. Water supply was lost to cooling tower, so an on-site shallow bore remediated the problem. There were significant cracks in the telecommunications cable tunnel in the street, leading to a potential to flood basement of the exchange. Repairs now completed. The risk of adjacent buildings collapse posted a high risk to operation and access of this site. Mitigation measures were in place to reduce the risk.

***Power***

Power outage duration and the time table of power restoration was difficult to access. Orion did provide a daily update, which helped and was much better than in September 2010.

Access network street cabinets were all battery backup only. Cell sites in urban areas have 2 hours of battery backup, while for rural areas the backup is 5 hours. In some instances, that was not long enough to allow generators to be brought in. Major exchanges have generator backup. About 500 sites were affected by power outage, the rate of power recovery was much slower than in September 2010. About 80 engine generator sets were brought in within 12 to 24 hours after the earthquake. Some of them were brought in by Air Force transport.

Customers with phones that require power could not access the network. Telecom shipped in a significant number of phones that could operate off power provided via the POTS lines and these phones were distributed via Telecom Hub centers and retail stores, free of charge.

***Cables***

In liquefaction affected areas, particularly along the Avon River, buried cable damage was extensive. Modes of damage were: i) cracked sheaths, ii) water leak into cable, and iii) cable being pulled apart. The cable fault levels had taken about 6 weeks to come to normal. Street cabinet affected by liquefaction and cable was damaged, Figure 5-17.

Due to extensive damage to the New Brighton area POTS[4] service cables that fed the 11 FTTN[5] Broadband cabinets, these cables were either not repairable or would take too long to be repaired. The decision was made to convert the approximate 1000 customers to a ISAM[6]-V type service using the fibre feeder cable to the new FTTN cabinets and then the copper to customers. Telecom had not previously used this technology for residential customers.

[4] POTS = Plain Old Telephone Service

[5] FTTN = Fiber To The Node (Neighborhood)

[6] ISAM = Integrated Services Access Manager

More manholes were affected by liquefaction than the September 2010 event. Both plastic conduits and fibre cables had minimal damage. Permanent restoration is estimated to take about 12 months.


*Figure 5-17. Street Cabinet impacted by liquefaction, note the slight uplift of the manhole*

***Property***

A standing contract with Structural Engineers was activated one day after the earthquake to assess all Telecom facilities within the earthquake affected area. All sites inspected were green ticketed except 3 facilities. The property inspection took about 4 weeks.

The Kaiapoi Exchange that sustained some damage in the September 2010 event did not have any further damage (ground motions in Kaiapoi were much smaller in the February 2011 event).

The Gailbraith Mobile Site also did not have any further damage and the fix fro the September 2010 event was still on going.

The Mt Pleasant Exchange sustained damage to its walls and floor. One equipment cabinet straddled across the crack was relocated. This building was yellow tagged originally.

The Shirley Exchange suffered a crack across the building extension. A permanent fix needed to be designed and specified, Figures 5-18 and 5-19.

*Figure 5-18. This equipment was straddled across a crack along the floor. It was relocated. (Courtesy Telecom NZ)*

*Figure 5-19. Weather seal was placed on the cracked expansion joint at Mt Pleasant Exchange.*

The Burwood Exchange had a minor external crack on the wall.

The Liwood Mall Cell Site had a bit dusty due to fallen ceiling tiles, Figure 5-20.

*Figure 5-20. Liwood Mall Cell Site, fallen ceiling tiles, the site was operational. (Courtesy Telecom NZ)*

At the Mt Pleasant Radio site, the end wall where the cable tray entry was located pulled away but did not collapse. The wall was shored to prevent damage to cables and cable tray, Figure 5-21.

*Figure 5-21. The URM wall was pulling on the cable tray at the MT Pleasant Radio site.(Courtesy Telecom NZ)*

***Cell Sites***

Two cell sites were destroyed; Sumner site was destroyed by rock fall and on the rooftop of the PGG Building was destroyed due to building collapse. There were a number of additional rooftop cell sites that were assumed to be permanently out of service, atop buildings that were deemed to be demolished. Five more sites than the September 2010 event had tilted antenna masts. Two cell sites on buildings significantly damaged were difficult to access and power was not available in one instance.

***Site Interdependence Issues***

Cables to condemned building had to be disconnection from the network. This task took lots of resources due to the large number of buildings to be demolished. Luckily service restoration in the CBD was not required as the customers could not access the cordoned area.

Restoring Cell Sites at leased sites within the cordoned area depended on building access. Coordinating with power restoration time table was also challenging. In areas where general power was not restore, there was no need to restore the FTTN cabinet, as the customers did not have power to run their computers.

***Emergency Response***

In general the overall emergency response executed by Telecom was effective. The long term relationship with contractors and the support from Civil Defense also helped to manage the impact and restore service.

However, Telecom NZ understands that there are works to be carried out to permanently restore normal service and also provide improvement. The continuous work includes:

- Mt Pleasant site – there are many options (repair, rebuild or relocate) to fully restore service from this site.
- Both Gailbraith and QE11 cell sites will continue to have an engine generator.
- Permanent accommodation solutions have been included in Telecom's local Christchurch decentralized business model.
- Testing of 250 FTTN street cabinets with battery ran out to ensure functionality.
- Protecting the access network such as cabinets and manholes to ensure the remaining network is operational.

### 5.5.3 Vodafone

With the experience just about six months ago, Vodafone NZ again mobilized their technology staff, and suppliers, including relief teams from other cities (Auckland and Wellington) in New Zealand. The priority was to restore service and maintain network functions for emergency response teams, Civil Defense, and businesses.

Due to extensive damages to Christchurch CBD, the network traffic was shifted to where the businesses were relocated. Vodafone technology staff quickly modified the network to meet the shifting demands.

The major problem again is loss of power to MTX, cell sites and Hub Site.

In addition to executing the highest priority actions, Vodafone technology staff also addressed the issues resulted from this earthquake. By addressing these issues, Vodafone will be in a better position to mitigate damage in future earthquake and natural disasters that can affect the network services.

The main issue was the cell site backup power. It did not perform to standard. From the September 2010 earthquake, battery aging was the problem causing cell sites to fail earlier than expected. The run down of batteries due to prolonged power failure and the time to set up mobile power generator sets in many cell sites did not help to maintain the same backup power duration after recharging. That is the September 2010 earthquake accelerated more batteries aging problem.

A program was in place to replace all old batteries right after the September 2010 earthquake. Now this program has to be accelerated. In this program, remote maintenance capability will be part of the upgrade. This capability allows operations to pin point battery problem locations so service teams can be dispatched quickly to fix the problem.

***Summary of impact***

The worst impact was in the CBD area, where Vodafone has major operations for both network and business. The major problem was the building damage of the Television New Zealand Building hub site, Figures 5-22 to 5-25. As the building is within the cordoned area, no one is allowed to enter the building. Although the operation has 24 hours of reserve power, and a power generator with 120 hours of fuel supply, Vodafone had to work quickly to transfer the functions of this site to other locations. Routing a new fiber cable out of Christchurch took 3 days. The most recent information is that this building will be reconstructed.


*Figure 5-22. The Television New Zealand Building that housed Vodafone hub site.*

*Figure 5-23. The rear of the building, note the microwave and cell site antenna.*

*Figure 5-24. The front columns of the building sustained significant damage.*

*Figure 5-25. TVNZ Building - close up of one of the columns damaged.*

The cell sites on roof tops of buildings that were set to be demolished were out of service. The total number could be up to 9 cell sites. 12 cell sites required significant remedial work, this included broken poles, foundation damage, etc., Figure 5-26.

*Figure 5-26. The cell site antenna pole tilted due to liquefaction in the Avon River area.*

The situation 15 days after the earthquake within the region was:

- 11 cell/hub on generator sets
- 10 cell sites were down
- 2 cell sites can't be repaired
- 4 COWs deployed to cover gaps and provide capacity at Civil Defense HQ (Art Gallery), Figure 5-27.

*Figure 5-27. COW set up outside of the Civil Defense HQ in Christchurch*

The large number of portable generator sets deployed required dedicated resources to keep them running. At the peak, refueling the 60 generator sets required two 24-hour shifts of 8 people per shift.

Microwave transmission repair and re-configuration to work around at high risk sites such as Price Waterhouse Cooper building.

Temporary Sales HQ with IT connections outfitted to connect to Vodafone network was carried out by the technology staff.

All in all, this earthquake required much more effort and resources than the September 2010 event.

***Emergency Response***

The remedial actions were:

- Deploy mobile generator sets,
- Send inspectors of buildings and equipment in the region to assess damage, and
- Deploy COWs for the uncovered sites.

## *5.6 Major Observations and Recommendations*

The risk of cell site installation on roof tops of commercial buildings that are not constructed for critical equipment is highlighted in the February 2011 earthquake.

Another major observation, which has repeatedly been seen in other earthquakes around the world, is backup reserve power of cell sites. The question is how much is needed. Each site has a different requirement, the main attribute is the time to get backup power generator to the site. Sites that require longer time to get to should have longer reserve power to keep the site functioning before power is restored. Of course, this is complicated by not knowing beforehand what will be the duration and extent of offsite power outages. As the Telecom operator will not normally be aware as to the seismic vulnerability of the power company, a first order estimate is that if the local power system uses buried cables (either transmission and/or distribution) and the area has lots of liquefaction zones, and the cables are not designed for earthquakes, then a strong local earthquake will result in long power outages.

This is a good opportunity for underground cable performance study by engineers to understand the modes of failure for the different styles of buried cables, due to liquefaction. A test program is envisioned at UC Berkeley to study the performance of buried power cables due to permanent ground deformations; further work in this area is encouraged.

## *5.7 Acknowledgements*

In addition to the kind support of Dave Brunsdon and Tony Fenwick, the authors are also indebted to Mr. Peter Anderson of Vodafone, Mr. Colin Foster of Chorus, Mr. Stewart Ross of Chorus, and Mr. Rob Ruiter of Chorus who gave us their valuable time providing us with their network performance details and their plans to mitigate future earthquake caused interruption of this critical lifeline services.

Their willingness to allow us to use the photos that they gave us in this chapter is much appreciated. Without these photos this chapter will not be complete and will not be useful to practitioners who read this chapter.

Except those figures/photos with a credit statement in the caption, all figures/photos belong to the ASCE/TCLEE team members.

# 6.0 Water

Potable water systems were damaged and in each of the three earthquakes. Much of the damage was due to broken water pipes due to triggered liquefaction (all three earthquakes). Liquefaction also damaged some wells in Christchurch in the September 4 2010 and February 22 2011 earthquakes. Landslides and road-fill slumps affected water pipes in the Port Hills areas in the February 22 2011 earthquake. Landslide movements may have contributed to damage to two concrete tanks in the Port Hills area in the February 22 2011 earthquake.

Repair of the broken buried pipes was generally the first order of business. After the first earthquake, one liquefied area has so much damage as to warrant complete pipe replacement; some HDPE pipe was installed in that area. In the February 22 2011 earthquake, substantial liquefaction occurred in the area with HDPE pipe; no damage was reported to the HDPE pipe. Prior to any of the earthquakes, HDPE pipe had been installed in Lyttleton to address ongoing corrosion and leakage issues with old cast iron pipe; in the February 22 2011 earthquake, ground shaking in this area was likely on the order of PGA = 0.7g to 0.9g; no damage was reported to the HDPE pipe.

The bulk of the discussion in Chapter 6 is for the water system serving Christchurch. One section highlights water pipe issues in neighboring Kaiapoi, which suffered liquefaction and water pipe damage only in the September 2010 event.

## *6.1 Historical Development of Water System*

Christchurch obtains its water supplies from wells which tap confined, high yielding, gravel aquifers. The groundwater reservoir underlying Christchurch and its environs supplies an average of 100,000 $m^3$/day (maximum to about 150,000 $m^3$/day) of high quality water to domestic users, and a comparable amount to industrial users.

Early settlers obtained their drinking water from ponds in the swampland. Later, wells were dug, with water raised from brick-lined wells by hand-pump or bucket and windlass.

Artesian water was discovered around 1858 from a shallow-driven pipe only 6 m deep. Soon, many wells became polluted from nearby cesspools, etc. Unhealthy sanitary conditions were reported in 1862 by the lack of surface drainage and sewage disposal. Thus, deeper wells were drilled, with an 1864-vintage well, with depth of 81 feet, spouting water up in a column at least 10 or 15 feet above the ground. By 1864, seven wells were completed, providing excellent water for potable and industrial purposes.

Many wells have since been dug, both public and private, ranging from 25m to 150m deep. Artesian aquifers have been found to underlie the coastal area extending inland to Kaiapoi, Belfast, Papanui, Fendalton, Riccarton and Beckhenham.

Surface flooding is a problem. Parts of the inner city have been flooded by the Waimakariri River in historic times. River control works, principally channel realignment and stop bank (levee) construction, have reduced the immediate risk, but have not entirely removed the flooding following heavy rain in the Waimakariri catchment. With the incidence of tectonic subsidence in eastern Christchurch north of the Banks Peninsula, lateral spreading of river banks resulting in reduction in river flow cross section, the potential for flooding (either heavy rain induced, or at high-high sea water level), has increased the potential for future flooding.

## 6.2 Christchurch City Council – September 4 2010

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 (Figures 6-1, 6-2) 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 (Figure 6-3) 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 (also 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.

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").

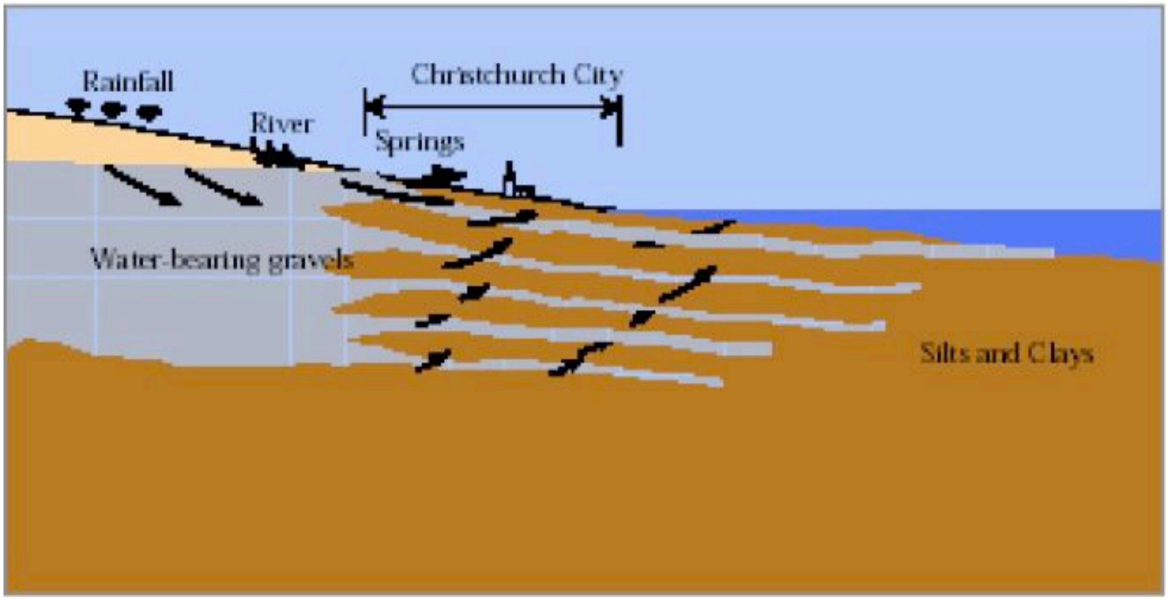


*Figure 6-1. Christchurch's Aquifers (from Water Supply Asset Management Plan, 2002).*

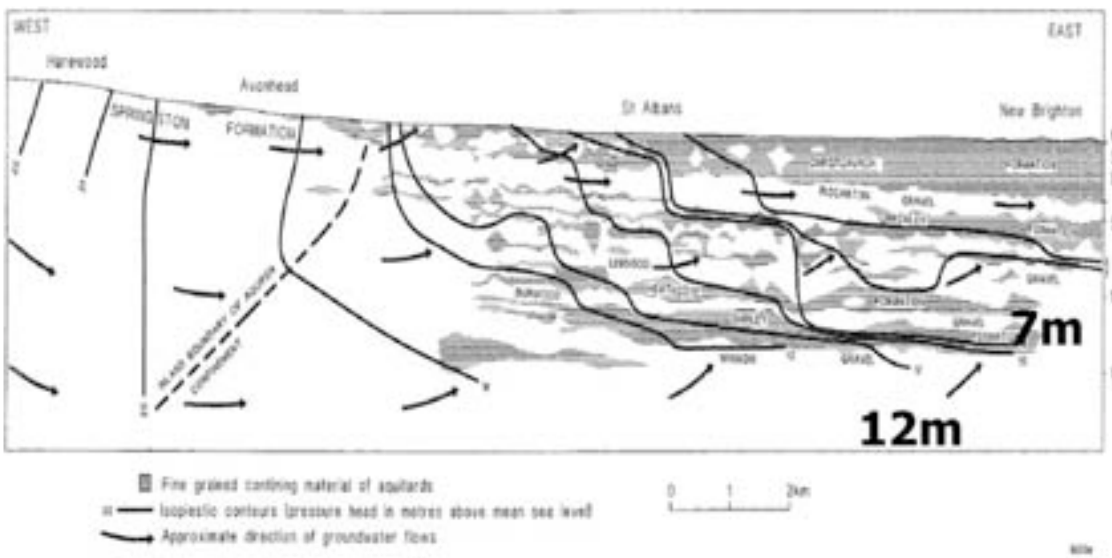


*Figure 6-2. Christchurch's Aquifers*

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).

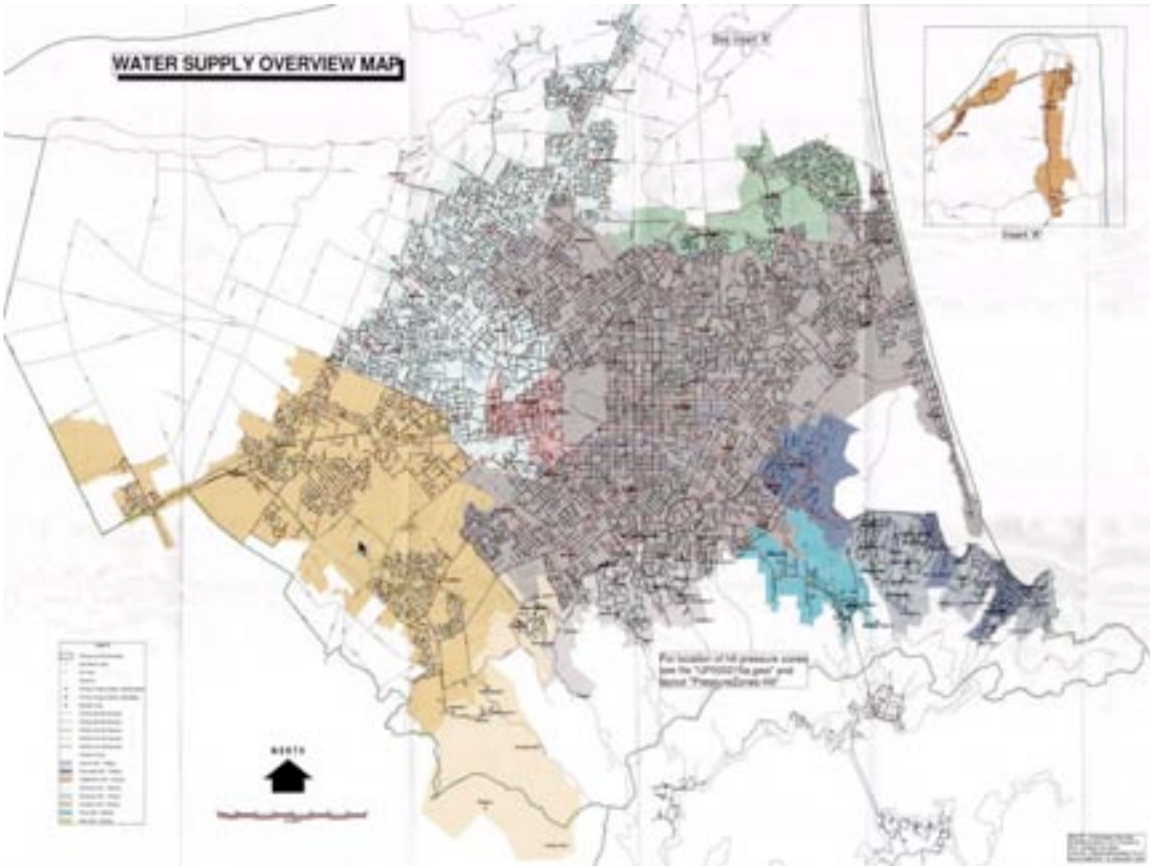


*Figure 6-3. Christchurch Potable Water System Map*

There are 27 water pump stations to boost water 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 complete building collapses in the water system, but it is understood that about 5 of the oldest structures were unreinforced; some were damaged. 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 in the September event; and over PGA of 0.5g in the February 2011 event). 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; instead the water in these tanks is used via gravity flow 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 (described below) there was no reported damage to the tanks in the September 4 2010 earthquake.

In the western edge of the CCC service area, one circular buried concrete tank with segmented concrete roof sustained damage to the roof, Figures 6-4, 6-5. 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.

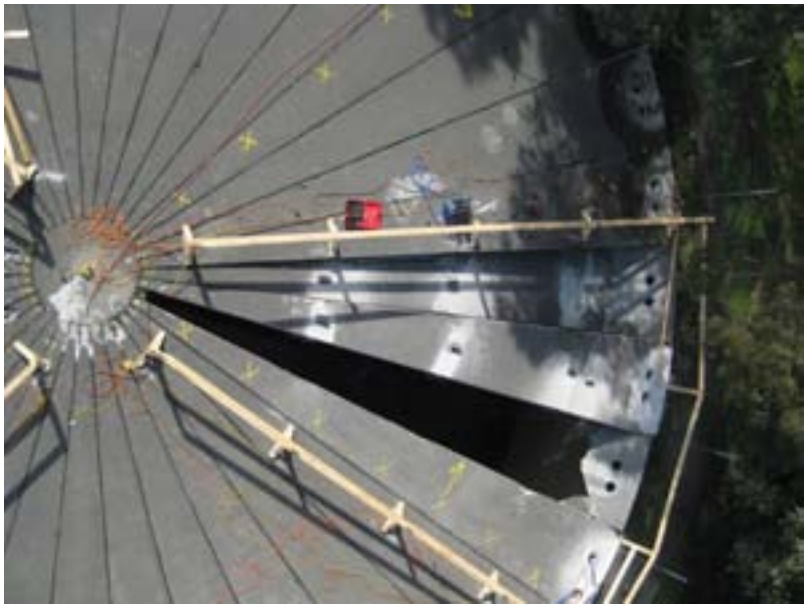

*Figure 6-4. Damaged Segmented Concrete Roof, CCC (September 2010)*

*Figure 6-5. Damaged Segmented Concrete Roof, Detail, CCC (September 2010)*

Within the CCC water system, about 8 water wells failed (September 2010), 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 2010, CCTVs had 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.

Figures 6-6 and 6-7 show a masonry pump station building damaged due to differential settlement due to liquefaction. This facility is located a New Brighton Road and Palmers Road.

*Figure 6-6. CCC Pump Station Damaged due to Differential Settlement*

*Figure 6-7. CCC Pump Station Damaged due to Differential Settlement*

Due to widespread liquefaction, covering perhaps 5% to 10% of the urbanized area within the CCC system (Figures 2-29, 2-32), there were a great number of failures to buried water pipes, as for example Figure 6-8.

*Figure 6-8. Broken Barrel of Water Pipe (September 2010)*

Figure 6-9 shows a map of the Christchurch water system, highlighting damage in the September 2010 earthquake:

- Light blue lines indicate water pipes with no post-earthquake repairs
- Dark green lines indicate water pipes that had been repaired and returned to service (as of the date the map was made)
- Orange lines indicate water pipes where crews were on site doing repairs.
- Dark red lines indicate water pipes that had been valved out, and that crews had not yet repaired.

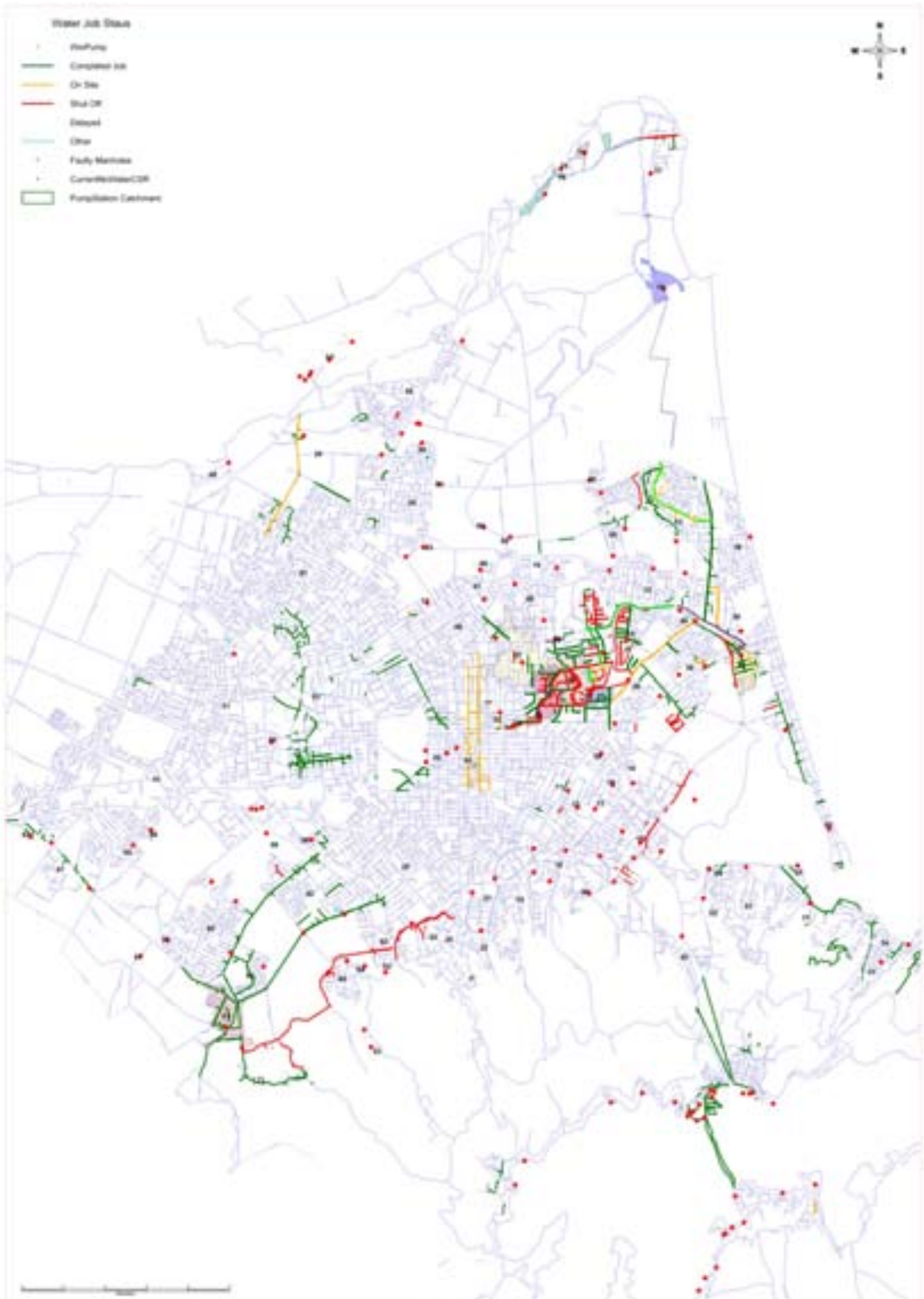

*Figure 6-9. Map of Water Pipe Repairs, CCC, September 2010*

Figures 6-10, 6-11 and 6-12 highlight three heavily damaged portions of the CCC water system in the September 2010 event. The large dots represent locations with main trunk pipes repaired; the small dots show locations with repairs to sub-mains (laterals).

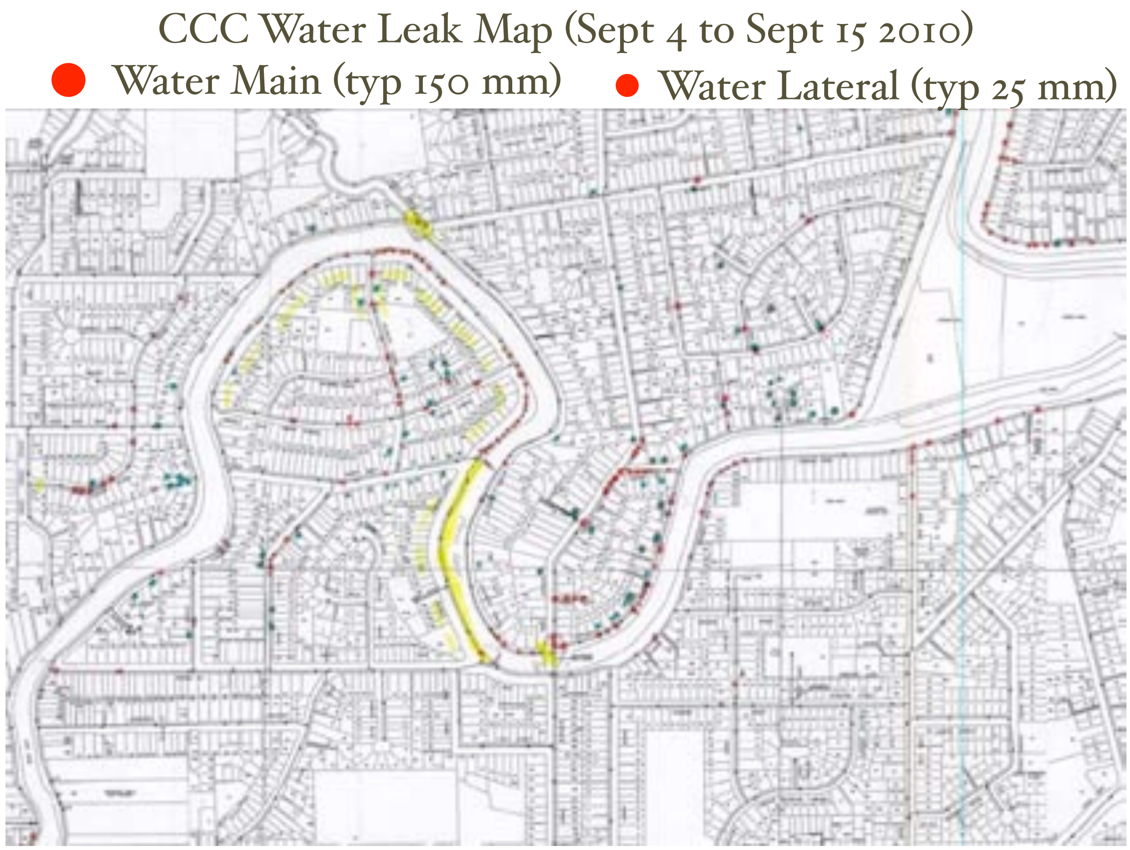


*Figure 6-10. Map of Water Pipe Repairs, Christchurch City Council, as of September 15, 2010 (partial)*

*Figure 6-11. Map of Water Pipe Repairs, Christchurch City Council, as of September 15, 2010 (partial)*

*Figure 6-12. Map of Water Pipe Repairs, Christchurch City Council, as of September 15, 2010 (Bexley Area)*

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.

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 September 2010 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, 2010 (6 weeks post-earthquake), there had been 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.

## 6.3 Water – Waimakariri District Council – September 4 2010

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, Figure 6-13. A map of the Pines Beach community is included in Figure 6-14. The Waimakariri River flows to the south of the town, and the Kaiapoi River runs through the town.

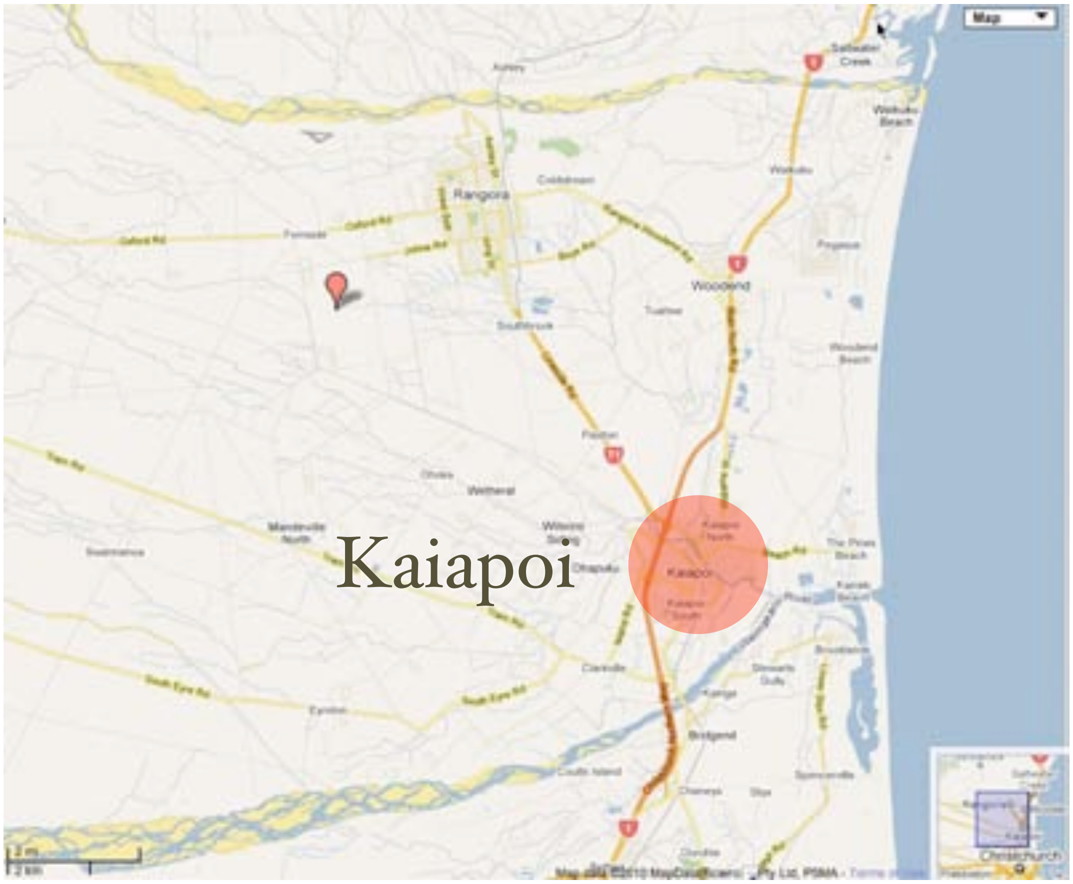


*Figure 6-13. Kaiapoi*

Rangiora is one of the two larger towns. None of the water pipes in Rangiora are known to have been damaged in the earthquake.

The Kaiapoi 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 (Figure 6-15), 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 100 mm to 200 mm (4 to 8 inches), Figure 6-16. 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.

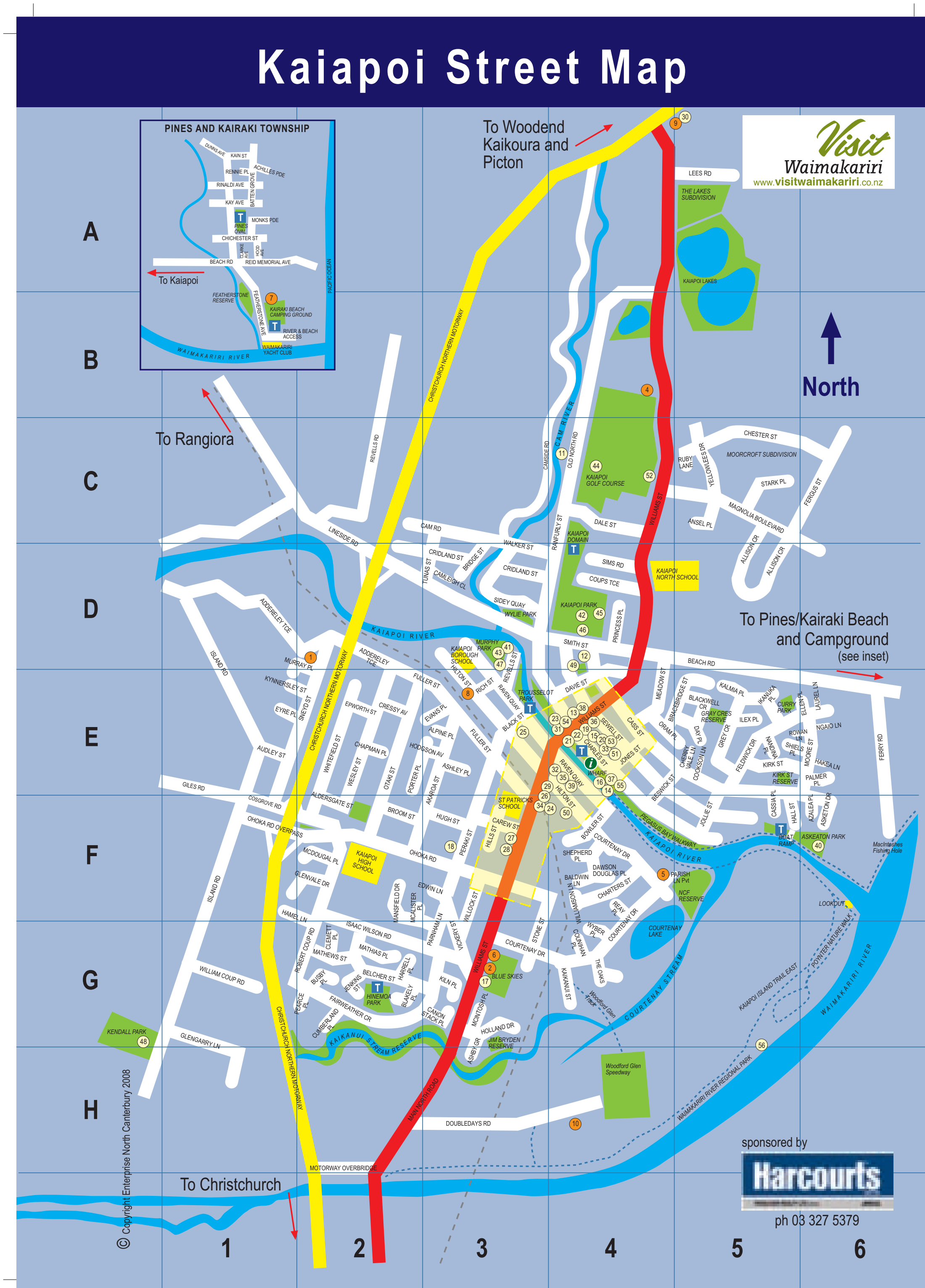


*Figure 6-14. Kaiapoi Street Map*

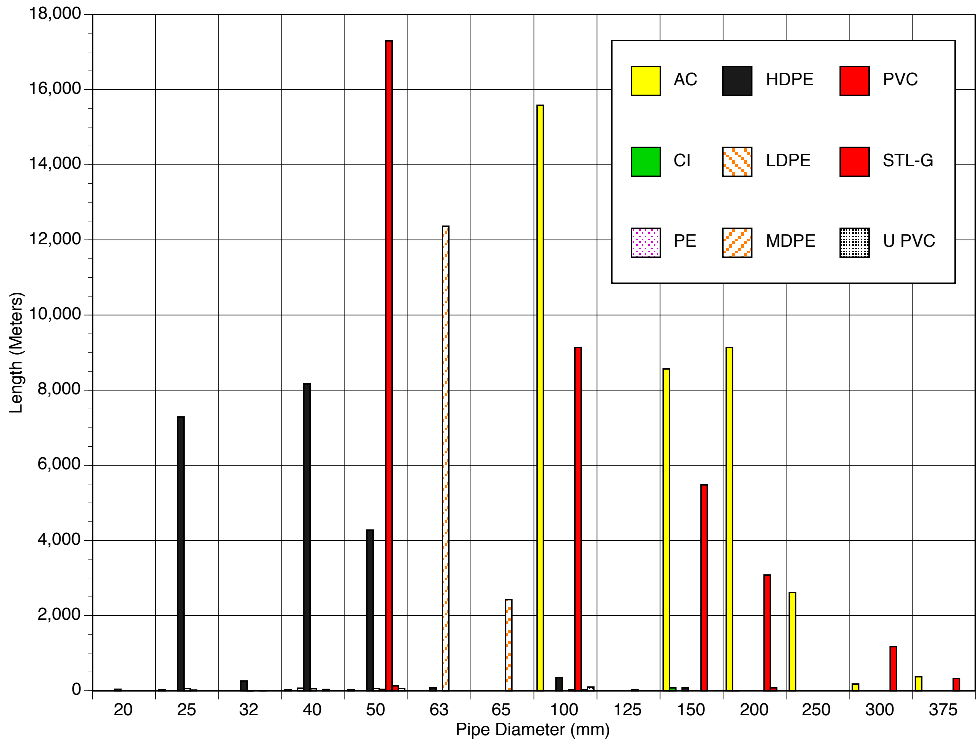


*Figure 6-15. Length of Water Pipe, by Pipe Type, Kaiapoi*

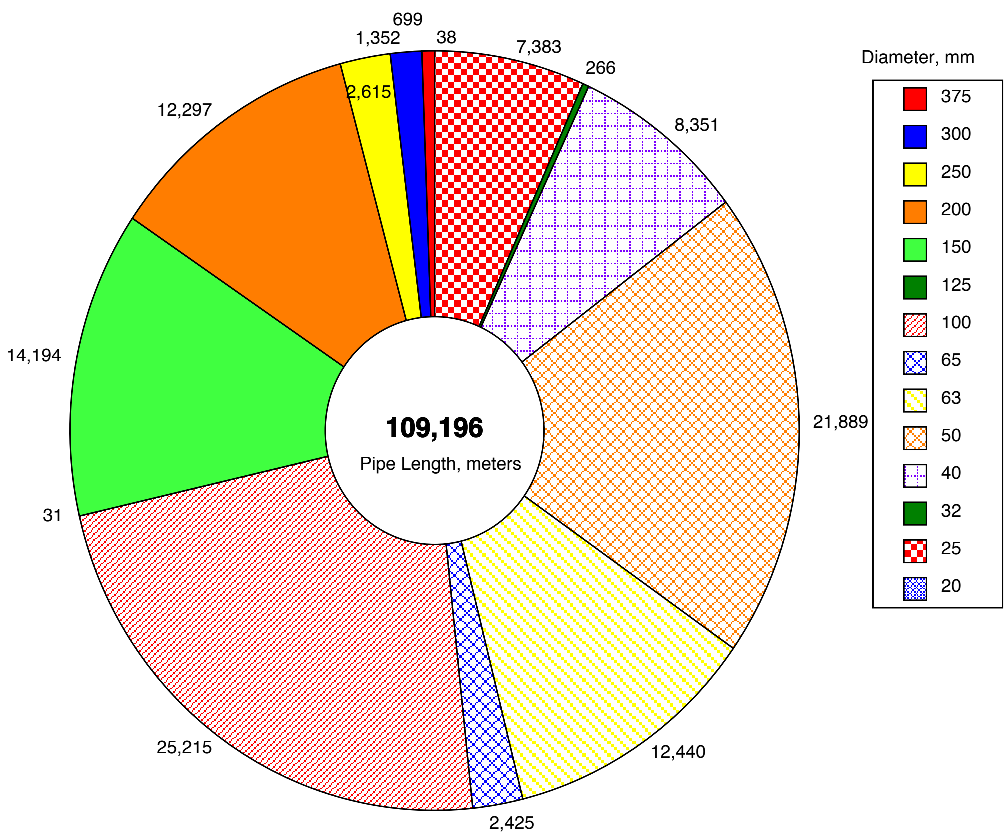


*Figure 6-16. Length of Water Pipe, by Diameter (mm), Kaiapoi*

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. Figure 6-17 shows a map of Kaiapoi, highlighting damage to roads (also a good proxy for damage to buried water pipes):

- Blue lines: reconstruct roads entirely (5.409 km)
- Green lines: reconstruct roads partially (7.563 km)
- Orange lines: minor road works (4.848 km)

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 2010) of $1,800,000.

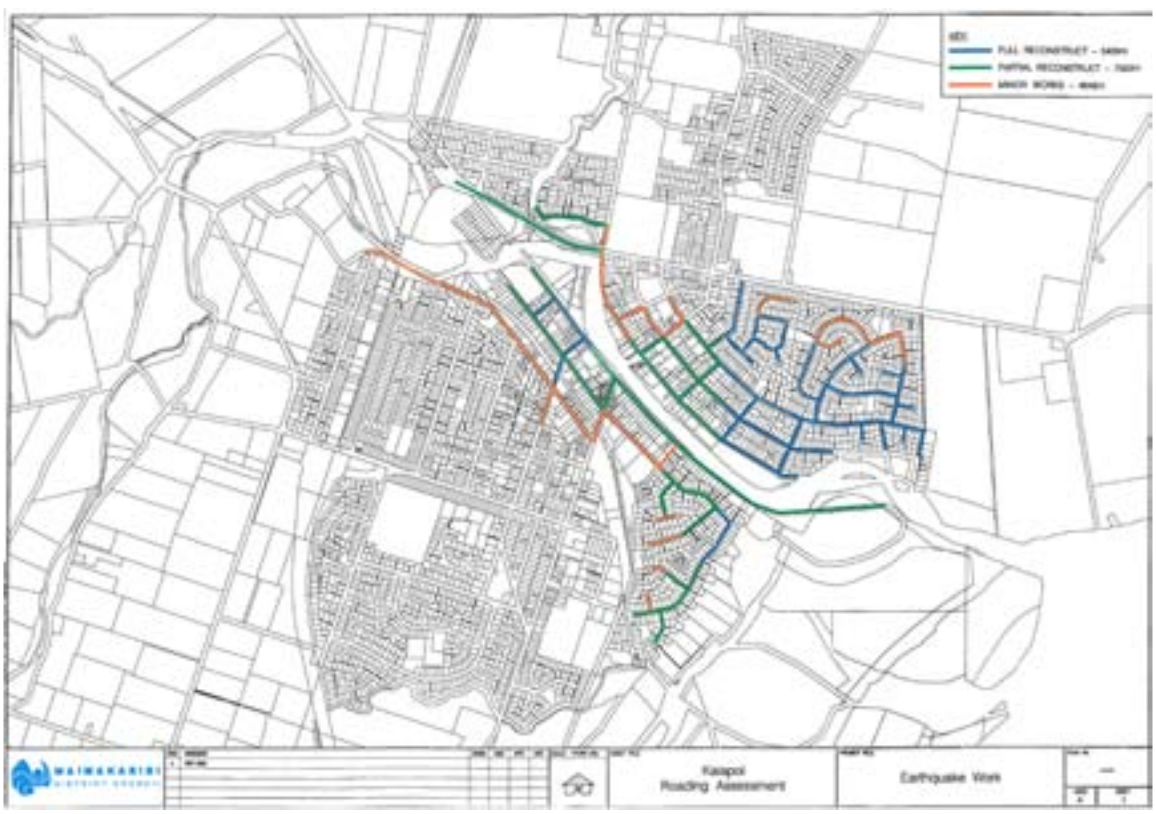


*Figure 6-17. Road Assessments, Kaiapoi*

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.

## 6.4 Performance of Tanks - February 2011 Earthquake

The McCormacks Bay concrete tanks are each 5,000,000 liters. These are post-tensioned circular concrete tanks; tank 1 was built in 1988, tank 2 in 1993. The site is excavated into a basalt formation. They are located in the Port Hills, Figure 6-18.

Boulders impacted tank 1 (Figure 6-19), but this did not result in damage / leakage to the tank. However, an apparent landslide has impacted the fill-side (Figure 6-20) and the downslope of the site (Figure 6-21), resulting in a leak to tank 2.


*Figure 6-18. McCormacks Bay Tanks, Aerial View, Port Hills*


*Figure 6-19. Boulder Impact McCormacks Bay Tank 1*


*Figure 6-20. Damaged McCormacks Bay Tank 2 (Foreground)*


*Figure 6-21. Landslide Scarp, McCormacks Bay Tank Site*

The Huntsbury Reservoir is a 36,000,000 liter (10 million gallon) water reservoir, Figure 6-22. It is a rectangular reinforced concrete tank, with reinforced concrete floor slab, concrete interior columns, concrete roof with soil cover. It is located in the Port Hills. Figure 6-23 shows an aerial view of the reservoir; downslope slope movement was noted on the east side of the reservoir.

After the February 2011 earthquake, the tank was found to no longer hold water. Initially, this was thought to be caused by damage to the outlet pipe, located just downhill of the tank. We observed clear evidence of ground failure on the downslope side of the tank, as highlighted in damaged buildings. Figure 6-24 shows a 600 mm (24") steel pipe being repaired, located at the northeast corner of the reservoir; this repair was being made in early April, 2011. Figure 6-25 shows some of the surface movement at the southeast corner of the concrete reservoir.

Further investigation has shown that a the interior concrete floor has suffered major cracking (1 inch wide in places), resulting is loss of the pressure boundary.

*Figure 6-22. Huntsbury Concrete Reservoir (Southeast Corner)*

*Figure 6-23. Huntsbury Concrete Reservoir*

*Figure 6-24. Repair of Outlet Pipe, Huntsbury Concrete Reservoir*

*Figure 6-25. Evidence of Ground Failure, Southeast Corner of Huntsbury Concrete Reservoir*

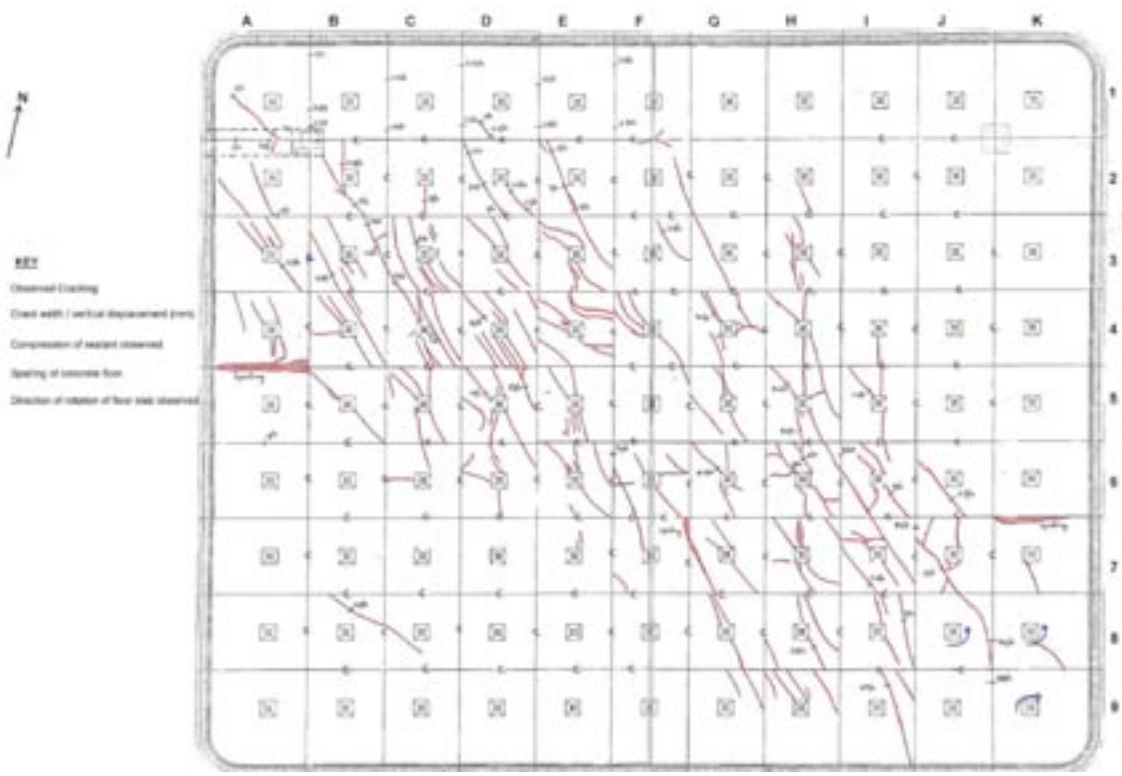


*Figure 6-26. Interior Inspection of March 3 and 4, 2011*

It has been speculated that the linear-type alignment of the cracks in the reservoir floor (Figure 6-26) might suggest surface fault offset. However, it might also reflect the formation of a scarp at the head of a landslide, as we observed clear evidence of building distortions downslope (eastward) of the reservoir. Possibly (?) a thin weak clay seam suffered large shears due to the very high levels of shaking at this site (PGA well over 0.5g, possibly as much as 0.9g or higher). Further investigation will be required to establish the cause() of the PGDs.

This large reservoir provides the primary water storage for the CBD. As the CBD remained largely out of service for months following the February 2011 earthquake, the water demands (and fire flow requirements) are largely nil, so the failure of this reservoir is not of immediate importance. However, the long term restoration of the CBD will require suitable water storage, and there are not likely to be good alternate sites for a new gravity tank.

It is noteworthy that while this tank lost all its contents, this failure did not result in inundation or life safety threat to nearby residences.

## *6.5 Performance of Water Pipes - February 2011 Earthquake*

Figure 6-27 shows a map of repairs made to the CCC water system prior to any of the earthquakes. The map shows that the leak distribution is fairly uniform throughout the city.

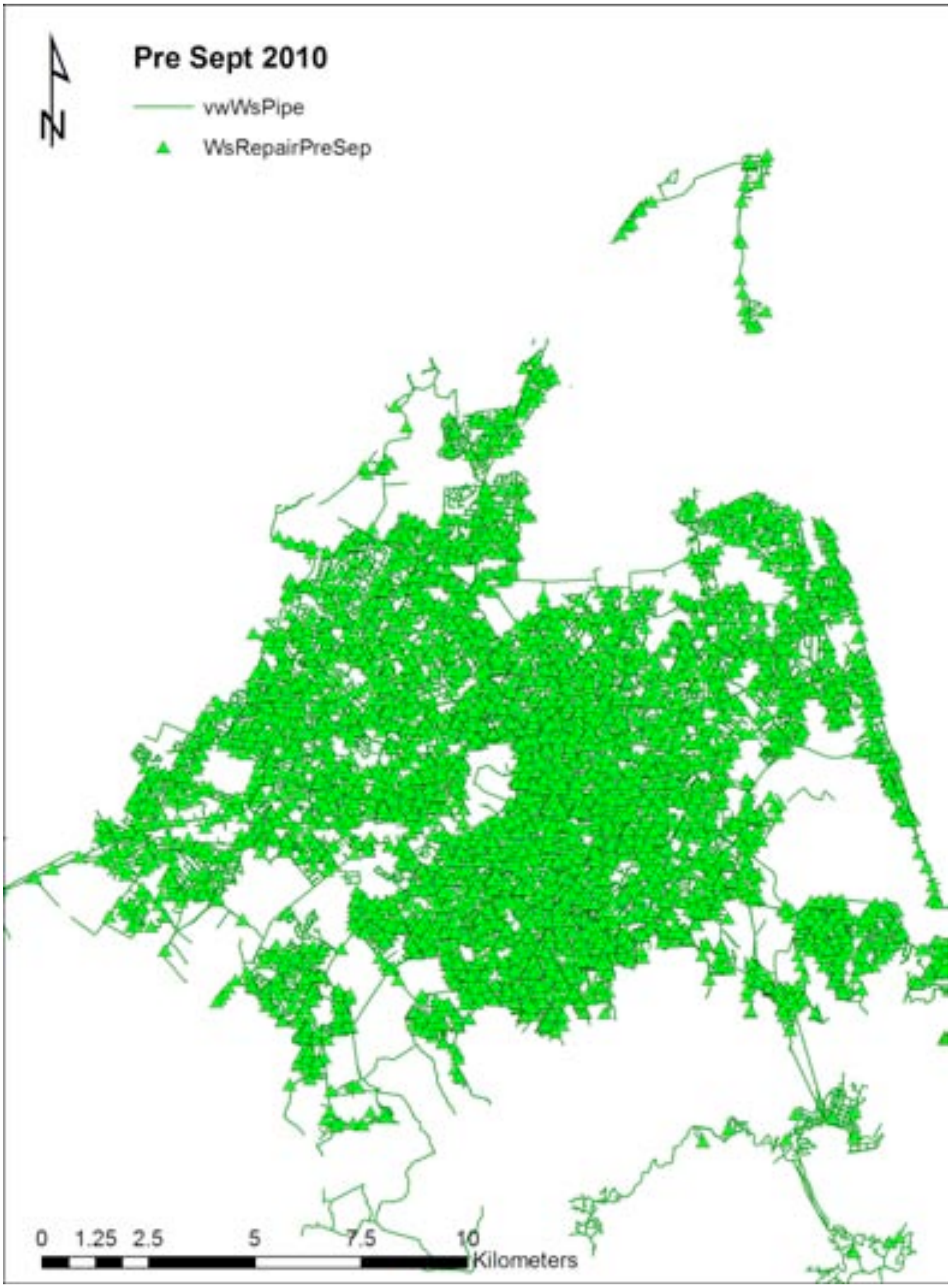


*Figure 6-27. Water Leak Repairs, Pre-Earthquakes*

Figure 6-28 shows the locations of leak repairs made in the six months following the September 2010 earthquake. The bulk of the repairs were in locations that coincide with the major liquefaction zones from the September 2010 event.

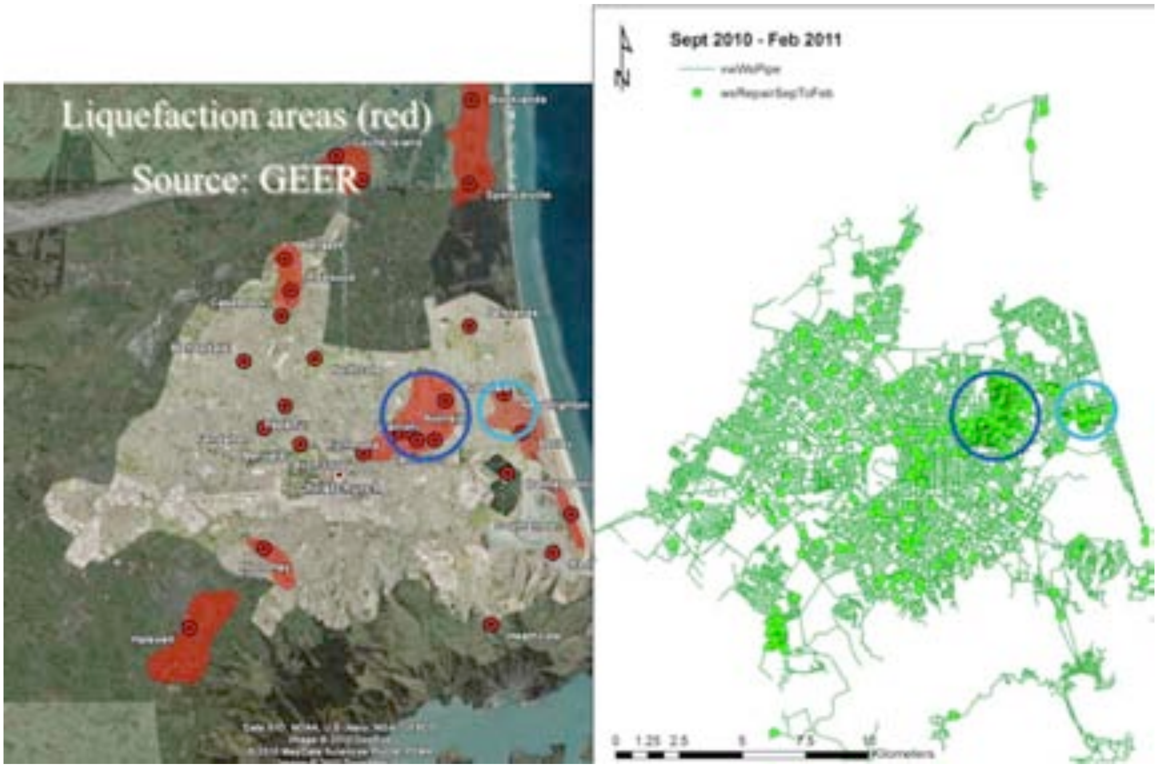


*Figure 6-28. Water Leak Repairs, September 2010*

The February 2011 event resulted in 14,000 water pipe repair reports; of which 3,000 were pipe repairs. Figure 6-29 shows the results of a burst pipe. The effort included 300 pipe repair crews, including those from mutual aid. As the repair effort continued, the number of crews were reduced to 150. It took 6 weeks to complete the repairs.

*Figure 6-29. Water Leak, February 2011 Earthquake*

Figure 6-30 shows the locations of leak repairs made in the months following the February 2011 earthquake. The bulk of the repairs were in locations that coincide with the major liquefaction zones from the February 2011 event.

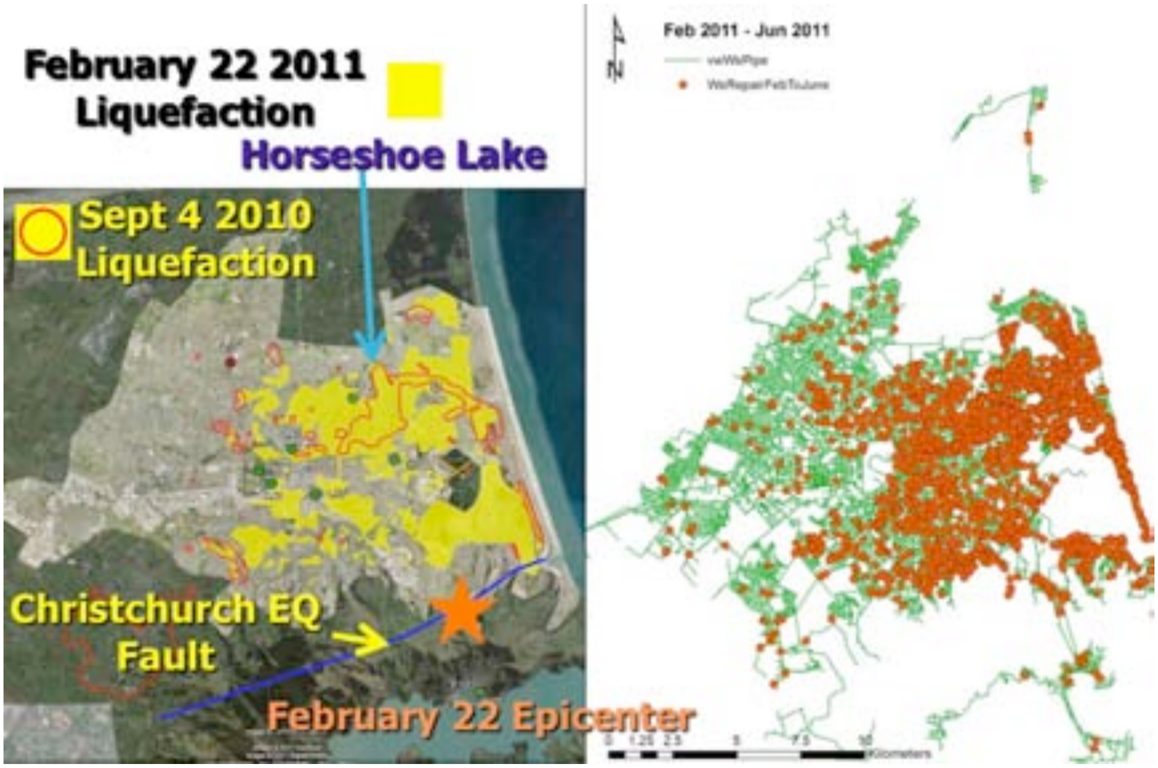


*Figure 6-30. Water Leak Repairs, February 2011*

Horseshoe Lake (Figures 6-11, 6-31) suffered some of the greatest liquefaction-induced pipe damage in the September 2010 earthquake. In the time between the September 2010 and February 22 2011 events, CCC replaced some of the pipe in this area with HDPE pipe; some existing AC pipe was repaired. This area suffered more extensive liquefaction in the February 2011 event: no leaks were reported for any of the HDPE-installed replacement pipe in either the February 2011 or June 2011 events.

*Figure 6-31. Horseshoe Lake Liquefaction, September 2010*

In Lyttleton, older CI pipe has been replaced with HDPE pipe, prior to the February 2011 event. While Lyttleton was not prone to liquefaction, it did sustain very high ground shaking in the February 2011 event (see Section 16 for description of some damage in Lyttleton); but there were no reports of damage to HDPE pipe.

## 6.6 Performance of Wells – February 2011 Earthquake

Figure 6-32 shows one of the wells in CCC that was located in a major liquefaction zone. In this location, differential settlements have resulted in the discharge pipe lifting off its saddle support (Figure 6-33) and well head differential settlement (Figure 6-34).

At this well site, there is 6 meters of artesian head. The well had just been repaired from the effects of the September 2010 earthquake, when it was damaged (again) by the February 2011 earthquake. The damaged well released about 150,000 liters per hour into the nearby street.

CCC operates more than 160 wells, and the February 2011 earthquake damaged more than 20. The range of damage includes collapsed casing pipes, and a range of damage caused by liquefaction settlements and lateral spreads in the upper 20 to 50 feet.

*Figure 6-32. Bixley Water Well*

*Figure 6-33. Pipe Support Settlement*

*Figure 6-34. Well-head Differential Settlement*

Figure 6-35 shows a sketch of the common well design used in CCC.

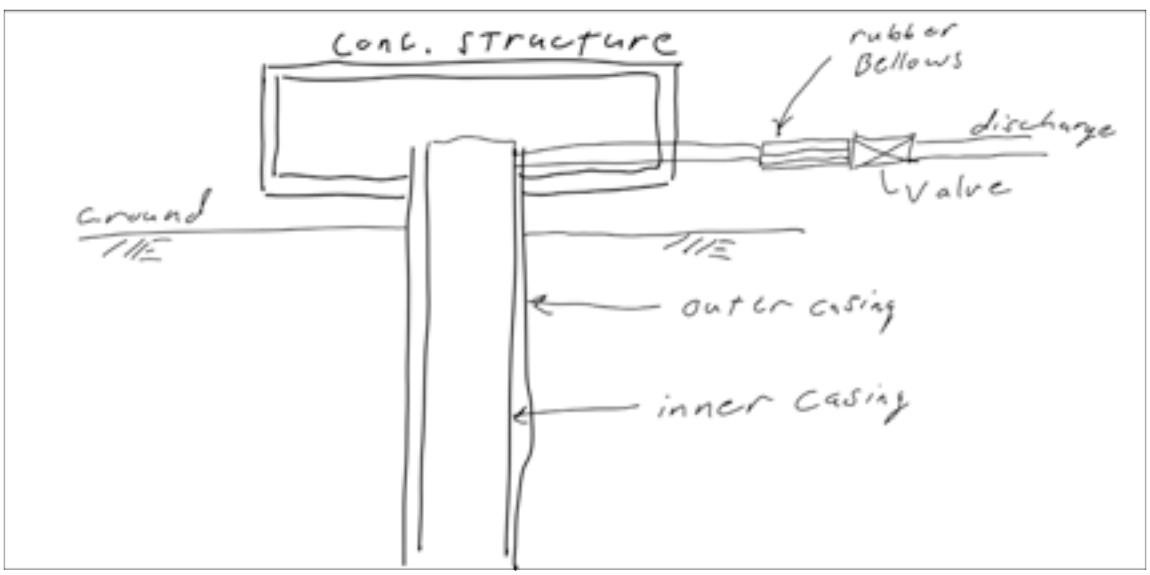


*Figure 6-35. Typical Well Design*

Figure 6-36 highlights some of the changes in ground water levels due to the September 2010 and February 2011 earthquakes. It is seen that the groundwater aquifer pressure rose by as much as 6 to 7 meters almost immediately after each earthquake; this higher pressure then dissipated in the days after each earthquake.

Note that in Figure 6-36, the recordings for the February 2011 event went off scale (flat-lines at about +3.5 m to +4 m); at Dyers Road, it is felt that the true pressure increased to about 7 meters. The reason(s) for the increase in aquifer pressure *might* have include the shutdown of nearly all pumping from the aquifer due to damage of wells / loss of power at the wells.

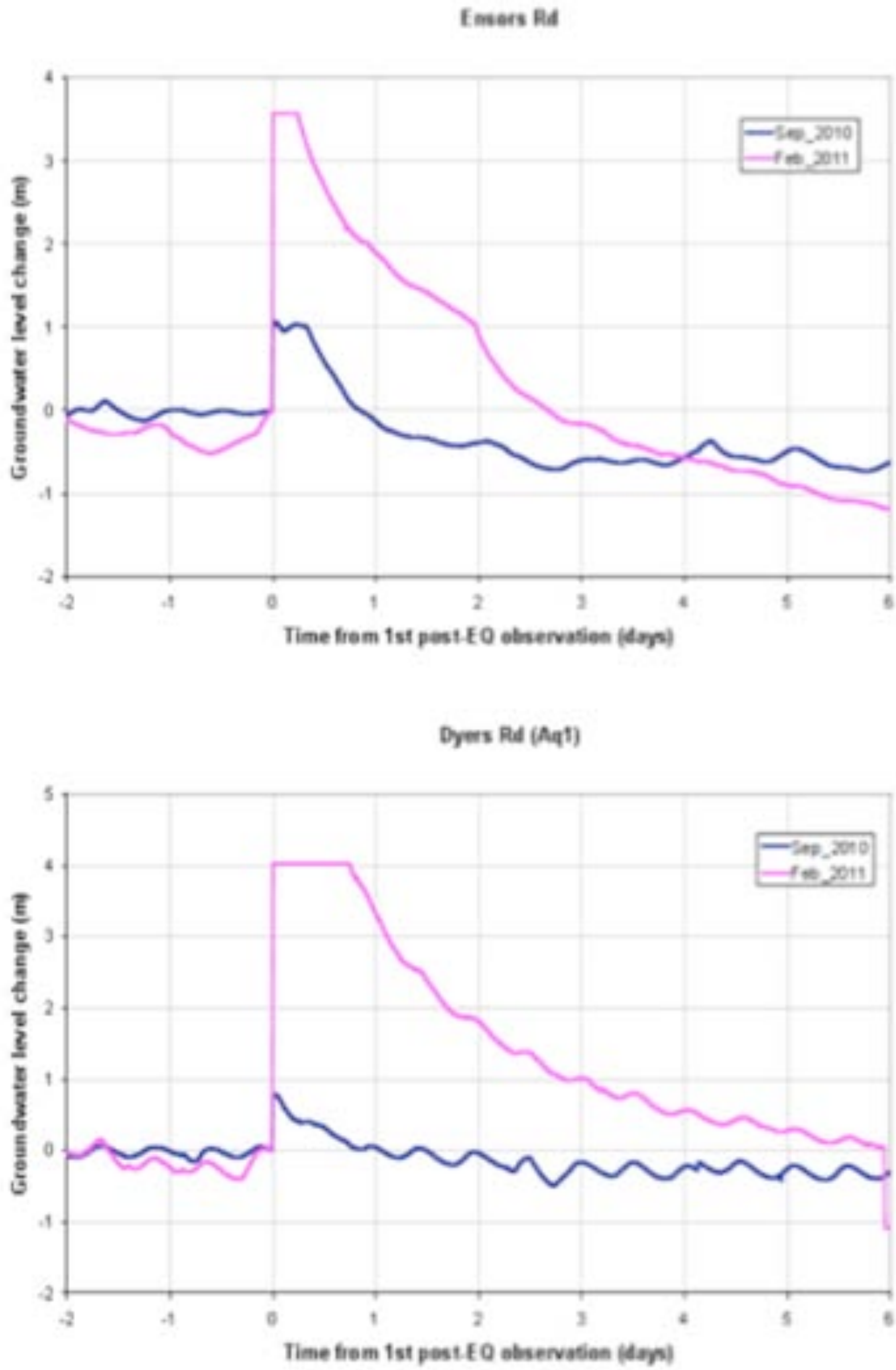


*Figure 6-36. Change in Groundwater Level After Sept 2010 and Feb 2011 Earthquakes*

## 6.7 Water System Performance – Three Earthquakes

Cumulatively over the three earthquakes, the following damage occurred and recovery actions taken by CCC:

- 60 water supply wells were repaired, with cumulatively 25% of capacity lost.
- 150 km of water mains were renewed. Normally, 10 km of water main are renewed each year.
- 100 km of water submains were renewed.
- The water distribution system remains fragile and with lost capacity. There is some concern that the system will be unable to meet maximum day (irrigation) demands.
- 2 boil water notices were issued.
- It was hoped, as of August 2011, that all chlorine injections could be halted by November 2011.
- HDPE pipe is being used for all new pressure mains, as if was found to perform well in the earthquakes. Large diameter PVC pipes also performed well. Small diameter PVC pipes performed poorly.

The nearby Waimate District Council (about 200 km southwest of Christchurch) reported that they had some cast iron pipe leaks. As of August 2011, they reported that nighttime flows have doubled, suggesting that there remain un-detected leaks.

## 6.8 Emergency Response

Some of the emergency response actions taken by CCC reflect similar actions taken by other water departments after large earthquakes, around the world.

The distribution of potable water to customers with broken buried water pipes was an important part of the post-earthquake response. Figures 6-37 and 6-38 show portable potable water trucks and distribution points. Many of these were set up in the areas that suffered liquefaction and/or landslide effects. These were generally un-manned by CCC staff.


*Figure 6-37. Deployed Water Tank and Hose Bib Manifold*

*Figure 6-38. Hose Bib Manifold*

The issue of "boil water alerts" was important after each earthquake. In most parts of Christchurch, owing to the very high quality water in the aquifers below, CCC normally does not treat its water supply: no disinfection, no fluoride, etc. After each earthquake, health officials were worried about contamination, and the outcome was to install portable chlorination stations at various locations in the City (Figure 6-39), as well as doing many water quality tests.

Only after the entire City had zero water quality issues for 14 days, was the "boil water alert" lifted for the City. Clearly, the extent of concern was high; but in fact there were no outbreaks of disease that could be attributed to water quality (or any other reason) after each of the three earthquakes. As the "boil water" requirement was lifted, CCC removed the disinfection processes. In an idealized world, if water quality could be assured, then the need for high chlorine residuals (or other disinfection processes) would be reduced or eliminated; but at this time, the controls to give this level of assurance are not available or acceptable to all parties involved.

*Figure 6-39. Temporary Chlorination System Deployed for First time in Christchurch*

## 6.9 Observations and Recommendations

It would be fair to say that after three major earthquakes in less than a year, that the CCC water department has become rather proficient at responding to earthquake damage.

The common trends in the response between the three earthquakes include the following:

- The earthquake occurs. Damage occurs to many buried water pipes. Some wells fail, either due to loss of power or local liquefaction issues. Some water tanks fail. Inspections and damage assessments need to be made so that the level of effort for response needs to be quantified. Not all data is available immediately.

- In all three earthquakes, CCC focused the bulk of its immediate response on restoring the potable water system to all customers that could take water.

- In all three earthquakes, CCC focused the bulk of its secondary response on restoring the wastewater collection and treatment systems (see Chapter 7 for more details). This required much a much larger effort, mostly as the repair of buried sewer pipes is most costly to perform, owing to its deeper burial in the ground. The issue of repair using gravity sewers or repair using pressure sewers is considered. A major effort is done inn procuring and mobilizing portable toilets and chemical toilets.

- In all three earthquakes, repair of broken storm sewers is kept as a lower priority than fixing water (first) or sanitary sewer (second).

In discussing the repair strategies with CCC, it was apparent that after the first earthquake, that most of the pipe damage were addressed with the fastest / quickest repair possible. Often, this involved installation of pipe clamps (mall cracks) or short lengths of new pipe (2 to 4 meters in length) to reconnect between adjacent undamaged pipe. Thus, the repaired pipe, while serviceable, remains as fragile as the original pipe. This strategy, of repairing "like-for-like" is the common strategy employed by water (and power) utilities around the world. The concept to replace old fragile pipe with new seismic-resistant pipe was largely left as a "nice to do" but not realistic in the immediacy of post-earthquake restoration efforts; except in a very few instances where entire lengths of pipe had to be replaced. Repairs were noted in GIS databases, but only with simple attributes (location of repair).

After the second earthquakes, the repair strategy was much the same (i.e., repair in kind). However, tracking of the damage became much more detailed, and GIS databases with many more attributes were maintained. In some fashion, these additional data collected after the second earthquake will help CCC understand its longer term asset management issues for the water system. Within a couple of months after the second earthquake, CCC made some observations as to what repairs from the first earthquake worked well and which did not. Preliminary indications show that HDPE water pipe installed after the first earthquake performed very well, while "repair-in-kind" repairs failed again.

After the third earthquake, CCC managers reported the following: "we now believe in the benefits of HDPE pipe for use in liquefaction zones".

The lessons learned with repair of water pipes are that seismic upgrades can be especially cost effective (worthwhile) if the hazard (future earthquakes) occurs on a pretty regular basis. This simple lesson can be demonstrated to be true by performing good seismic vulnerability analyses and then developing suitable mitigation strategies. As the bulk of a water utility's assets are the buried water pipes, this suggests a prudent course of asset management planning should include two major factors:

- Replacement of aging pipes due to ongoing corrosion / leaks
- Replacement of aging pipes due to seismic vulnerability

If both of these issues are considered in a long term (20 to 50 year) asset replacement program, then a water utility can develop a sound and cost effective long term capital program for pipe replacement, that addresses both issues. As a quick guideline, the following approach could be adopted:

- Distribution pipes. Pipes (diameter 300 mm and smaller) that have leaked and been repaired more than 2 times (3 times in residential areas) over the past 7 years, per 1 km length, deserve replacement. The replaced pipe, if located in soils that are prone to liquefaction, should be designed to accommodate up to 150 mm of movement; plus all other requirements, with suitable corrosion protection. The replaced pipe, if located in soils not prone to permanent ground deformations, do not need any special seismic design.

- Transmission pipes. Pipes (diameter 750 mm and larger) that have leaked and been repaired more than 2 times (3 times in residential areas) over the past 7 years, per 1 km length, deserve replacement. The replaced pipe, if located in soils that are prone to liquefaction, landslide or surface faulting, should be designed to accommodate the expected permanent ground deformations associated with earthquakes that occur once every 1,000 years or so; plus all other requirements, with suitable corrosion protection. The replaced pipe, if located in soils not prone to permanent ground deformations, still require design for slip joints to accommodate ground shaking effects.

- Emergency response plans need to be developed to reflect the likely vulnerabilities of the water agency, and the needs of the local community. A balance of emergency response and pre-earthquake mitigation will need to be considered.

Another major observation in all three earthquakes is that post-earthquake fires were not important to overall community response. The topic of fire ignitions is discussed in Chapter 13. Herein, the major point is that the widespread loss of water pressure in the CCC water system in the three earthquakes (same for WDC in the first earthquake) did not impact fire department response. This might suggest that the fire ignition models (ASCE 2005) need to be updated (almost for sure); or that possibly they are not applicable for New Zealand. As one of the areas needing further research, the issue of fire ignitions and fire spread, and its influence for water system design, needs to be further studied.

# 7.0 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).

Section 7.1 discusses the wastewater system performance in the September 4, 2010 earthquake. Section 7.2 discusses the wastewater system performance in the February 22, 2011 earthquake.

While both earthquakes created a lot of damage to the wastewater systems, the February 22, 2011 event was far more catastrophic for the following reasons:

- Liquefaction was far more extensive in the February 22 2011 earthquake. This led to:
- Many more pipe failures in the February 22 2011 earthquake, as well as damage to a few additional sewer lift stations. This led to:
- Far more infiltration of sand and silts into the broken sewer pipes, which eventually made it downstream to:
- The Bromley WWTP. The huge amount of silts and sands entering the primary settling tanks at Bromley led to constant failures of the grit removal system. In the 6 weeks after the February 22 2011 earthquake, it is estimated that about 1,000 tons of silts and sands were removed from the primary setting tanks at Bromley using excavators. Compounding this was:
- Liquefaction seriously damaged three (possibly all four) circular clarifiers (secondary treatment) at the WWTP. These were not functional months after the earthquake.
- Sloshing forces were the likely cause of many pipe breaks of the aeration pipes at the WWTP.
- The trickling filters and digesters were non-operational two months after the earthquake.
- High BOD in the effluent through the limited settling action from the primary settling basins was being discharged into the aeration ponds. Unless this could be mitigated, there was concern that the ponds would turn anaerobic within a few more months. If this happened, the site would smell like a cesspit; as the prevailing winds are from the east, the smell would drift over the central business district and many other parts of Christchurch, which would likely hamper restoration efforts and lead to de-population of the City.
- Damage to the sewer pipes and treatment plant has required about 2/3 of the raw sewage to be discharged directly into the rivers and estuaries.

## 7.1 Earthquake of September 4 2010

Figures 7-1 to 7-4 show the Christchurch City Council (CCC) Bromley wastewater treatment plant (WWTP). 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 7-1. Christchurch WWTP at Bromley*

The primary damage to the WWTP in the September 2010 earthquake was State Highway 71 between Ponds 2 and 4 (Figure 7-2) was closed due to 50 cm cracks. The pipe between oxidation ponds 2 and 4 had to be replaced. The levee between Ponds 1 and 2 cracked and slumped. There were sand boils in many placed, with observed PGDs of 30 cm horizontal and 20 cm vertical.

*Figure 7-2. Christchurch WWTP at Bromley*


*Figure 7-3. Bromley WWTP*

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 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 dry well lift stations (Figures 7-4, 7-5) 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.

*Figure 7-4. Floated and Tilted Wastewater Life Station 26, Porritt Park, Avonside*

*Figure 7-5. Floated and Tilted Wastewater Life Station 27, Avonside*

Damage to sanitary sewers (Figures 7-6 and 7-7) 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 ground water.

*Figure 7-6. Floated Sewer Manhole, Brooklands (one of fifteen)*

*Figure 7-7. Floated Sewer Manhole, Brooklands (one of fifteen)*

Figure 7-8 shows a lift station in the Brooklands area. It appears that there was as much as 6 to 10 inches of settlement around the concrete wet well.

*Figure 7-8. Settlement due to Liquefaction, Lift Station in Brooklands*

Figures 7-9 to 7-12 show typical images from CCTVs as to the type of damage within sewer pipes. The damage to brittle pipe is obvious. High volume infiltration of ground water, taking with it silts and sands of the streets, was problematical in the September 4 2010 earthquake, and an absolutely critical problem in the February 22 2011 earthquake.


*Figure 7-9. CCTV picture of Broken Sewer, WDC*


*Figure 7-10. CCTV picture of Broken Sewer, WDC*

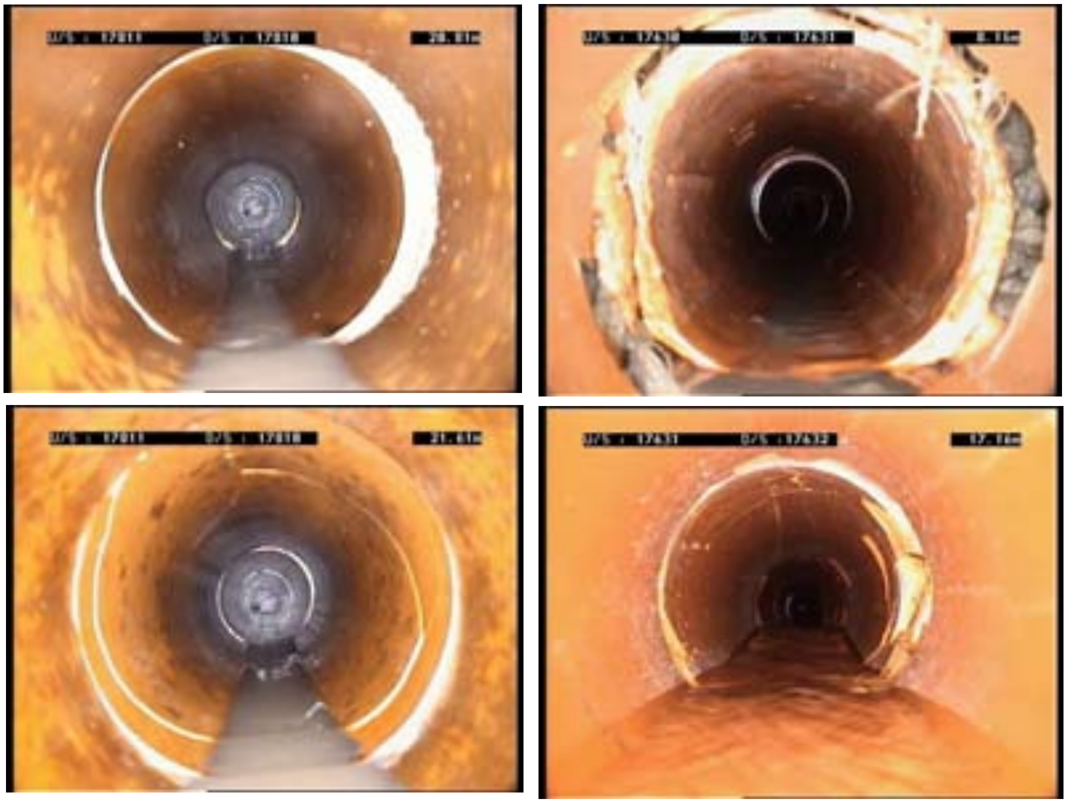

*Figure 7-11. CCTV picture of Broken Sewers, WDC*

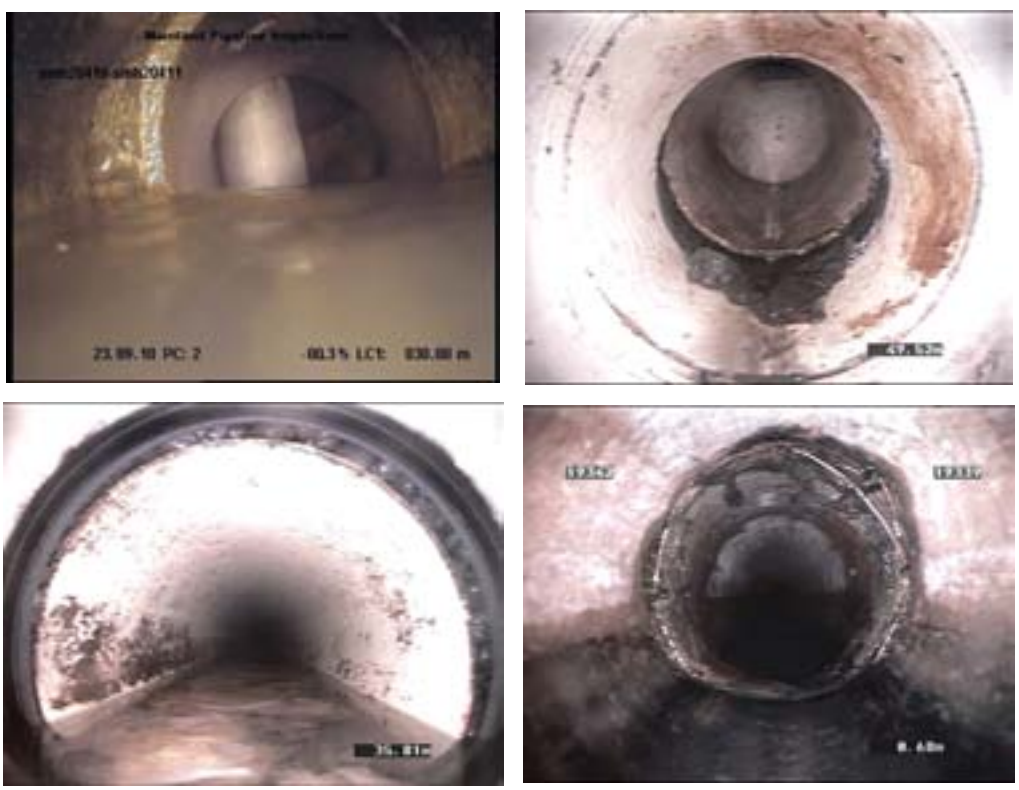

*Figure 7-12. CCTV picture of Broken Sewers, WDC*

Figure 7-13 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. As of September 29, 2010, there were 150 customers in Kaiapoi and 50 in Pines Beach without any piped sewage service; with the remaining ~95% having piped sewage service.

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.

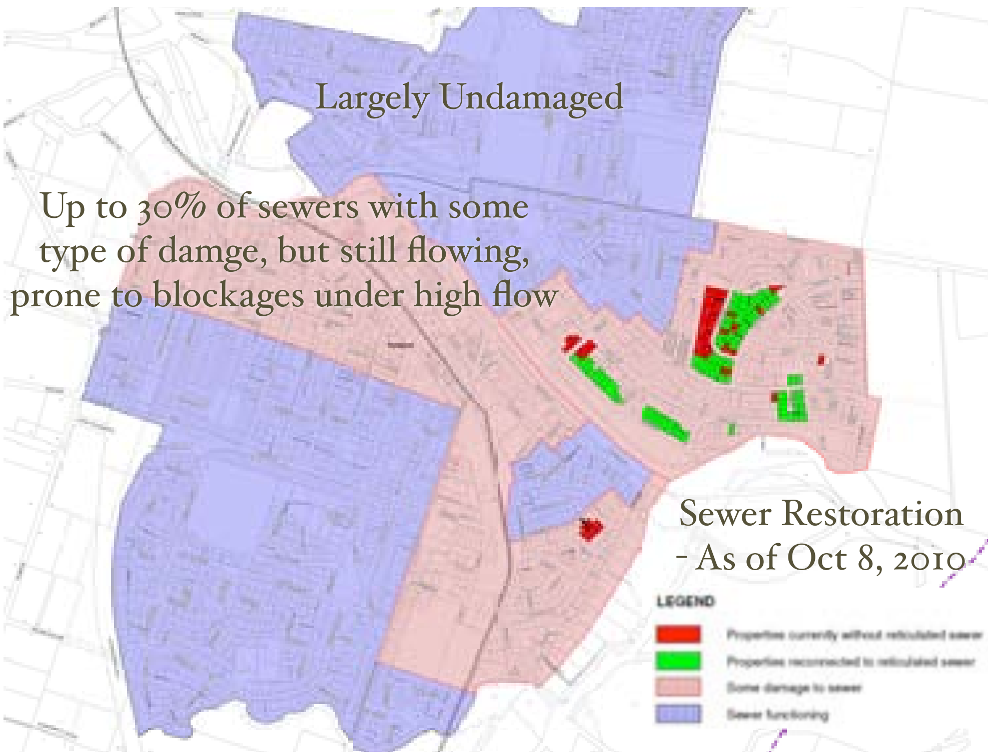


*Figure 7-13. Map of Sewer Restoration, Kaiapoi, WDC, as of October 8, 2010*

Figure 7-14 shows a broken sewer pipe that was hung on the side of a bridge. The blue "flex hose" was added to the broken pipe to direct sewer discharges directly into the creek. According to the design of this bridge, the bridge was originally built in the 1960s; it suffered no damage (except for settlement of the roadway of a couple of inches at each abutment). At the time it was originally built, it had no attached pipes. The broken sewer pipe is attached to the bridge at several points using both gravity-only as well as lateral supports; nominally, it would "be acceptable" per the IBC 2009 code. However, the pipe was too rigidly supported, and settlement of one abutment (far side in this photo) led to failure of the pipe.


*Figure 7-14. Broken Sewer Pipe*

Releases of raw sewage into rivers was not uncommon. In Kaiapoi, the discharge pipe from the Charles Street pump station broke where it crossed underneath the Kaiapoi River. WDC repair the pipe, and then it was damaged again. It took weeks to replace the pipe under the river, all the while discharge was going directly into the river.

It was estimated in early October that it would take until late October 2010 to repair the sewer pipes form Pines Beach / Kairaki to the Kaiapoi WWTP; until that time, sewage was being discharged directly into the lower Waimakariri River.

The Avon/Otakaro, Haathcote, Styx and Halswell Rivers were all considered polluted with raw water sewage spills as of October 8, 2010. Also affected were the Kaiapoi River, Kairaki / Saltwater Creek and Lower Waimak Rivers. There was concern that heavy rainfall may flush accumulated sand and silt from the storm water drains into the rivers, creating high turbidity. By mid-October 2010, it was felt that the remaining broken sewers could "mostly" be bypassed during dry weather, but spills would be much harder to control in wet weather.

All Oceanside areas from Sefton in the north, including Christchurch, Lyttleton Port, the entire Banks Peninsula, to Tumutu in the south, were considered to have high coliform / bacteria counts and deemed unsafe for swimming.

Figure 7-15 shows a common approach to repairing the damaged sewers. First, the site had to be dewatered. Second, as the pipes are buried deeply (commonly 3 meters of cover), sheet piles (or trench shields) needed to be installed. Finally, the pipe could be repaired / replaced. This is both a time consuming and expensive effort. Figure 7-16 shows a crew working on repair of a deep sewer. Figure 7-17 shows a damaged vitrified clay pipe to be repaired.

*Figure 7-15. Repair of Sewer Pipe*

*Figure 7-16. Repair of Sewer Pipe*

*Figure 7-17. Repair of Vitrified Clay Sewer Pipe*

Figure 7-18 shows a map with the location of repairs made to water (blue dot), wastewater (red dot) or storm water (green dot) pipes in Pine Beach. It would appear that most of the Pines Beach community underwent some amount of liquefaction. Figure 7-19 shows a similar map for the main urban area of Kaiapoi.

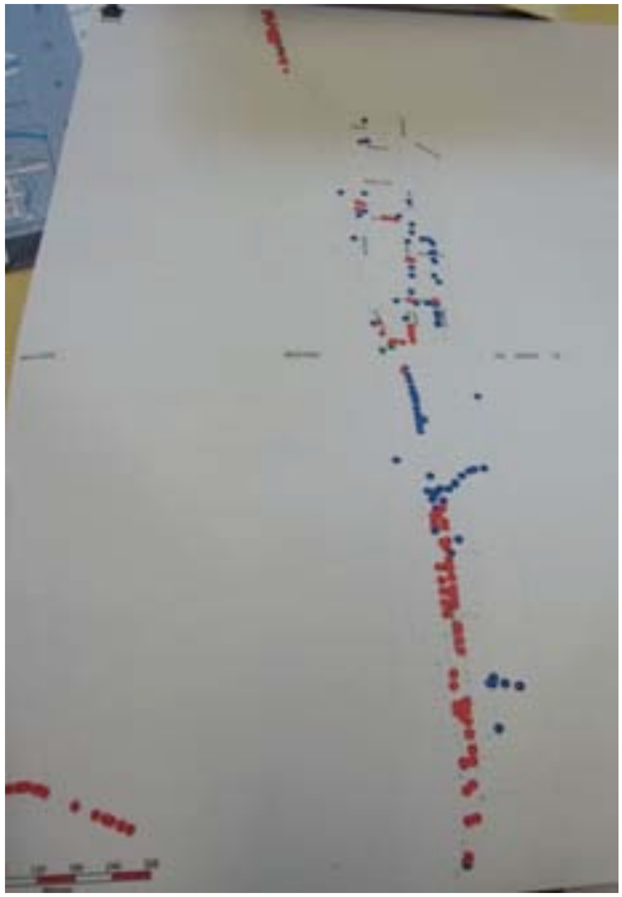

*Figure 7-18. Pipe Repairs in Pine Beach*

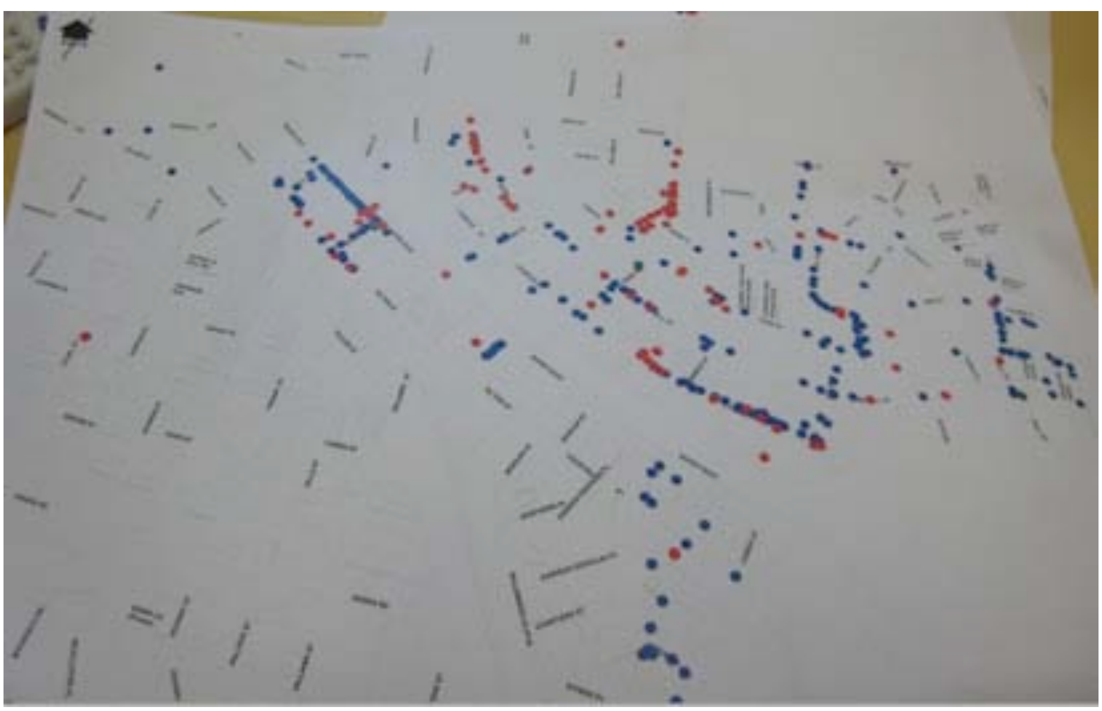

*Figure 7-19. Pipe Repairs in Kaiapoi*

In Christchurch, the sewer repair strategy included the following:

- Portable toilets were placed outside houses that lost sewer service, generally one portable for two houses (Figure 7-20).

- By October 15, small tanks were installed on berms or in front of properties without sewer service, where the sewer mains were so badly damaged that they cannot be repaired. These portable tanks were attached to the sewer from the house, to allow the households to use internal toilets, showers and washing machines. By October 15, 37 households had these tanks installed, and the goal was to install these tanks for all 235 households still out of service. Five crews worked on this effort

- By October 15, 2010, limited wastewater service had been restored in the CCC area to 2,518 properties.

- For permanent repair, CCC was considering installing pressure pipes (force mains) at the affected houses in the liquefaction zones. These pressure pipes would require a pump to be installed at each house. It was felt that a pressure system, while costlier in terms of electricity and pumps, would be faster to install than a traditional deeply buried gravity main. The issues as to who pays for the pressure pipes, pumps and ongoing maintenance was not resolved as of October 15, 2010.

Figure 7-20 shows the locations where portaloos were in use as of October 11, 2010, in the Dallington / Avonside / Burwood area of Christchurch. The colored dots reflect the agency that provided the portaloos (numbers indicate the number of portaloos at the site). The color road lines indicate roads where sewage service has been fully restored (blue), partially restored (green) or remained out of service (yellow). Figures 7-21 to 7-26 show similar information for the Bexley, Brooklands, Hallswell, South New Brighton / Southshore, Spencerville and Kainga areas. It would be reasonable to assume that all streets indicated by colored lines in these four maps suffered at least 1 inch, and in many cases several inches, or settlements at depths of the sewers (commonly 3 meters deep). Damage maps of the non-seismically-designed sewer pipes, coupled with those for non-seismically-designed water pipes, can be used to construct updated high resolution liquefaction hazard maps for Christchurch.

*Figure 7-20. Portaloos in Service, October 11, 2010*

*Figure 7-21. Portaloos in Service, Bexley / New Brighton, October 11, 2010*

*Figure 7-22. Portaloos in Service, Brooklands, October 11, 2010*

*Figure 7-23. Portaloos in Service, Halswell, October 11, 2010*

*Figure 7-24. Portaloos in Service, South New Brighton, Southshore, October 11, 2010*

*Figure 7-25. Portaloos in Service, Spencerville, October 11, 2010*

*Figure 7-26. Portaloos in Service, Kainga, October 11, 2010*

## 7.2 Earthquake of February 22 2011

Following the February 22, 2011 earthquake, the CCC sewer system was investigated. There were no reported building collapses in the sewer system, but several were damaged from liquefaction and the CCC main headquarters was damaged from shaking. Due to the distance from the Feb 2011 earthquake to Kaiapoi, there was no reported liquefaction or incremental to the WDC sewer system.

The CCC wastewater system was heavily damaged in the Feb 2011 earthquake.

As of April 2, 2011, the sewerage system was on the "brink of failure", threatening the city with an "almighty stink" by Christmas 2011. CCC was requesting residents to work harder to conserve water, or risk overloading the sewage ponds. If the ponds become overloaded, it will create an almighty stink.

The choke point is the Bromley WWTP, which as of April 2 2011, was operating at 30% of normal capacity.

Damage to the sewer pipe collection system was so extensive that as of early April 2011, it was estimated to take 8 months to identify and suitably repair the pipe damage. Interior inspection of sewer pipes was hampered by having so many of them clogged with sand. The repair strategy for the sewer system was to first restore the larger downstream mains then continue working their way upstream. In this way CCC could take as much sewage as possible to the WWTP and also contain as much sands as possible in the pumping station wet wells, thus removing a significant sand load from the WWTP. Seven of eight reinforced concrete cylinder pipe force mains leading to the WWTP were damaged from the earthquake (the eighth was leaking); as of April 2011 all of these mains were functioning.

Six percent, or about 96 km of the collection pipes were not working, with a further 27%, or 474 km, working only slowly. As of early April, 2011, CCC had 92 trucks flushing sand out of the collection pipes, and 11 crews putting cameras through pipes to survey the damage. Figure 7-27 shows a crew working to flush sewer pipes with a water jetting method. The jetting cleans the pipes and cameras are deployed after the jetting process to inspect the pipes. Waste from this process is hauled in trucks and disposed at the WWTP. At locations where large sewer pipe breaks occurred, the jetting process sometimes effectively mined the sand from the ground surrounding the pipes and resulted in sink holes in the roadway above. Some cars have fallen into sink holes. The process was modified to reduce the possibility of creating sink holes by monitoring the rate of progress of the jetting holes, when the rate significantly slows the crews stop the jetting and report a location of potential significant damage.

*Figure 7-27. Crew flushing sewer pipes.*

The slow moving effluent in the pipes was the biggest headache, both for CCC as well as health authorities, because the sewers were still leaking millions of liters of raw sewage into backyards, rivers and the sea. It was estimated that as of April 2 2011, about 25% of total sewage volume, or a leak rate of about 40 million liters per day, was leaking out of the damaged sewer pipes; this leak rate was down from about 60 million liters per day two weeks previously. At this rate of repair, it was estimated to take months before rivers and beaches would be found safe enough to swim or surf in. The estimated time to restore piped sewage for residences in eastern Christchurch ranged from one month to one year.

Ground water infiltration has increased about 100%. This increased the load on the WWTP, thus magnifying the sewage treatment problems.

For residents in eastern Christchurch, the use of chemical toilets and portaloos was common as of April 3, 2011. Figure 7-28 shows the deployment of portaloos. Figure 7-29 shows deployed chemical toilets and portaloos. About 30,000 chemical toilets have been placed in homes and in excess of 10,000 Portaloos mobilized. At the time of the February 2011 earthquake, Kaiapoi still had portaloos being used since the Sept. 2010 earthquake; although very few, if any, portaloos remained in Christchurch as a result Sept. 2010 earthquake.

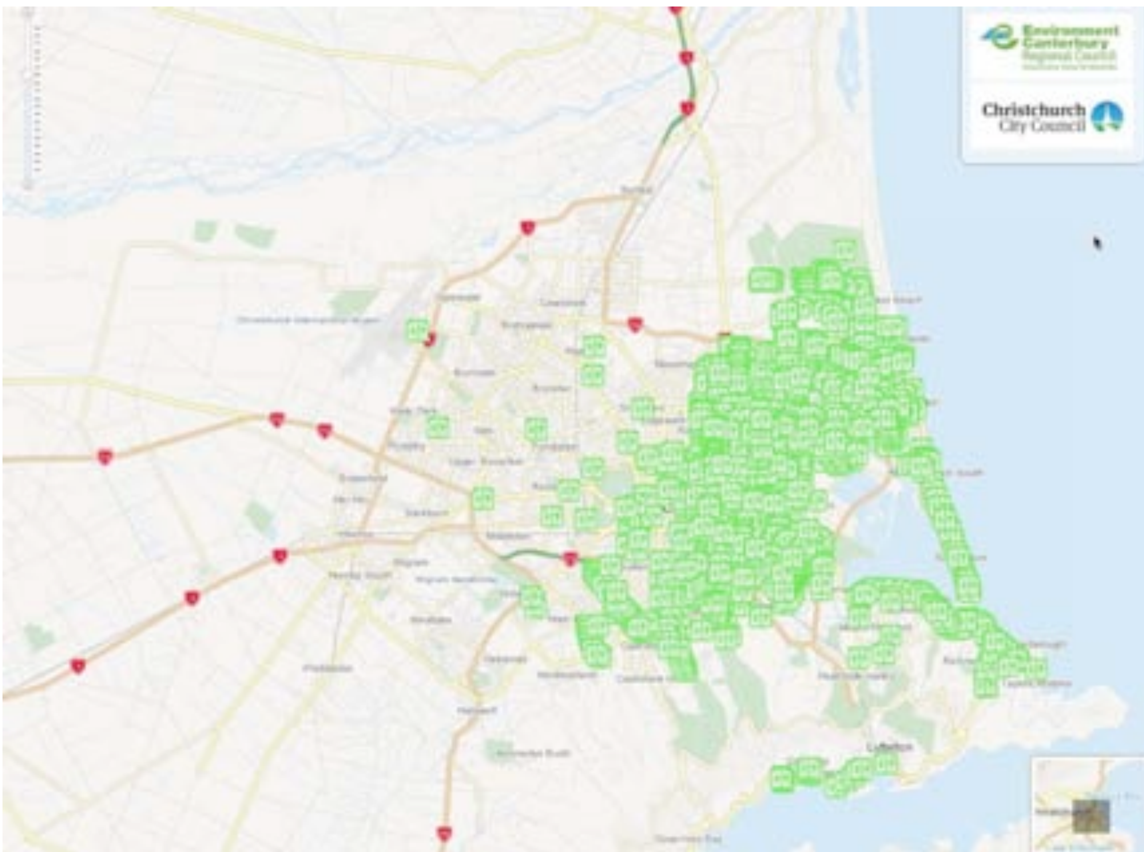


*Figure 7-28. Portaloos in Service, March 2011*

*Figure 7-29. Portaloos and chemical toilet tank deployed in residential neighborhoods.*

Figure 7-30 shows raw sewage being spilled into the Avon River (note the ducks). The sight of solids floating on the river surface has been judiciously cut-out of the images in this report.


*Figure 7-30. Raw Sewage in Local River, April 2011*

Figure 7-31 shows the additional movement of a sewer dry well lift station, due to the February 2011 earthquake. Compare this with the movement of the same lift station from the September 4 2010 earthquake, Figure 7-4.


*Figure 7-31. Rotation and Sewer Lift Station, April 2011 (see Fig 7-4 for Comparison)*

Figure 7-32 shows another dry well lift station that floated in the February 2011 earthquake.  Several other dry well pumping stations floated during the February, 2011 earthquake due to the more extensive liquefaction.  The total uplift between the two earthquakes at some stations was measured at about 0.6 m and could exceed a meter at other stations.

*Figure 7-32. Flotation of Sewer Lift Station, April 2011*

Figure 7-33 shows the Pages Road Sewage Pumping Station. The pump station site suffered severe liquefaction. The suction well floated about 4" to 6" and connections with the sewage pipes broke outside the station, but the pumps and internal piping remained functional. Measurements on the outside indicated differential movements of 4" to 10" across the entire building. There were no flexible connections for piping at this station. Figure 7-34 shows the interior wall differential movement.

Figure 7-35 shows uplift of the suction well at sewer Pumping Station No. 36. The concrete pumping station was not damaged by the earthquake, but liquefaction in the area damaged the inlet and outlet pipes and kept the station from functioning. CCC began sucking sewage from the wet well to dispose of the sewage in a truck. As they were sucking out the sewage the wet well began to float (should have been no surprise!)

Sewer pipelines were damaged at bridge crossings where the bridge abutments were damaged by lateral spreading. Figure 7-36 shows a HDPE pipe used as a temporary bypass line placed overtop of the Brighton Bridge.

*Figure 7-33. Pages Road Pumping Station.*

*Figure 7-34. Pages Road Sewer Pumping Station differential movement.*

*Figure 7-35. Sewer Pumping Station No. 36*


*Figure 7-36. Sewer pipe bypass over the Avon River at Brighton Bridge.*

Figure 7-37 shows the sewer system network status as of April 2, 2011. The green lines identify pipelines that are fully functional. Yellow lines indicate pipes that provide limited service. Red lines show areas having no service, and brown lines are locations needing confirmation of their status.

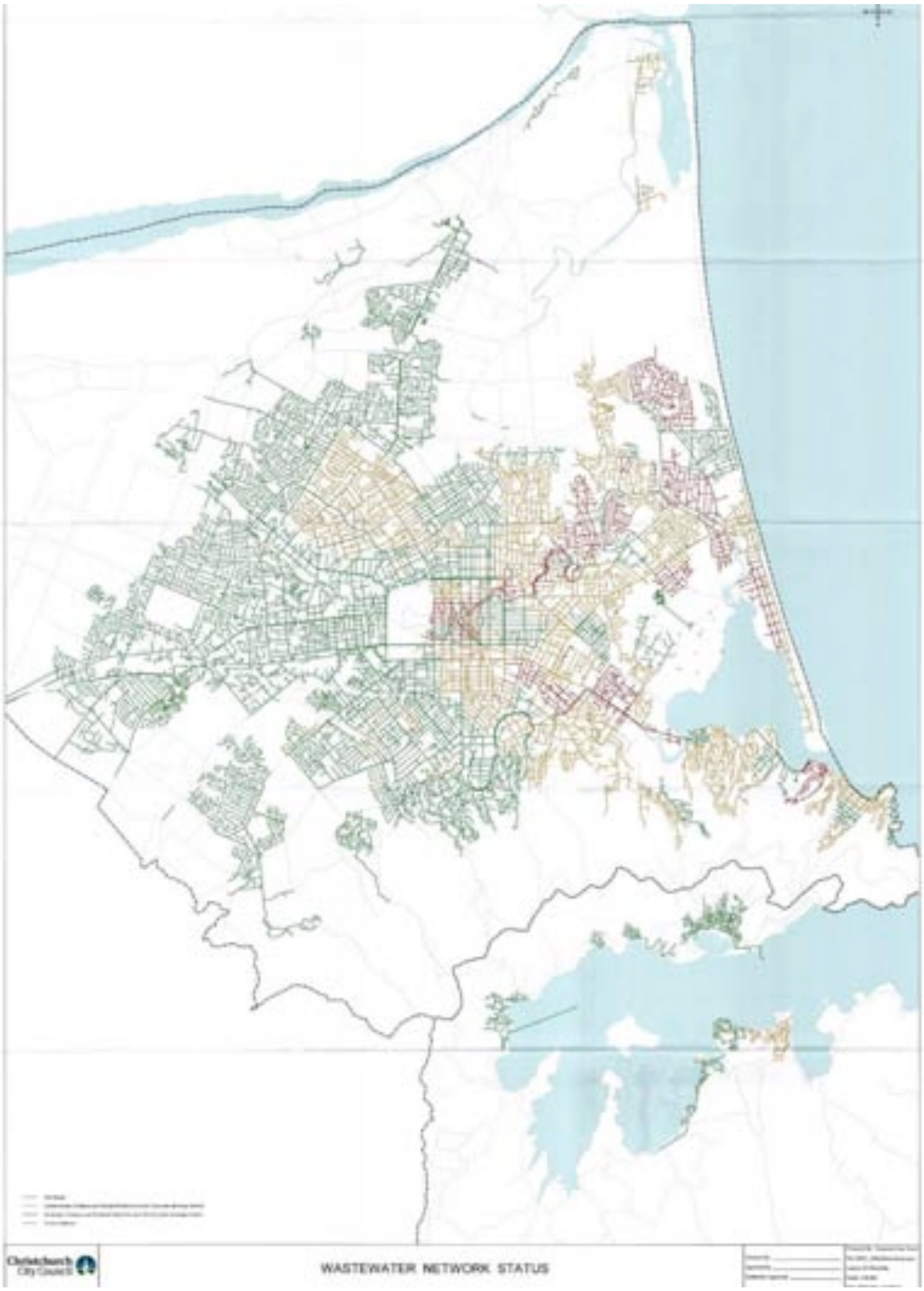


*Figure 7-37. Wastewater pipe network status*

Figure 7-38 shows the process flow diagram for the Bromley WWTP. Figure 7-39 shows an aerial view of the WWTP following the February 2011 earthquake. Figure 7-40 provides a close up from the areal above the digester tanks showing how one of the two tanks had its roof thrown off during the earthquake.

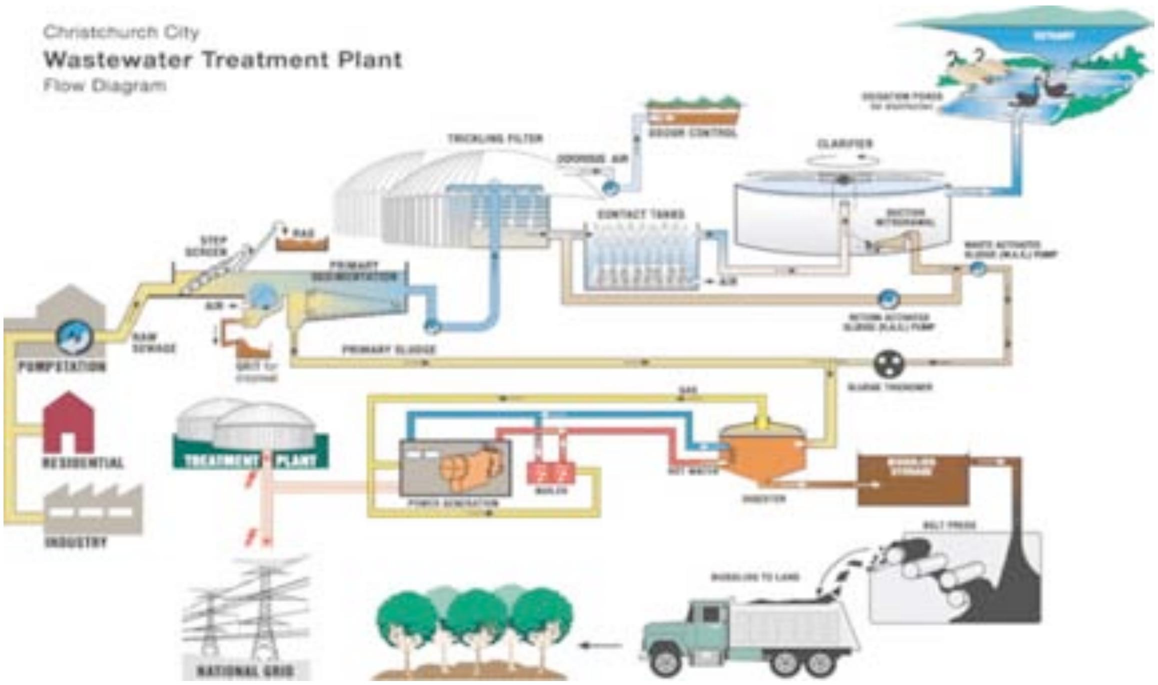


*Figure 7-38. Process Flow Diagram, Bromley WWTP*

*Figure 7-39. Aerial view of Bromley WWTP following the Feb. 2011 earthquake.*

*Figure 7-40. Aerial view of digester tanks at Bromley WWTP*

Figure 7-41 shows a cracked pipe leading to one of the digesters. There was no leak, as the pipe has an internal liner (and the digester was out of service).

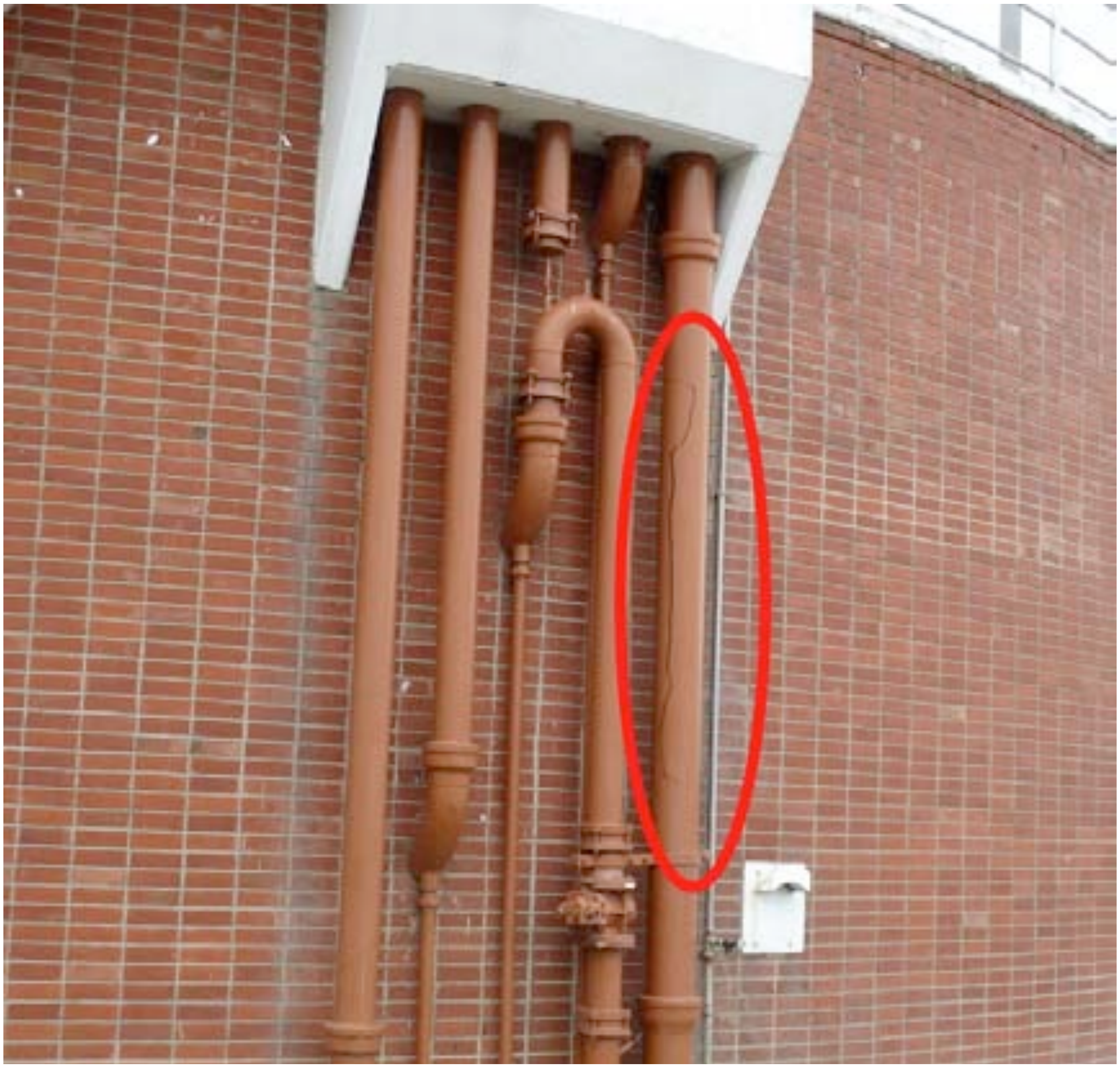

*Figure 7-41. Cracked Pipe to Digester, Bromley WWTP*

Figure 7-42 shows a cable spreading area at the Bromley WWTP. While the facility shook with PGA = 0.5g, there was no damage to these rod-supported trays and pipes; showing that intelligent New Zealand engineers have recognized the wastefulness of ASCE 7 2010 and related non-structural code that would require seismic lateral braces in such a situation.

Figure 7-43 shows damage to the scrapers in the primary sedimentation tanks. The tank on the right has wood scrapers, reflecting that the original metal channels have buckled and failed. This photo was taken in April 2011, while repairs were being made to these basins.


*Figure 7-42. No Damage to Rod-Hung Cable Trays, Bromley WWTP*


*Figure 7-43. Scrapers, Bromley WWTP*

Figures 7-44 and 7-45 show workers cleaning sand from the grit chambers and the primary settling basins, respectively. These basins were reportedly completely filled with sand and were at the end of cleaning at the time of photos taken in early April 2011. The depth of sand reached about 6 m completely filling the grit chamber in Figure 7-44 to the top water mark notable near the top of column. One set of grit chambers and primary settling basins were restored within about 1.5 to 2 weeks after the earthquake. Since then the plant has been working at about 1/3 capacity and the different sets of grit chambers and primary settling basins have been rotated between cleaning of sands and treating of sewage.

*Figure 7-44. Grit Chamber cleaning, Bromley WWTP*

*Figure 7-45. Primary Settling Basins Cleaning, Bromley WWTP*

The Bromley WWTP has two pumping stations called Pumping Station A and Pumping Station B. There was no damage reported to pumping Station A. Pumping Station B had damage to a mechanical coupling shown in Figure 7-46 that allowed sewage to leak and fill up the station. The cause of damage to the coupling was not known as of April 2011, but is suspected to be from small differential movements, as observed during time of site visit.

*Figure 7-46. Pumping Station B leak at mechanical coupling, Bromley WWTP*

Figure 7-47 shows damaged 6" PVC pipe in the aeration contact tank. This type of damaged PVC pipe was seen at several other places in this tank.

*Figure 7-47. Broken PVC Pipe in Aeration Tank, Bromley WWTP*

Figure 7-48 shows one of the four secondary clarifiers. Three of four clarifiers were heavily damaged, due to a combination of liquefaction and sloshing forces on the sludge mechanisms. CCC believes that some of the clarifier floors have experienced up heaving. Dewatering is necessary prior to emptying the tanks for inspections, thus significantly delaying ability to determine needed repairs/replacements. These will likely have to be rebuilt entirely.


*Figure 7-48. Broken Secondary Clarifier, Bromley WWTP*

Figure 7-49 shows external clamps placed on leaking reinforced concrete pipes (3-foot diameter) at the WWTP.


*Figure 7-49. Broken Secondary Clarifier, Bromley WWTP*

The Bromley WWTP has an underground corridor, called a gallery constructed of reinforced concrete, and used for housing piping and conduits. The gallery was damaged and separated at construction joints as shown in Figure 7-50. Water and sand flowed into the gallery through the drainage pipe system and the joint separations.

*Figure 7-50. Gallery Damage, Bromley WWTP*

The overall damage at the WWTP required CCC to release untreated wastewater into the 230 hectares of oxidation ponds. Water from the ponds is disposed in an ocean outfall. The sewage can bypass the treatment plant to the ponds, but the ponds cannot be bypassed to send sewage directly to the outfall. CCC estimated that there was a 50% chance that the oxygen levels would drop below functional levels, turning the normally placid ponds into a vast cesspit. Should this happen, CCC estimated it would be difficult to reverse and the smell could linger for months. The Bromley WWTP has also been dealing with an influx of debris and sand which has infiltrated the crippled wastewater collection pipe system, putting pressure on the already-distressed filtering tanks. Through early April 2011, CCC estimated that the WWTP had sucked about 400,000 tons of sand from the sewerage pipe network. The WWTP received up to 1000 tons of sand in one day. This is compared to about 30,000 tons of sand removed in total after the September 2010 earthquake.

Damage at the Bromley WWTP itself could take between 6 months to 2 years to fix.

## 7.3 Wastewater System Performance – Three Earthquakes

Cumulatively over the three earthquakes, the following damage occurred and recovery actions taken:

- 12 km of pressure main (force main) will have to be built; CCC normally renews about 10 km per year.

- Immediately after the February 2011 earthquake, the wastewater treatment plant received zero flow. As of August 2011, all processes were back in service, except for UV. It was estimated it would take until mid 2012 before the plant would be back to pre-earthquake standards.

- Silt from the WWTP is being stored at the Burwood landfill.

- Solid waste service was not disrupted.

- There was damage at the composting plant; tunnels were damaged, but with temporary fixes in place. The plant was re-opened in May 2011.

- It was hoped that by the end of August 2011, all residents would be off chemical toilets.

- It was hoped that by August 31 2011, all major (but not all) overflows of raw sewage into local streams and rivers would be halted. It was hoped that beaches and rivers would be back to bathing standards by November 2011.

## *7.4 Observations*

Relative to other lifelines, sewer systems have often been neglected with regards to seismic vulnerability assessments and mitigation. In the Christchurch earthquake sequence of 2010 to 2011, the extent of liquefaction has proven that this neglect might be misplaced. Most citizens would say that the damage to the sewer system had the most severe impacts to daily life, as compared to the damage to power, water, telecom, gas, bridges, etc.

The extent of pipeline damage to the sewer system rivals or exceeds that of the water system; and yet takes 3 to 10 times as long to repair, owing to the depth of gravity sewers. The damage due to liquefaction at the WWTP in Bromley is very expensive to repair. The combination of sewer and WWTP damage can lead to a big stink; big repair costs; ongoing inconvenience for citizens to use portable toilets, etc.

Rebuilding of 100 mm to 300 mm diameter water and wastewater pipes in liquefaction zones using fusion butt-welded HDPE or clamped electric-welded HDPE or ductile iron pipe with chained joints 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.

## 7.4 Acknowledgements

We want to acknowledge Mark Christison, James Feary, Terry Howes, Ian Johnson, Richard McCracken, and John Noonan from the Christchurch City Council and thank them for generously sharing their information and time to explain the earthquakes affects on the Christchurch sewer system and provide access to their facilities.

# 8.0 Gas and Liquid Fuels

## *8.1 Description of System*

There is a liquid petroleum gas (LPG) reticulated (piped) distribution system that serves the Central Business District and other parts of Christchurch, owned by Contact Energy operating under the Rockgas brand. This is the only gas pipeline supply network in Christchurch. It is about 10 to 15 years old (portion within the Central Business District (CBD) is 15 years; the outer parts are about 10 years old).

In Figure 8-1 the red lines show streets with gas pipelines, while the remaining streets shown in light color do not have piped gas service. A small amount of the LPG is supplied by rail and truck. The distribution system includes about 170 km of pipelines, ranging in nominal diameter from 63 mm to 315 mm; all are medium density polyethylene (MDPE) with electrofusion welds. The common pipe wall thicknesses are about 9 mm (90 mm pipe) to 14 mm (160 mm pipe).

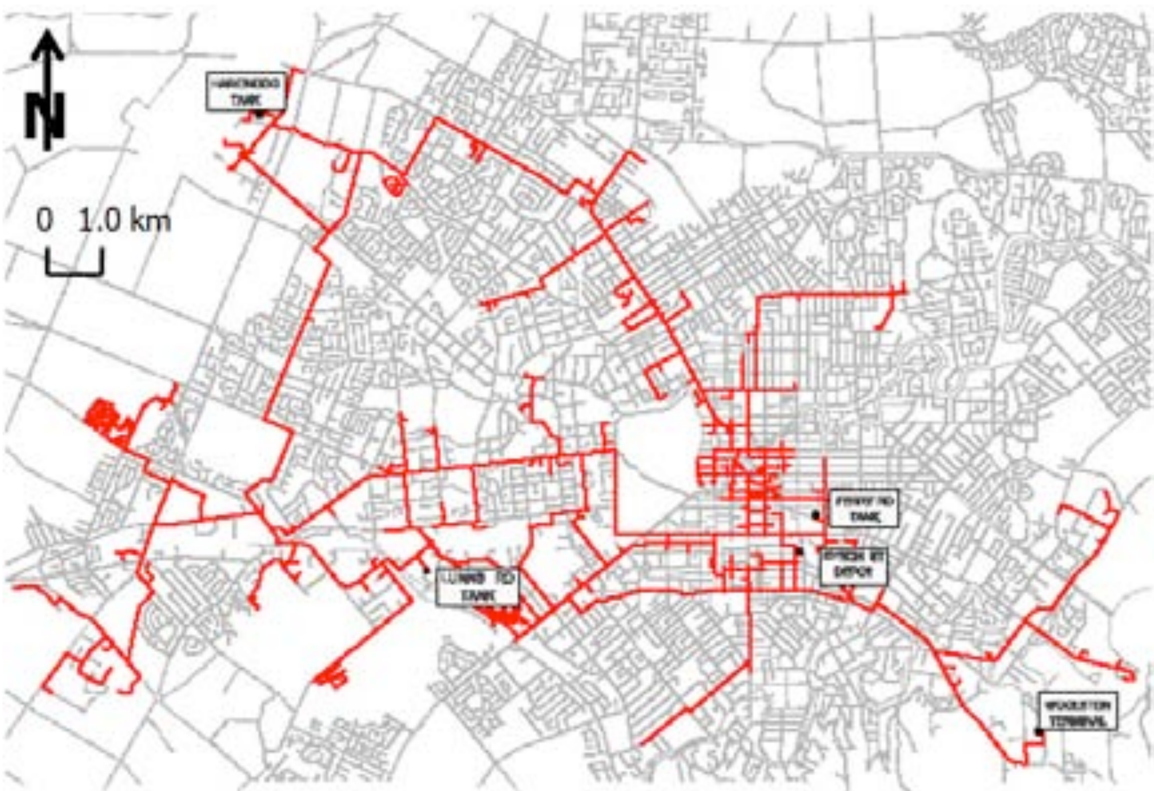


*Figure 8-1. Contact Energy Gas Service Areas and Pipeline Network in Christchurch*

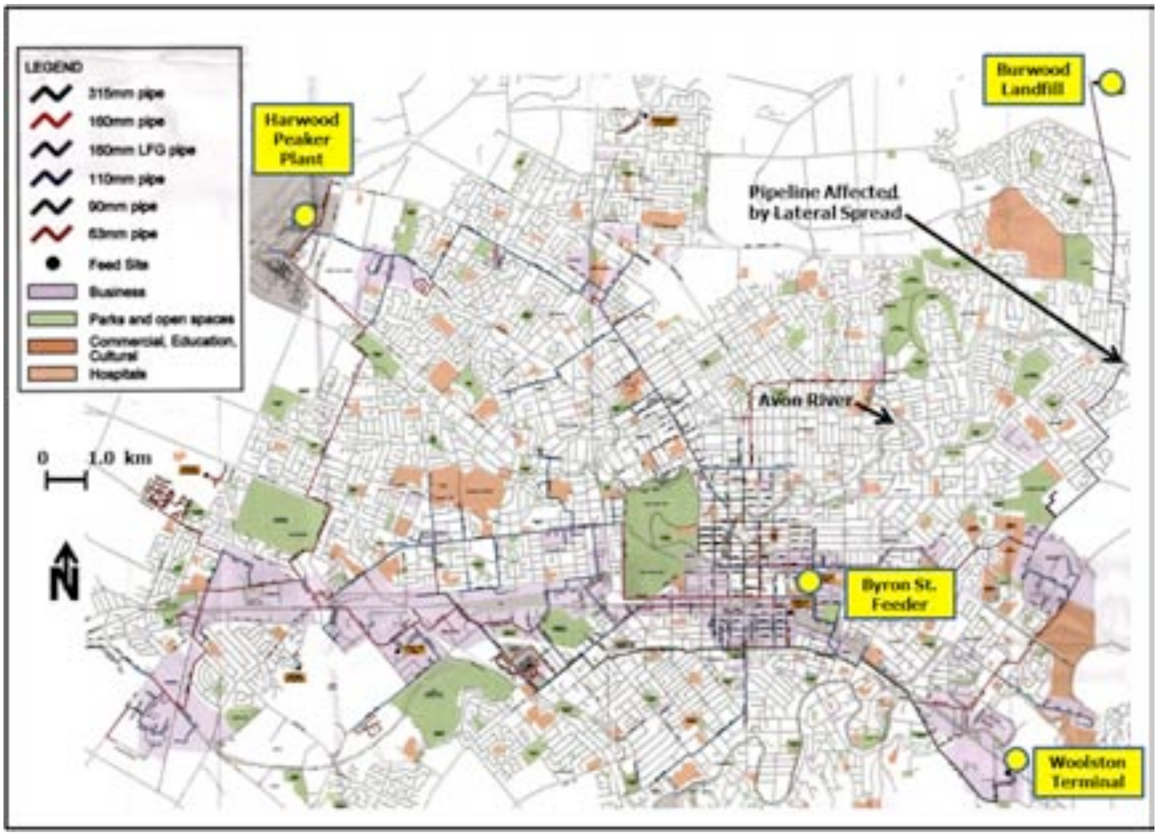


*Figure 8-2. Contact Energy Gas Distribution Network with Road System and Cultural Features of Christchurch*

Most of the gas for the distribution system is supplied from Woolston Terminal (Figures 8-1 and 8-2), which receives LPG through a pipeline from the neighboring wholesaler, Liquigas. Liquigas has 2000 tonnes storage, supplied by a pipeline across the Port Hills from Lyttelton Port. There is 500tonnes of tank storage at the Woolston Terminal and a vaporization plant to convert LPG to gas phase. There is a peaker plant at Christchurch Airport and three back-up feeder plants, all of which receive LPG by truck.

The Woolston Terminal requires water for hot water heating to vaporize the LPG as well as electric power for controls to manage the heating of the water. Water is also used for the fire sprinkler system. Diesel engines and electric generators are available for backup power.

The petroleum gas consists of a mixture of propane and butane. At the feeder plants the LPG is vaporized. The vaporization process predominantly uses hot water to heat the gas to transform it from a liquid. As a backup, gas can be supplied for a limited time from residual pressure in the tanks.

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

## *8.2 September 4, 2010 Darfield Earthquake*

At the time of the September 4, 2010 earthquake, the gas mixture was 60% propane and 40% butane, at an average network pressure of about 90 kPa.

Overall, the system performed very well in this earthquake. There was no disruption to gas service. The only loss to the system was failure of a backup generator at the peaker plant at Harewood. Power was restored to this site late Saturday September 4, 2010. There was no damage to the distribution pipelines. Most of the gas pipelines were outside zones of liquefaction-induced ground deformation, although some were located close to a zone of liquefaction adjacent to Hagley Park. One 160 mm MDPE pipeline from the Burwood Landfill (see Fig. 2), owned by the Christchurch City Council (CCC), was located in areas of liquefaction along Bower Avenue, Palmers Road and Carisbrooke Street, but did not sustain damage.

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

Contact Energy performed a gas leakage survey after the earthquake. It was found that there were a number of valve pits where the surface of the road sustained permanent ground deformation relative to the buried valves. Although some restoration around the valve pits was warranted, there was no damage to the underlying pipelines.

## *8.3 February 22, 2011 Christchurch Earthquake*

After the February 22, 2011 earthquake, gas flow into the Christchurch CBD was shut off, starting about 3:00 pm at the request of Civil Defense. All feeders were shut off in stages. Selected valves were closed to ease the relivening process. The Harewood peaker was the last to be turned off around 6:00 pm. The lines were shut down from about 70 - 90 kPa and equalized at approximately 20 kPa, which was the shut-in pressure during restoration of the system.

All shutdowns were manual. Because traffic was a hindrance, bicycles were used in many instances to negotiate traffic and gain access to various valve locations.

Difficulties were experienced with hand held radios. There was topographical interference with some radio transmissions. Most cell phone service was restored by 23 February, and cell phone communication was used extensively among the crews during restoration of service.

Crews from Wellington and Queenstown came to assist, arriving on February 23. Twenty-two gas company staff and contractors, with help from 8 additional personnel from the parent company worked on restarting the system. A hazard risk analysis was performed on February 23 and determined it was acceptable to start re-pressurizing (livening) the main lines. Livening was initiated the night of February 23, starting with the Harewood peaker. Both water and electricity were available in the western parts of the city when livening was started.

Once a section of main was re-pressurized, a 1-hr test was run to ensure the pressure could be held. The pressurization process was as follows: (1) isolate pipeline sections, (2) shut all customer services, (3) put a gage on one service, and (4) ensure system is holding pressure before accepting. This process was repeated until the entire system was livened.

Although electric power had been lost at the Woolston terminal during the first day after the earthquake, backup diesel-powered generators were available. Loss of water interrupted operation of the hot water vaporizers, but residual pressure was available in the storage tanks for gas flow. Refueling storage tanks was suspended until water was restored to operate the sprinkler system for fire suppression.

It took about 12 days to re-pressurize the entire system, excluding the CBD. Approximately 1400 services were shut down. No services were energized until the customers were contacted. All services except those in the CBD were restored within 2 weeks, proceeding slowly with about 15% of customers restored at 8 days and 60% at 14 days. Basically, within two weeks gas was restored to customers who could receive it.

To protect against gas leakage, all Rockgas pipelines supplying damaged portions of the CBD were cut and capped. These pipelines represent approximately 15% of the pipelines within the system. The Byron St. feeder plant was not placed back in operation until water service was restored to it.

There was no damage to any of the MDPE mains in the system that was restored to operation. Significant parts of the system in eastern Christchurch were located in areas with liquefaction-induced ground deformation.

Figure 8-2 shows the 160-mm pipeline conveying gas from the Burwood Landfill that is owned by CCC. A portion of this pipeline parallel to the Avon River moved in an area where there was displacement and contact by a nearby borewater wellhead. The deformed portion of the pipeline was circumvented by replacing approximately 100 m of pipe between two elbows that had not moved.

Gas service was not restored to many customers due to lost buildings and businesses. In April, 2011 Rockgas had lost about 40% of its customer services, and was providing about 1/3 of the gas supply prior to the February 22, 2011 earthquake. Approximately

25% of the gas supply customers had been businesses, such as hotels and restaurants, which were located in the CBD.

Damage in the gas distribution network was minimal. There has been damage documented in only one service, which was tied into a concrete block that reportedly was subjected to ground deformation. There were two minor flange leaks on steel pipework at the Woolston Terminal. There were no known gas related fires.

## 8.4 June 11, 2011 Earthquake

There was no damage in the gas distribution system as a result of the June 11 2011 event.

## 8.5 Major Observations and Recommendations

Under the combined effects of the Darfield and Christchurch earthquakes, as well as the 13 June aftershocks, there has been no damage observed in any of the MDPE gas mains and only one instance of damage in a service line. Approximately 20 km (of a total 170 km) of gas mains have been isolated within the heavily damaged CBD, and no inspection of these pipelines has been made since the Christchurch earthquake as of the preparation of this report.

The performance of MDPE pipelines in the Canterbury earthquake sequence demonstrates the earthquake resistance of this type of pipeline when constructed well. Despite being affected by strong ground motions and liquefaction-induced permanent ground deformation, there has been virtually no damage in the pipeline network. The Christchurch gas network illustrates several interdependencies among lifeline systems, such as water to operate the gas vaporizers and provide sprinkler water for fire suppression, electric power to heat the water, and cell phone service to enhance communication among crews restoring the system. Durable pipelines and gas services, coupled with careful preparations (e.g., diesel powered generators at feeders, dispersion of feeders throughout the system, and planning for rapid shut down and restoration of services, including arrangements with independent contractors for emergency shut down and restoration) demonstrate effective measures for resilient lifeline performance.

## 8.6 Liquid Fuels

Liquid fuels (gasoline, kerosene, diesel, etc.) are imported to Christchurch via the Port at Lyttleton. At the Port, there are several tank farms (see left side of Figure 9-1) in which the liquid fuels are stored. From this tank farm, a pipeline is used to transport much of this fuel over the Port Hills, to a receiving and distribution tank farm just north of the hills. At this location, tank trucks pick up the fuel for delivery to local gasoline (petrol) stations as well as the airport or other uses.

Exxon Mobil operates one of the tank farms at the Port, as well as the distribution facility north of the Port Hills (Figure 8-2). Each site has 8 at-grade steel tanks; all had seismic design. They reported no damage to any of these tanks: all the tanks have steel roofs (no floating roofs); most of the tanks were nearly empty (under 20% full) at the time of the February 2011 earthquake; in prior studies, they had identified any tanks that had insufficient capacity for PGA = 0.40g, and maintained lower operating levels for those tanks. The 4-inch diameter pipe that goes over the Port Hills was dented due to a rock fall (it did not leak); the pipe was shutdown after the earthquake, and the damaged section was replaced.


*Figure 8-2. Undamaged Steel Tanks at Woolston*

Several petrol refilling stations had damaged canopy structures (Figure 8-3). All the failures appeared to coincide with stations location in liquefaction zones, suggesting that the overturning moment of the canopy exceeded the capacity of the liquefied foundations.


*Figure 8-3. Repairs to Canopy at Petrol Filling Station*

## 8.7 Acknowledgements

We acknowledge Rowan Smith and Wai Yu of Contact Energy and thank them for their generosity in sharing information and providing time to explain the earthquakes effects on the Rockgas system.

# 9.0 Lyttelton Port

The deep water port of Christchurch is located at Lyttelton Harbor, Figure 9-1 in the Banks Peninsula south of Christchruch. The main port consists of four wharves (right side of Figure 9-1) named the Cashin Quays 1, 2, 3 and 4), an oil / liquid fuels berth (left side of Figure 9-1), a container yard (middle right in Figure 9-1), and office building facilities (top of Figure 9-1). There are several breakwaters and piers.

*Figure 9-1. Lyttelton Port*

This deep water port is the major trade gateway to the South Island that was initially established in 1849. The Banks Peninsula was once a volcanic island and Lyttelton Harbor the sea-filled crater of a volcano that erupted 11 million years ago but is now extinct.

The oil berth is primarily constructed of hydraulic fill placed behind a rock dyke, with a wharf constructed along the harbor. Quays 1 and 2 are timber supported constructed in the 1960's. Quay 3 is steel pile supported constructed in the 1970's. Quay 4 is prestressed pile supported constructed in the 1990s. The native subsoils consist of weak silts which have settled out in the relatively calm waters within the old caldera.

## 9.1 Earthquake of September 4, 2010

Figure 9-2 shows the time histories for a ground motion instrument located at the Port, on firm ground / rock site immediately north of the Quays. A photograph of the recording site is presented in the next section. Highest PGA values are about 0.32g (S10E) or 0.22g (N80E); PGV values are 0.19 cm/sec (S10E) and 16 cm/sec (N80E). The duration of strong ground shaking, having PGA > 0.10g, is about 7 seconds, or about half the duration commonly encountered at firm / rock ground sites for M 7.1 events.

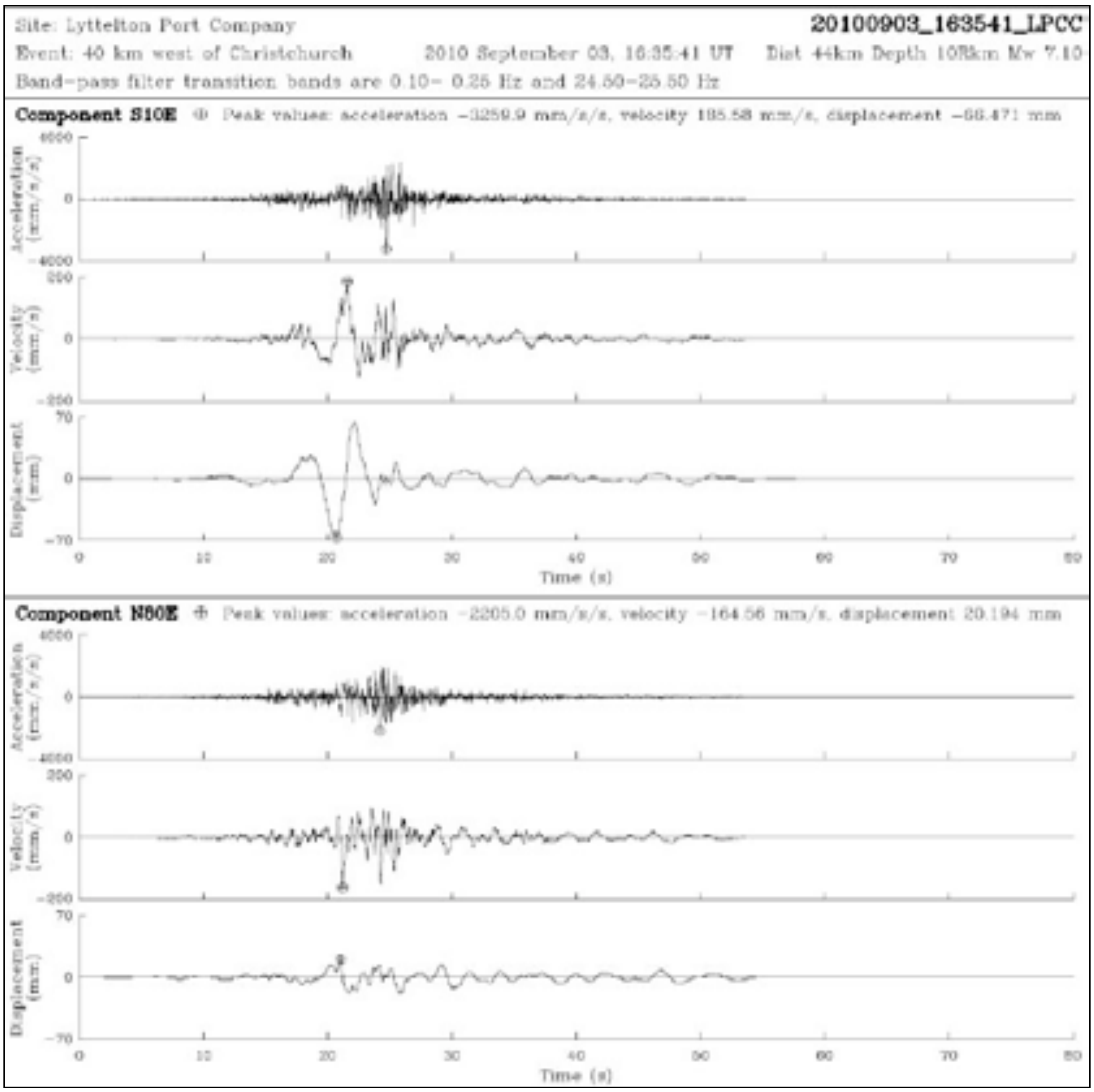


*Figure 9-2. Ground Motion Time Histories, Lyttelton Port*

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, Figure 9-3. 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.

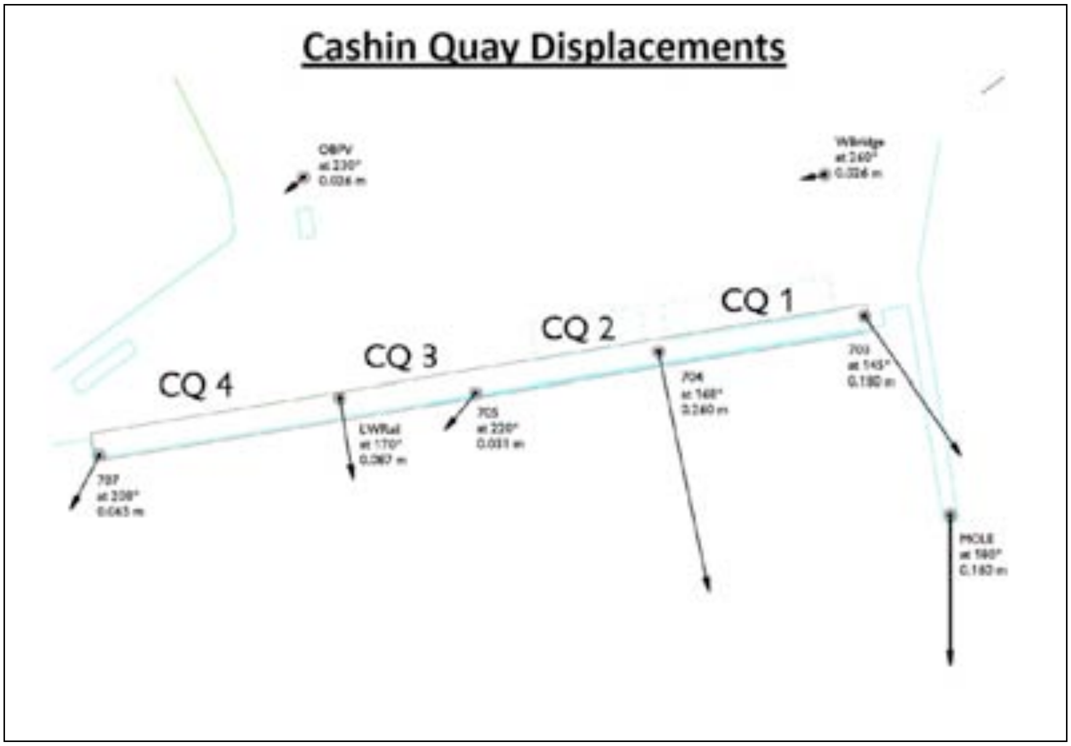


*Figure 9-3. Cashin Quay Displacements*

Figure 9-4 shows the settlements along the deck of Quay 1. This photo is taken looking towards the west, and the coal handling loader is in the left foreground. In the first few hours after the earthquake, in the spirit of precaution, coal loading onto adjacent boats was limited to avoid having to move the loading crane over the settled tracks; this did not adversely affect the ability to load the coal on September 4. By September 5, it was determined that it was feasible to move the coal loader over the displaced rails. The earthquake also damaged the coal conveyors, likely due to differential movement of the steel conveyor supports where they were supported on Quay 1 (with some PGDs, and on land (with no PGDs).

*Figure 9-4. Cashin Quay 1 – Settlement of Deck*

Figure 9-5 shows the lighthouse, tilted, at the end of the Z berth along the eastern mole.

*Figure 9-5. Lighthouse, Z Berth, Slumping of Eastern Mole*

Figure 9-6 shows the oil berth. Prior to the earthquake, the Port had considered various possible upgrades to this berth, including seismic improvements. An intermediate level of upgrade was selected and implemented. These improvements are felt to have been sufficient to have allowed the Oil Berth to remain serviceable after the earthquake, although some PGDs and damage did occur, Figure 9-7.

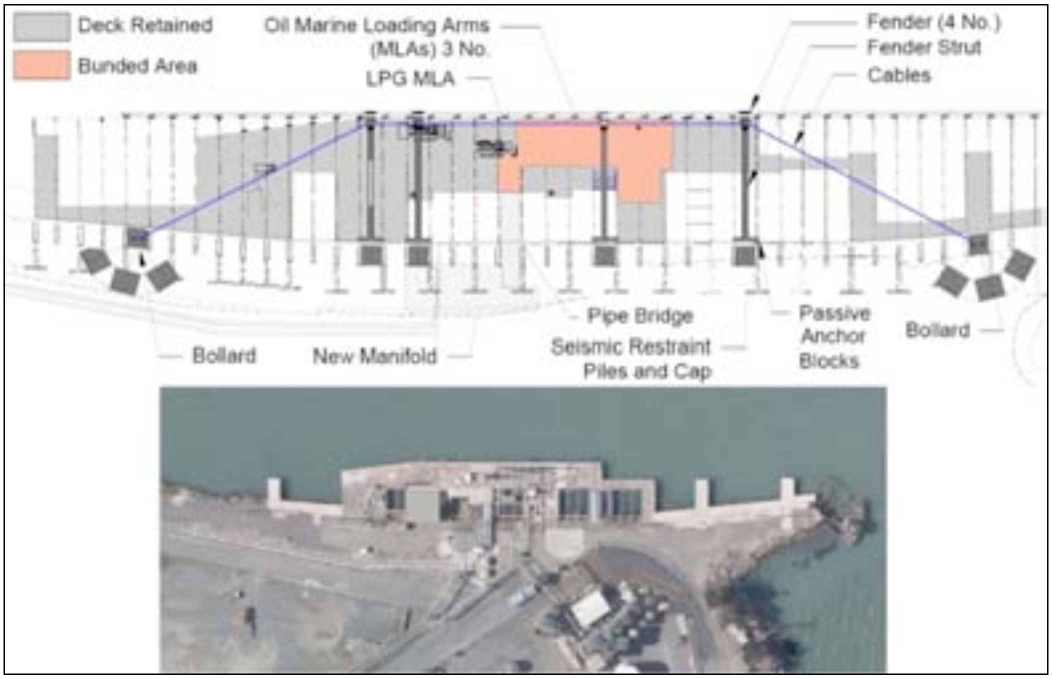


*Figure 9-6. Oil Berth*

*Figure 9-7. Slumping of the Rubble Mound Sea Wall, 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 9-1.

## *9.2 Earthquake of February 22, 2011*

Figures 9-8 and 9-9 show a plan and cross-section with displacement vectors on the Cashin Quays (CQ). As seen in Figure 9-9 the Cashin Quays berths are made of fill over weak silt sediments, having relatively steep outer slopes, with a wharf supported on piles. The fill was end-dumped from the shore and records indicate that the dumping process caused many subterranean slides in the underlying weak silt muds. Some slides were so large the bulldozers and equipment slid into the sea. CQ3, shown in Figure 9-9, is supported by timber piles with an iron bar pile at the end. The iron bar pile has two jointed connections and a length of about 150 feet. The channel was dredged to about 13m depth. A deep seated slide developed during the earthquake shaking and caused quay damages. As indicated in Figure 9-8, CQ3 moved horizontally about 180-190 mm in the February 22, 2011 earthquake and a total of about 232 mm from both earthquakes (Feb. 2011 + Sept. 2010). As indicated in Figure 9-9 the ground behind the wharf settled a total amount of about 800 mm from both earthquakes, with about 2/3 of that coming from the February 22, 2011 earthquake. The 40,000 ton cranes shown in Figure 9-10 jumped the rails. There was lots of damage at main container wharf CQ3. The piles disconnected from the pile caps. As seen in Figure 9-10, there is a backward rotation in the crane due to the slide movement.

Figure 9-8 indicates CQ2 moved as much as 607 mm in both earthquakes (Sept. 2010 + Feb. 2011). Figure 9-11 shows the ground cracking that formed at CQ2. Figures 9-12 and 9-13 show damages to the piles and beams at CQ2.

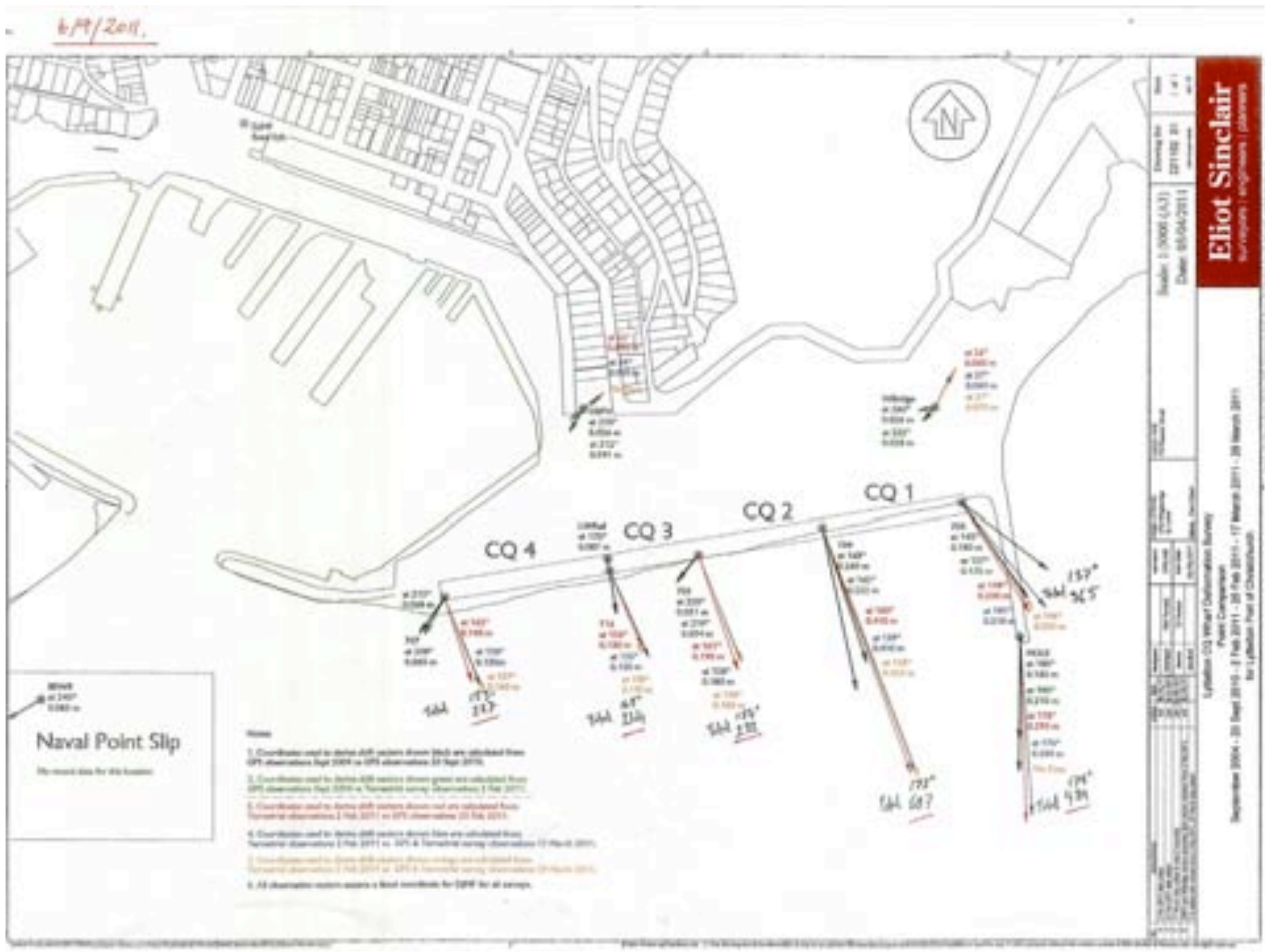


*Figure 9-8. Plan of Cashin Quays showing displacement horizontal vectors from the February 22, 2011 earthquake and total movement (hand written) combined from Sept. 2010 and Feb. 2011 earthquakes. Values as calculated on April 4, 2011 (K. McManus).*

*Figure 9-9. North-south cross section of the container berth CQ3.*

*Figure 9-10. 40,000 ton container crane at the container berth CQ3 (looking west).*

*Figure 9-11. Ground cracks at berth CQ2 (looking west).*

*Figure 9-12. Damaged piles and beams at berth CQ2 (looking west).*

*Figure 9-13. Damaged piles and beams at berth CQ2 (looking west).*

The coal gallery from CQ1 had a measureable permanent tilt. Figure 9-14 shows ground cracking, formed as part of the head scarp on the deep seated slide, on the north side of the coal gallery. Figure 9-15 shows damages to piles and beams at CQ1.

The Lyttelton Port reports that after each earthquake event the critical Port services were restored within 96 hours. The wharf still works and is operable, but needs significant repairs and replacements. Figure 9-16 shows a satellite photograph taken shortly after the February 22, 2011 earthquake showing repairs and improvements underway at CQ1. As seen in Figure 9-17, many cranes are located at the port for post-earthquake construction activities. The port was able to mobilize these repairs and improvements nearly immediately after the February 22, 2011 earthquake because they had prepared an improvement plan following the observed damages from the September 4, 2010 earthquake. The damages sustained in February 2011 matched relatively well that expected from the evaluations performed after the September earthquake so the port mobilized to make the previously recommended improvements as soon as they could. This allowed them to acquire many of the large cranes in Christchurch, that were not being used at the time while others were determining what improvements and repairs were needed to infrastructure elsewhere in the area. Figures 9-17 and 9-18 show on-going construction activities the first week of April 2011. Figure 9-16 shows that four large cranes were mobilized and in operation by March 23, 2011.

The improvement work includes adding new 610 mm diameter steel pile tubes 50 m deep. The piles are being placed at 6 m on center. Improvements also include placing continuous flight augers (CFA) on back side of wharf to support cranes (shown in Figures 9-16 to 9-18) that are placing new piles. As indicated by the cranes being in place, these CFA were completed before March 24, 2011.

*Figure 9-14. Ground cracks on north side of coal gallery at berth CQ1 (looking east).*

*Figure 9-15. Damaged piles and beams at berth CQ1 (looking east).*


*Figure 9-16. Satellite photograph showing construction underway at berth CQ1. Google Earth photo from 3/24/11.*

*Figure 9-17. Post-earthquake construction (April 2011) at berth CQ1.*

*Figure 9-18. Post-earthquake construction (April 2011) at berth CQ1.*

In addition to the damages to CQ1, the coal facility was impacted by a significant volume of rock falls from the hills on the north. Figures 9-19 and 9-20 show ballasted shipping containers stacked around and over a portion of the processing facility to protect against rock falls.


*Figure 9-19. Ballasted shipping containers placed at the coal facility to protect against rock falls following the February 22, 2011 earthquake (looking east).*

*Figure 9-20. Ballasted shipping containers placed at the coal facility to protect against rock falls following the February 22, 2011 earthquake (looking west).*

The breakwaters also sustained significant settlement, possibly a meter or so, making them less effective. Figure 9-21 shows the permanent deformations sustained to the eastern breakwater and a crane at work fortifying the breakwater to withstand wave attacks.

*Figure 9-21. Breakwater east of harbor showing differential permanent deformations and ongoing repairs (looking south).*

Figure 9-22 shows permanent deformations on the western edge of CQ4 at the transition to Z-Berth; the cool storage building is shown in the background. Z-Berth was badly damaged in the earthquakes and is no longer usable for cargo. Figure 9-23 shows settlements on the north side of the cool storage building; notice the large resulting slopes, down to the south, in the concrete slab. Figure 9-24 shows permanent deformations on the north side of the cool storage building. Figure 9-25 shows the large permanent deformations sustained on the west side of the cool storage building on Z berth, just west of the lighthouse shown in Figure 9-26. The lighthouse was left at a 15-degree lean as a result of deformations to the supporting timber structure. The Z Berth needs significant remediation. The cool storage has been demolished. The light structure has been temporarily relocated until the remediation is completed. The lighthouse has been at the port since 1878 and is intended to be replaced at its original location following completion of the Z Berth improvements. The loss of Z Berth and the cool storage has had a significant impact on the local fishing industry, and a number of fishing vessels have had to move to other ports. This has resulted in loss of business for the Port, and for local marine, engineering and supply businesses as well. Plans are underway for constructing a new cool storage building and fishing wharf just north of the oil berth.

*Figure 9-22. Ground deformations on east end of CQ4 at transition toward Z berth (looking west).*

*Figure 9-23. Ground settlements on north side of cool storage building (looking east).*

*Figure 9-24. Ground settlements on north side of cool storage building (looking west, north of Figure 9-25).*

*Figure 9-25. Deformations on west side of cool storage building (looking east).*

*Figure 9-26. Lighthouse, Z Berth, Slumping of Eastern Mole following the February 22, 2011 earthquake (looking east).*

The Lyttelton Port Company has had a long-term need for additional land reclaimed from the sea. As a result, the Company has obtained emergency consents for a 10-hectare Te Awaparahi Bay Reclamation east of the Cashin Quay; in front of the coal facility. The project is using clean hard debris, resulting from building and other infrastructure demolitions in Christchurch, for the land fill. Figure 9-27 shows equipment placing the concrete and rubble debris. The use of the demolition debris for landfill at the harbor is considered a good use of materials, preventing the need for dumping in other landfills and making a new quarry near the harbor. Care must be used to prevent landsliding as the debris is dumped into the bay. Some sliding has already occurred, similar to that described previously during initial port construction.

Despite the earthquake damages, the port has experienced a significant increase in container volumes. May 2011 was reported as a record month for containers, with a total of 26,525 TEUs, up from 25,144 TEUs in May 2010. The increase is attributed largely to dairy exports that were relatively unaffected by the February 2011 earthquake in addition to additional goods brought in for the rebuild of Christchurch (http://www.lpc.co.nz/Home.jasc).

*Figure 9-27. Processing and placement of rubble for the Te Awaparahi Bay reclaimation.*

Figures 9-28 and 9-29 show a satellite view of the oil berth and a northeast-southwest cross section through the wharf at the oil berth. As seen in Figure 9-29 the oil tanks making up the tank farm are founded on hydraulic fill and the hydraulic fill overlies a weak silty mud. There is over 40 m of soil natural silt deposits and a few meters of fill below the tanks. The wharf is supported by 600 mm diameter piles that were constructed a few years ago to help stabilize the oil berth against a deep seated slide and allow the channel to be dredged deeper. This deep seated slide was mobilized during the February 22, 2011 earthquake. The ground movement displaced the wharf horizontally about 0.55 m and the ground behind the wharf dropped about 1 m. The slide continued to creep for some time following the earthquake. Figure 9-30 is a photograph of the wharf (looking northwest from Z berth) showing the backward rotation resulting from the deep seated slope movements.

Figures 9-31 and 9-32 show lateral spreading and ground cracking at the oil berth. The lateral spreading shown in Figure 9-31 is located just northwest of the wharf shown in Figure 9-30.


*Figure 9-28. Satellite image of the oil berth and wharf showing horizontal displacement vectors and change in height shown in parenthesis (K. McManus).*

*Figure 9-29. Northeast – Southwest oriented section through tank farm and wharf at oil berth.*

*Figure 9-30. Oil berth wharf (looking west) showing backward rotation resulting from deep slide movement.*

*Figure 9-31. Lateral spreading at the Lyttelton Port oil berth.*

*Figure 9-32. Ground cracking at the Lyttelton Port oil berth.*

Figures 9-33 through 9-36 show photographs of above ground oil piping and tank connections at the oil berth tank farm. There were reportedly no damages to the piping. The pipe for the most part was constructed above ground except in places where the pipe had to cross roads. In all the Figures 9-32 to 9-36 the pipe is shown to span between supports that have little to no anchorage on the pipe. Figures 9-33, 9-35, and 9-36 show bends designed into the pipe to allow flexibility. Figure 9-36 shows vertical shapes at the tank connections.

*Figure 9-33. Above ground piping at the Lyttelton Port oil berth.*

*Figure 9-34. Flexible pipe connection to tank at the Lyttelton Port oil berth.*

*Figure 9-35. Above ground piping at the Lyttelton Port oil berth.*


*Figure 9-36. Pipe connections to tank at the Lyttelton Port oil berth tank farm.*

The fire fighting pipeline that runs along and is fixed to the wharf broke and disrupted ability to move gas and oil from ships. The fire system is made up of a sea water pump and piping.

There were no damages to the oil tanks or any oil or liquid fuel pipelines. The tanks were reported to have been empty or very little oil in them at the time of the earthquake.

There are two means of transporting the oils and liquid fuels to Christchurch: (1) pumping through a fuel pipeline that runs over the Port Hills, and (2) by trucking through a tunnel through the Port Hills into Christchurch. The fuel pipeline was damaged by boulders rolling down the steep slopes. When tanker trucks travel through the tunnel, tunnel is shut down to all other traffic and a pipeline is used to provide water for firefighting. Due to water system damages there was no water available to pressurize this line immediately after the earthquake. These two problems initially caused problems in importing fuels into Christchurch. However, within a few days the Tunnel Road water pipeline was re-pressurized and allowed trucks to resume transporting fuels into Christchurch.

## *9.3 Major Observations and Recommendations*

The Lyttelton Port suffered significant damage in the September 4, 2010 and February 22, 2011 earthquakes, but was able to resume providing critical services within a very short timeframe. Damage resulted primarily from deep seated slides in loose hydraulic or dumped fills overlying silty bay muds. The slide movements damaged the wharf structures. Preparations for seismic mitigations following the September 4, 2010 earthquake allowed the port to very rapidly mobilize for restoring and improving the port following the February 22, 2011. The rate of mobilization and initiation of remediation construction was impressive. The port was also able to increase the level of container cargo despite the earthquake damages. Damages to Z-Berth have had a significant impact on local fishing and the port plans to develop new cold storage and docking facilities for the local fishermen.

The oil container berth suffered damages, but no damage resulted to the oil tanks or piping. The seawater fire pipeline was damaged on the wharf and temporarily eliminated the ability to off load oil products. However the more critical impact on importing oil and liquid fuel products into Christchurch was the ability to transport the products through the over-land pipe or trucking through the tunnel.

In addition to ground deformations resulting from weak soils at the berths and piers, the coal facility was impacted by rock falls from the steep Port Hills on the north. Barricades were installed to help protect the workers and equipment from continued falling rock.

## *9.4 Acknowledgements*

We want to acknowledge Kevin McManus of McManus Geotech Ltd. And the Littleton Port for their generous sharing of information and time to explain the earthquake affects on the Lyttleton Port facilities.

# 10.0 Airport

The commercial airport for Christchurch is located immediately northwest of the city, and northeast of the fault rupture. Recorded ground motions near the airport for the September 4, 2010 event were about PGA = 0.30g. Known damage at the airport in this event 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 10-1), it was in service shortly after the earthquake.

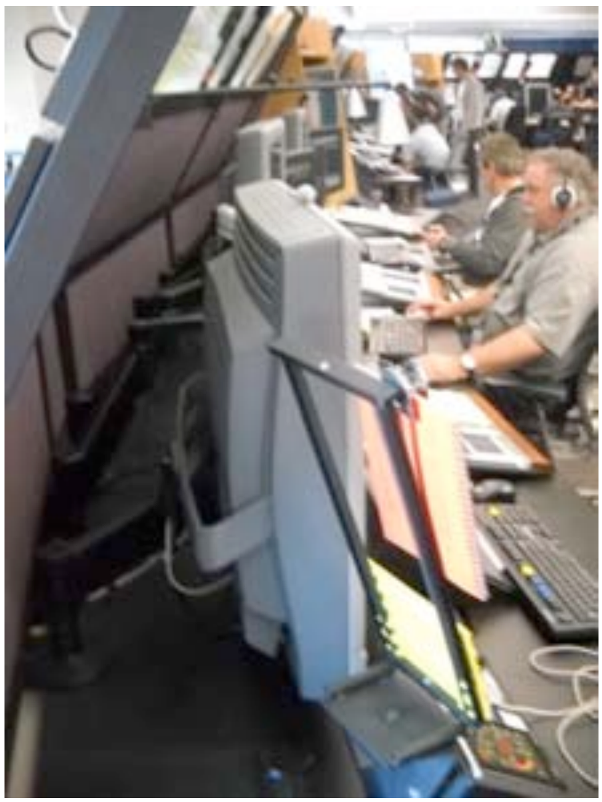

*Figure 10-1. Air Traffic Control*

# 11.0 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).

Sections 11.1 and 11.2 examine performance of the road and bridge network in the September 4, 2010 earthquake. Sections 11.3 examine the performance of the bridges in the February 22, 2011 earthquake.

NZTA had $6 million in damage from the September 2010 event; and $40 million in damage from the February 2011 event.

## *11.1 Roads and Bridges – September 4 2010*

Fault offset resulted in damage to several surface roads. Figure 11-1 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 (Figures 2-20, 2-21). 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 11-1. Road surface up heaving due to permanent ground deformation*

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 11-2 and 11-3).

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 11-4 and 11-5 show a broken sewer pipe crossing a bridge; the broken pipe remained in service and was discharging into the creek below.

*Figure 11-2. Rubber bearing deformed*

*Figure 11-3. Deck and abutment impact damage*

*Figure 11-4. Plastic hose connected to broke pipe to discharge wastewater to stream*

*Figure 11-5. 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.

## 11.2 Roads and Bridges — February 22 2011

Over 800 city and highway bridges are located in the Christchurch and vicinity areas. During the February 22, 2011 earthquake, many of these bridges were subjected to ground motion shaking at level significantly higher than their design level. Despite having experienced significantly stronger than design level excitations, only a small number of bridges suffered significant damage. Overall, bridges performed well during the February 22 2011 earthquake. There were about 60 bridges, which included 9 pedestrian footbridges, suffered damage from the earthquake. The damages were mostly concentrated in the central and eastern part of Christchurch areas. Among the 60 damaged bridges, 49 were river crossing bridges spanning across the Avon or other rivers in the Christchurch and vicinity areas. The most common causes of the observed bridge damage were lateral spreading of the river banks and rotation of bridge abutments precipitated by liquefaction failure of the surrounding soil. The approach roadways of many damaged bridges were also observed to have differential settlement relative to the bridge superstructures due to movement of the abutments and lateral spread of the approach roadway materials. Most damaged bridges were able to reopen to traffic after emergency repair. Bridges of the State Highway system in the earthquake areas performed well with no bridge suffered damage that required closure over extended period of time.

After the earthquake, traffic patterns on the city road and highway systems in the Christchurch and vicinity areas changed significantly with more congestions observed. The traffic network system is currently being reassessed in light of the traffic pattern changes in the earthquake areas.

Members of the reconnaissance team visited more than 12 damaged bridge sites to gather information and bridge performance data of lessons learned from the New Zealand earthquake experiences.

### 11.2.1 City Bridges

The majority of the damaged city bridges were crossings over the Avon River. Along the Avon River, widespread liquefaction failure of soil was observed in areas next to the river banks which contributed to the observed damage and performance of the overpass bridges.

<u>Ferrymead Road Bridge</u>

The Ferrymead Road Bridge (1967) is a continuous 3-span concrete bridge. It spans the Heathcoate River in the south-eastern part of Christchurch. The Ferrymead Road Bridge is classified a critical lifeline bridge, an important link in the transportation lifeline network. It also carries essential utility services. The Ferrymead Road Bridge was not damaged during the September 4, 2010 earthquake. Before the February 22 2011 earthquake, a new $10 million NZD bridge was under construction at the same location to replace the existing bridge, as shown in Figure 11-6. During the February 22 earthquake, the existing bridge suffered serious damage due to rotation and lateral movements greater than 1 m at the abutments, as shown in Figure 11-7, and piles of bridge piers. The substructure of the bridge was damaged and had moved up by 80 mm. The utility service lines collocated with the bridge superstructure ruptured during the earthquake resulting in loss of utility services in surrounding communities. Emergency repairs at a cost greater than $200,000 NZD, which include tie-backs for the bridge piers, as shown in Figure 11-8, and temporary supports of bridge spans, have been carried out. Rotation and lateral movement of the piers and abutments of the bridge are currently being monitored.

*Figure 11-6. Existing Ferrymead Road Bridge and new replacement bridge under construction.*


*Figure 11-7. Rotation and lateral movement toward river of Ferrymead Road Bridge abutment and partial view of emergency tie-back measure to bridge pier/pile*

*Figure 11-8. Temporary tie-back measure to arrest further lateral movement of pier/pile of Ferrymead Road Bridge (Photo: Lloyd Greenfield)*

<u>Moorhouse Avenue Bridge</u>

The Moorhouse Avenue Bridge (1960) at Colombo Street, as shown in Figure 11-9, is a 11-span T-girder concrete bridge supported by two-column bents with diaphragms.

*Figure 11-9. Moorhouse Avenue Bridge at Colombo Street*

The columns have a hexagonal cross-section and are slightly tapered and flare at the top, as shown in Figure 11-10. The column has 1-1/8 in diameter smooth longitudinal rebars and smooth 5/8 in transverse ties at 12 in spacing. The Moorhouse Avenue Bridge suffered significant damage during the earthquake. The bridge has expansion joints at column bents 4 and 7 from the west abutment of the bridge. The presence of the expansion joint reduces the depth of the column cross-section to half of that in the other columns. Thus, the columns at the expansion joint locations have a significantly smaller stiffness as compared to the other columns of the bridge. During the February 22, 2011 earthquake, the columns at the expansion joint locations suffered significant damage of shear failure at the column base and buckling of the longitudinal rebar, as shown in Figure 11-11a, b. Evidence of liquefaction failure of the foundation soil was observed at the bridge site, as shown in Figure 11-12. After the earthquake, temporary repair measure of bracing of the damaged column bents at the expansion joints taken. The bridge was reopened to vehicle traffic.

*Figure 11-10. Temporary bracing support of column bent with expansion joint of Moorhouse Ave Bridge at Colombo Street*

*Figure 11-11a. Column bent with expansion joint*

*Figure 11-11(b). Shear failure and buckled smooth rebar of column of Moorhouse Avenue Bridge at Colombo Street*

*Figure 11-12. Liquefaction .of foundation soil at Moorhouse Ave Bridge at Colombo St.*

Boathouse Bridge

A 1920 single span steel truss arch pedestrian bridge with wooden walkway deck, as shown in Figure 11-13, near the Christchurch Hospital next to a boathouse over the Avon River was damaged during the February 22, 2011 earthquake. The abutments at both ends of the bridge had severe shear cracks due to lateral spreading movement of the river banks, as shown in Figure 11-14. The approach pavement near the joints with the bridge buckled due to pounding movement of the bridge deck superstructure.

*Figure 11-13. Boathouse Bridge for pedestrian traffic*

*Figure 11-14. Abutment failure of Boathouse Bridge.*

Fitzgerald Avenue Bridge

The Fitzgerald Avenue Bridge (1964) consists of two parallel concrete bridges, Figure 11-15. Each bridge is a 2-span girder on wall pier structure. During the February 22 earthquake, the abutments suffered shear cracks and rotation because of lateral spread movement of the river embankment soil, as shown in Figures 11-16 and 11-17, respectively. One of the bridge girders was damaged due to movement of the abutment. The approach and nearby roadways had significant lateral spread settlement after the earthquake. Before the Christchurch earthquake, the bridge had been retrofitted with steel seat width extender brackets at the abutments and wall piers.

*Figure 11-15. Fitzgerald Ave Bridges*

*Figure 11-16. Shear crack in abutment of Fitzgerald Ave Bridge*

*Figure 11-17. Rotation of abutment of Fitzgerald Ave Bridge*

### 11.2.2 State Highway Bridges

There are 25 bridges in the State Highway System in the earthquake areas of the February 22, 2011 earthquake. Several of these bridges had been retrofitted before the February 22 earthquake. During the Feb 22 2011 earthquake, the bridges were subjected to very severe ground shaking, well exceed the level specified in current design standard. The current design requirement is that typical highway bridges are designed for 1,000 year return period earthquakes, whereas important bridges are designed for 2,500 year return period events. Rural bridges are designed for 500 year return period earthquakes.

Despite the very strong shaking, only two state highway bridges suffered damage and one bridge required restriction to single lane traffic, and six other bridges were being monitored. The total estimated cost including post-earthquake initial response and long-term repairs is $6 million NZD.  Overall, the state highway bridges performed very well during the February 22, 2011 Christchurch earthquake.

<u>Anzac Drive Bridge on State Highway 74</u>

The Anzac Bridge (2000) is a concrete bridge of 3-span void slabs on 4-column bents over the Avon River, as shown in Figure 11-18 (Photo taken October 2010). During the February 22 Christchurch earthquake, the bridge sustained seismic forces and demands greater than design values.  The abutment rotated (Figure 11-19) and moved laterally more than 2 m (design 0.5 m) toward the river. Liquefaction of foundation soil was estimated in depth significantly greater than the design assumption of 2 m. The pile supporting the abutment shown in Figure 11-20 was observed to have rotated after the earthquake. As a result of the lateral movement of abutments at both ends of the bridge, the bridge deck superstructure sustained compressive forces from the abutments. The bridge piers had flexural and shear cracks, as shown in Figure 11-21, due to plastic hinging and lateral movement of the piers.

*Figure 11-18. Anzac Drive Bridge on SH 74 (October 2010)*

*Figure 11-19. Rotation of left abutment of Anzac Drive Bridge (February 2011)*

*Figure 11-20. Damaged rotated pile at abutment of Anzac Drive Bridge*

*Figure 11-21. Flexural and shear cracks in column of Anzac Drive Bridge*

<u>Port Hills Road Overbridge on State Highway 74</u>

Port Hills Road overpass (1970) on SH74 is a 6-span voided slab single column bent concrete bridge, as shown in Figure 11-22. Prior to the February 22 earthquake, it had been retrofitted with span tie-links and seat width extension brackets, lateral restrainers and short column collars to mitigate the short column effect for the columns next to the abutments, as shown in Figure 11-23. During the Feb 22 2011 earthquake, the middle column sustained flexural crack and spalling of concrete, and buckling of the longitudinal rebar at the base, as shown in Figure 11-24.

*Figure 11-22. Port Hills Road Overbridge on SH74*

*Figure 11-23. Retrofit measures of lateral restrainer, span tie-link/seat width extension bracket, and short column collar on Port Hills Road Overbridge on SH74*

*Figure 11-24. Flexural crack and buckling of rebar in column of Port Hills Road Overbridge*

Horotane Valley Road Overbridge on State Highway 74

The Horotane Valley Road overbridge (1963) shown in Figure 11-25 is a 3-span T-girder concrete bridge. It was retrofitted with span tie-links and shear keys with seat width extension before the earthquake. After the February 22 earthquake, cracks were found at the abutments, as shown in Figure 11-26, and many bolts of the seat width extension brackets were sheared off, as shown in Figure 11-27.

*Figure 11-25.Horotane Valley Road Overbridge on SH74*

*Figure 11-26. Cracks in abutment of Horotane Valley Road Overbridge*

*Figure 11-27. Shear-off of anchor bolt of seat width extension bracket of Horotane Valley Road Overbridge*

## 11.3 Acknowledgements

The technical information and assistance provided to the reconnaissance team by the following individuals and their organizations are gratefully acknowledged

John Reynolds, Lloyd Greenfield, Peter Connors, Steve McNeil, David McNaughton, Mark Gordon, Tony Fenwick, Sonia Giovinazzi, Tom Wilson, Misko Cubrinovski, Alessandro Palermo, Gregory MacRae, and Richard McCracken.

# 12.0 Railway System

KiwiRail operates a heavy rail network and a limited (two line) passenger train system for the South Island. The rolling stock includes 63 mainline diesel locomotives, Figure 12-1. Typical rail speeds range between 55 and 80 km/hr.


*Figure 12-1. Kiwi rail - Locomotive*

The main rail traffic in the Canterbury region is transport of dairy products ($140 million annually) and coal ($50 million annually). The majority of the dairy product transported is bulk milk with a minor amount of processed dairy product. Distribution is throughout the South Island. Coal is principally transported from the western side of the South Island to the Port of Lyttleton, via the Midland Line, see Figure 12-2.

## 12.1 Performance in September 4 2010 Earthquake

Figures 12-3 and 12-4 show the buckled rails where the right lateral fault (red line in Figure 12-2) crossed the Midland Line, northwest of Rolleston. The engineer in the locomotive seen in Figure 12-4 reported that the train was moving at about 80 kph when the earthquake occurred; he observed that the headlight was wavering, and that the front wheels "seemed to loose traction"; he then used emergency braking, and the locomotive stopped at the location seen in Figure 12-4, just a few meters before the buckled track section.

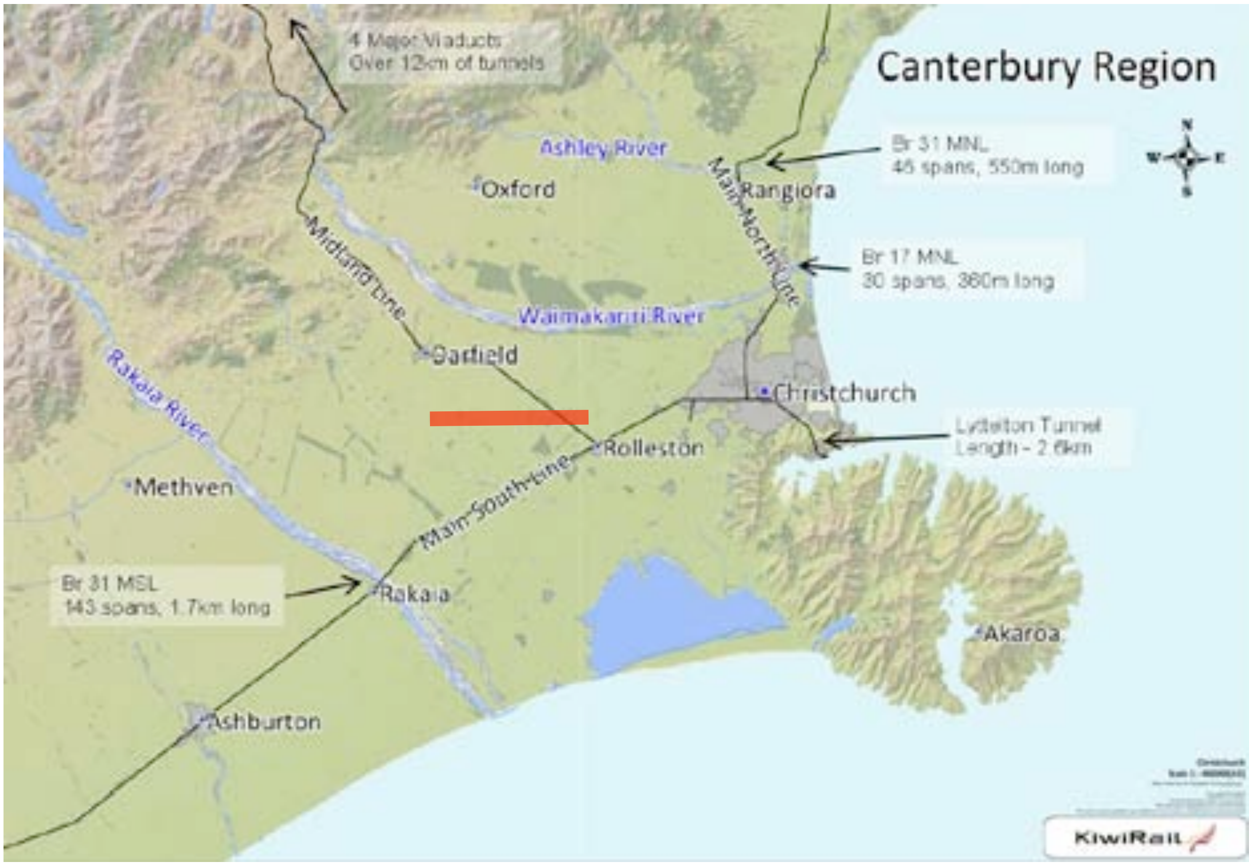


*Figure 12-2. Rail System in the Canterbury Region*

The track in Figures 12-3, 12-4 and 12-5 was repaired within 5 hours after the earthquake (Figures 12-6), 12-7. 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 12-3. Buckling of Rails at Fault Offset Location*


*Figure 12-4. Buckling of Rails at Fault Offset Location (Baxter)*

*Figure 12-5. Buckling of Rails, Highlight of Figure 12-4 (Baxter)*

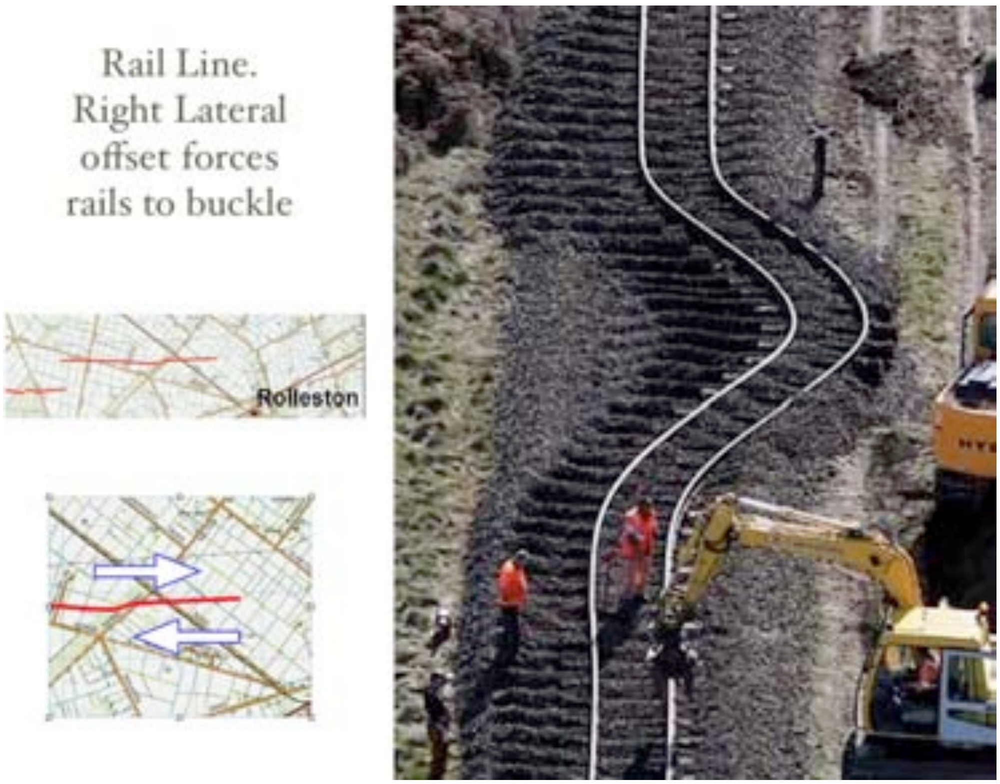


*Figure 12-6. Rails Being Repaired*

*Figure 12-7. Rails Repaired, September 4, 2010*

Figure 12-8 shows the removed sections of rail. This clearly shows that the rail buckling was largely inelastic (post-yield).

*Figure 12-8. Removed Rail Segments*

Figure 12-9 shows the repaired track some time after the earthquake. Additional wrinkles in the track can be clearly observed, suggesting the effects of post-earthquake fault creep.

*Figure 12-9. Wrinkled Track*

Figure 12-10 shows settlement of the approaches near the abutments of this bridge on the Main North Line. The photo also indicates lateral spreads that require the track to be re-ballasted. Figure 12-11 shows the two abutments for bridge 18 along the Main North Line. These abutments cold not withstand the soil pressures imposed on them due to the earthquake.

Figures 12-12 to 12-13 show the damage to a segment of track at a curve. Figure 12-14 shows the effects of liquefaction near Kaiapoi on the Main North Line located north of the Waimakariri River. This section of track required re-ballasting many times following the main shock on September 4, presumably because of re-liquefaction during aftershocks. Significant liquefaction and ground deformation also occurred at this location during the February 22, 2011 earthquake (see the discussion for the February 22, 2011 earthquake).

*Figure 12-10. Soil Movement Next to Bridge Abutments*

Figures 12-14 and 12-15 show the effects of liquefaction near Kaiapoi on the Main North Line located north of the Waimakariri River. Figure 12-14 shows the rail displacements just a few hours after the earthquake Figure 12-15 a few days later. This section required re-ballasting many times: see the discussion for the February 22 2011 earthquake.

*Figure 12-11. Main North Line, Bridge 18*

*Figure 12-12. Kaiapoi, Looking towards Rangier (Baxter)*

*Figure 12-13. Kaiapoi, Looking towards Kaiapoi (Baxter)*


*Figure 12-14. Liquefaction along the Main North Line near Kaiapoi (Sept 4 2010)*

*Figure 12-15. Ongoing Liquefaction along the Main North Line near Kaiapoi (mid-Sept 2010)*

## 12.2 Performance in February 22 2011 Earthquake

The rail network in Canterbury was closed until 8 am the morning after the February 22 2011 earthquake. By that time, the network was functional with temporary repairs except for limited sections. Maximum rail speeds were reduced to 40 km/hr. Nearly a week passed before the network was fully operational and several months was estimated to be required for completion of permanent repairs. KiwiRail management anticipated that it would be two or three years before operations will be “back to normal” given the emotional toll on staff of consecutive earthquakes. To aid the recovery process, KiwiRail provided drinking water, washing machines, and refrigeration units for employees and their families.

The Linwood maintenance facility building was red-tagged after the earthquake and the staff was moved to the Middleton facility. As of the first week of April, three locomotives were still “trapped” at the Linwood facility because of the tagging. The water tank at the facility was also damaged.

The two passenger lines operated by KiwiRail were primarily for tourism. Following the February 2011 earthquake, one line was operating at 40 percent of its pre-earthquake level and operation of the other was suspended until August when a decision regarding its continued use would be made. The former Christchurch passenger station (an unreinforced masonry building) was red-tagged. Although the structure was no longer used by KiwiRail, it had been leased to a commercial entity.

Six bridges experienced major damage during the main shock, but no trains derailed. Bridge outages and rail damage along the Main North Line resulted in 12 trains, transporting perishable food products, being backed-up outside of Christchurch. The earthquake occurred near the peak season for bulk milk transport.

Most of the damage was due to settlement and lateral spreading of liquefied ground. Bridge 7 on the Main South Line over the Heathcoate River was a classic example, see Figure 12-16. Installation of temporary cribbing to repair the bridge reduced clearance for the roadway below to 2.4 m.


*Figure 12-16. Timber cribbing*

A temporary height restriction of 2.8 m was also placed on Bridge 3 of the same line over Martindales Road. Figure 12-17 shows the temporary bracing with steel supports to repair the damage at this location. The abutments moved and cracked during the extreme shaking and caused deformation in the track ballast and tracks. Stabilizing walls were also placed in front of the brick masonry wingwalls as a temporary repair.

*Figure 12-17. Bracing with steel supports*

The embankment near Kaiapoi, shown previously in Figures 12-14 and 12-15, required periodic re-ballasting of the track to maintain alignment following the September 4 2010 earthquake. The frequency of maintenance had decreased to once every two weeks before the February 22 2011 earthquake struck. Figure 12-18 shows re-ballasting during the first week of April 2011. By this time, on-going displacement of the alluvial foundation soils had slowed the requirement for additional ballast to twice a week.

*Figure 12-18. Re-ballasting the Main North Line (also, compare with Figures 12-14, 12-15)*

Figure 12-19 shows buckled tracks due to a lateral spread at a culvert.

*Figure 12-19. Buckled Tracks*

*Figure 12-20. Damaged North Bridge*

Rock falls in the Port Hills area led to closure of one of the two parallel rail lines that serviced the Port of Lyttelton. Rocks were also dislodged from the roof of the Lyttleton tunnel and additional groundwater springs have developed. Figure 12-21 shows the north portal of the Lyttelton tunnel where additional cracking was observed. Train engineers reported that the tunnel invert appears to be crowned more than it was before the February earthquake. Given the location of the tunnel, fault offset may have occurred (?? but not verified) at this location.

*Figure 12-21. North Portal Lyttelton Tunnel*

Additional damage to the rail network during aftershocks was a primary concern. Consequently, KiwiRail monitored aftershock activity diligently. Figure 12-22 shows the location and magnitude of aftershocks during a 24-hour period on February 23 with respect to the rail network in Christchurch. For each aftershock, a second map (see Figure 12-23) was generated showing, among other things, train locations at the time of the event and most importantly trains located within 1 km of a bridge structure. KiwiRail used this information to efficiently mobilize bridge inspection and repair crews.


*Figure 12-22. Aftershock Sequence with Respect to KiwiRail Lines*

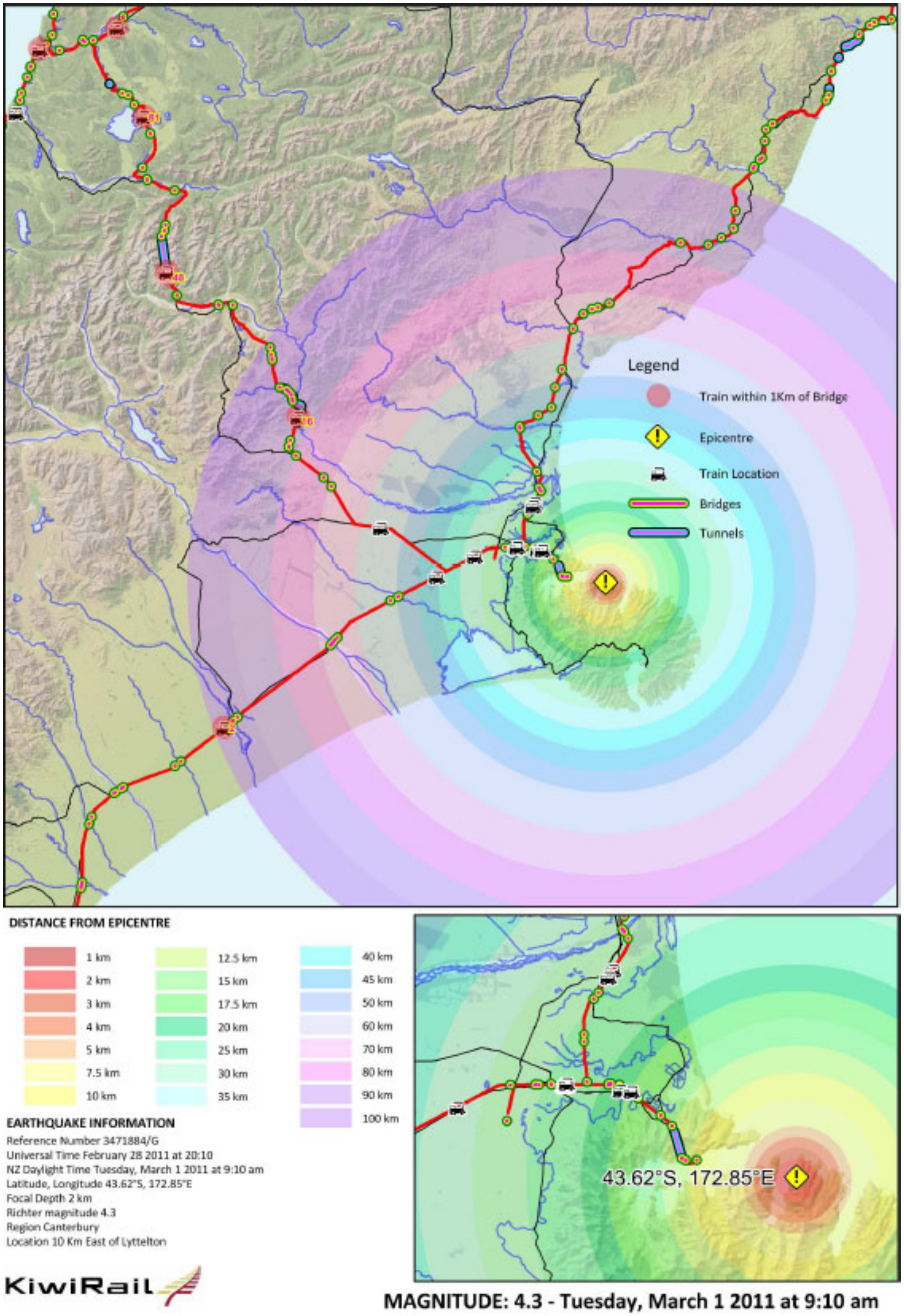


*Figure 12-23. Map to Monitor Train Location with Respect to Epicenter*

## 12.3 Major Observations and Recommendations

The September 2010 and February 2011 events both triggered various types of damage to the railway system. Rail damage occurred due to fault offset and liquefaction; once repaired, ongoing fault creep and soil movements required additional repairs. Strong inertial shaking coupled with liquefaction at abutments led to damage of a variety of bridges. Strong ground shaking, plus possibly some fault offset, damaged a tunnel in the February 2011 event.

Throughout all these events, KiwiRail's activities were geared towards life safety and then restoring rail traffic as rapidly as possible.

## 12.4 Acknowledgements

This chapter was written by John Eidinger (September 2010 event) and David Baska (February 2011 event). We appreciate the efforts and support by Bronwyn Woodham, Wayne Ramsey, and Richard Priddle of KiwiRail to provide us with information about all aspects of the damage and recovery process.

# 13.0 Fire Following Earthquake

Table 13-1 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 M 7.1 earthquake occurred at Sept 4 2010 at 4:36 a.m.

| 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 13-1. 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, and it suffered essentially no damage. This may have limited the fuel to feed ignitions.

The list in Table 13-1 is a subset of some 20+ structure fires over this period. The fires not listed in Table 13-1 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.


*Figure 13-1. Fire in Downtown Christchurch*

Only one significant structure fire occurred in the February 2011 earthquake, at the CTV building (Figure 16-18). The collapse of the building likely led to the ignition.

There were no reported fire ignitions form the June 2011 or December 2011 earthquakes.

# 14.0 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 12-1. Seven stretches of levees mapped in Figure 14-1 suffered severe damage, having large scale instability, spreading and gross settlement over 0.5m (red lines). Four stretches of levees suffered major damage, including cracks greater than 1 m in depth, with deep seated movement and settlement (yellow lines). Eleven stretches of levees suffered moderate damage, including cracks 0.4 meter to 1 meter in depth, with some settlement (dark blue lines). Fourteen stretches of levees suffered minor damage, including cracks less than 5 mm wide, 30-140 mm deep with negligible settlement (light blue lines). Levees with no observed damage are shown in green lines.

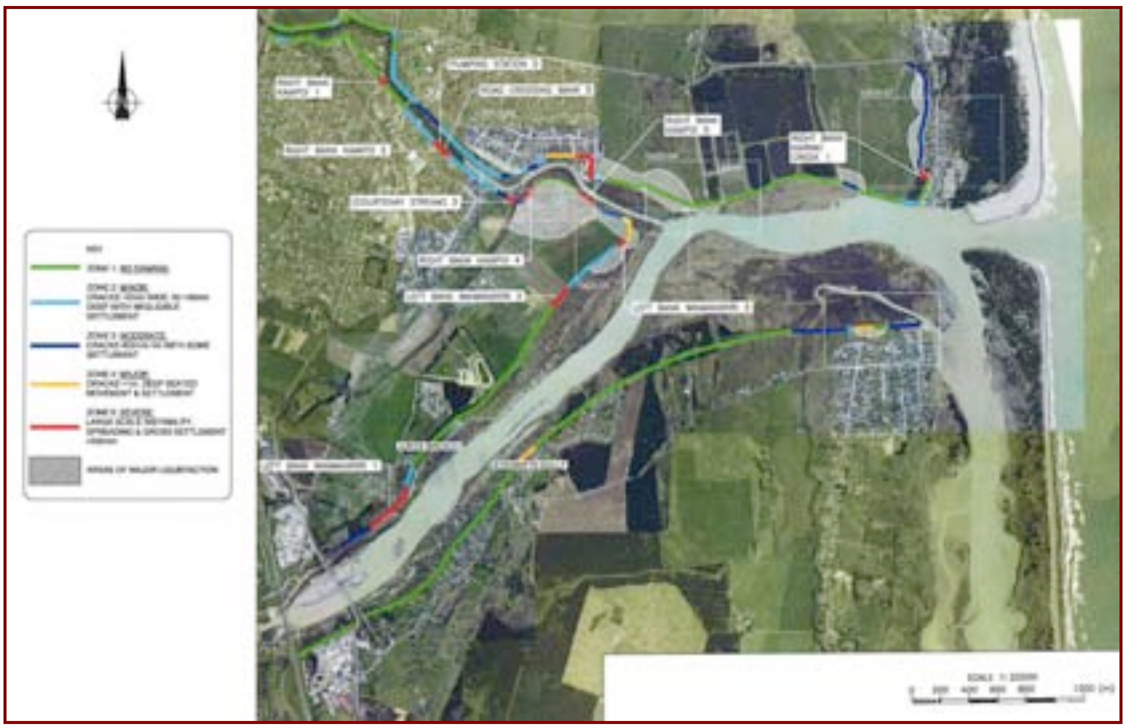

*Figure 14-1. Stopbank damage surveyed by Riley Consultants*

As the rainy season will eventually 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.

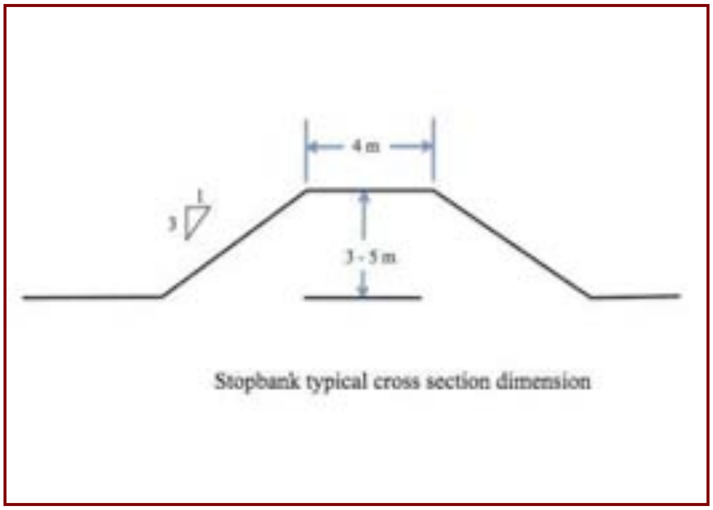


*Figure 14-2. Stopbank Cross Section*

The typical cross section of the stopbank is shown in Figure 14-2. 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 14-3 to 14-5.

*Figure 14-3. Severe Damage – Stopbank*

*Figure 14-4. Major Damage – Stopbank*

*Figure 14-5. Moderate Damage – Stopbank*

Figures 14-6 to 14-8 show slope failures along the levee in Kaiapoi.

*Figure 14-6. Levee Damage - Kaiapoi (Sept 2010)*

*Figure 14-7. Levee Damage - Kaiapoi (Sept 2010)*

*Figure 14-8. Levee Damage - Kaiapoi (Sept 2010)*

As of August, 2011, LiDAR mapping showed that several areas along the Ashley River floodplain subsided by as much as 0.4 meters. Much of this subsidence occurred in areas that already had forecast flood heights of 1 to 2 m (200 to 500 year events), so in many cases the increase in flood depth is of secondary importance. LiDAR mapping along the Halswell River showed a decrease in channel capacity, which could lead to increased flooding potential for short return periods (< 10 years).

# 15.0 Lifeline Interdependence

The following general observations are made about lifeline interdependence, as evidenced by the September 2010 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 September 2010 earthquake, due to water pipe damage, several 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 generally require power: CCC wells generally did not have on site generators (some CCC wells can provide flow by artesian water pressure); 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).

# 16.0 General Building Stock

It is generally beyond the scope of TCLEE reports to address damage to the general building stock. However, a few photos are included to allow the reader to gain an impression of the performance of masonry buildings under strong shaking, the collapses of two engineered buildings, and a few other buildings of interest.

## *16.1 September 4 2010*

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, heritage buildings (Figure 16-1), Churches (Figures 16-2, 16-3), 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.) (Figure 16-4); a few had major damage and outright collapses (Figure 16-5). 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. The performance of the URM building stock was much worse in the February 2011 event.

*Figure 16-1. Damage to Parapets and End Gables for this URM Heritage Building*

*Figure 16-2. Damage (Parapets, Falling Debris Damaged Roof) to URM Church*

*Figure 16-3. Fallen Debris Damaged Roof (Close Up from Figure 16-2)*


*Figure 16-4. Damage to Parapets these URM Buildings*


*Figure 16-5. Damage to Walls for these URM Buildings*

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 (Figure 16-6). There are no known injuries due to fallen chimneys.

*Figure 16-6. Damage to URM Chimney*

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.

Figure 16-7 shows the effects of surface fault rupture through a wood frame (with brick façade) house. It is estimated that about half the total rupture movement was "taken up" by the house. The house did no collapse.


*Figure 16-7. Fault Offset Through a House*

## 16.2 February 22 2011

In the Sumner area, community center (URM) was heavily damaged and red-tagged.

*Figure 16-8. Sumner District Council Building*

*Figure 16-9. Sumner District Council Building (Failed Masonry Arch)*

The Port of Lyttleton includes a small town. It is largely founded on bedrock. In the February 2011 earthquake, local ground motions were very high (PGA > 0.5g), and many of the masonry buildings were damaged, Figures 16-10.

*Figure 16-10. Lyttleton Church (February 2011)*

*Figure 16-11. Lyttleton Church Interior (February 2011)*

*Figure 16-12. Lyttleton House (February 2011)*

*Figure 16-13. Lyttleton Commercial Building (February 2011)*

Figure 16-14 highlights outdoor tables where Prof. Tom O'Rourke and John Eidinger ate lunch in September 2010. It was remarked at the time that the building's parapets were dubious and potential life safety threats. Some other eateries and brew-houses visited by the TCLEE team in September 2010 (in conjunction with many Kiwi earthquake specialists) collapsed outright in the February 2011 earthquake.


*Figure 16-14. Lyttleton Commercial Building (February 2011)*

The Christchurch Cathedral occupies a central location in the central business district, and serves as a focal point in the history of Christchurch. Recognizing its importance, this building had undergone a seismic upgrade prior to the September 2010 earthquake; reportedly for about PGA = 0.15g (about 2/3 of then current code). It partially collapsed in the February 22 2011 earthquake, Figures 16-15, 16-16. Shoring was installed, as seen in Figure 16-17, photo taken March 9, 2011. The façade shown in Figure 16-17 collapsed in the June 11, 2011 earthquake, Figure 16-18, photo taken December 12, 2011.

*Figure 16-15. Christchurch Cathedral (February 2011)*


*Figure 16-16. Christchurch Cathedral (February 23 2011)*


*Figure 16-17. Christchurch Cathedral (March 9 2011)*

*Figure 16-18. Christchurch Cathedral (December 12 2011)*

Figures 16-19, 16-20 (Pyne Gould Guinness Building), 16-21, 16-22 (CTV Building) show the two collapsed engineered buildings in which most of the loss of life occurred in the February 2011 earthquake.


*Figure 16-19. Pyne Gould Guinness Building (1:10 pm February 22 2011)*

*Figure 16-20. Pyne Gould Guinness Building*

*Figure 16-21. CTV Building (7:49 pm February 23 2011)*

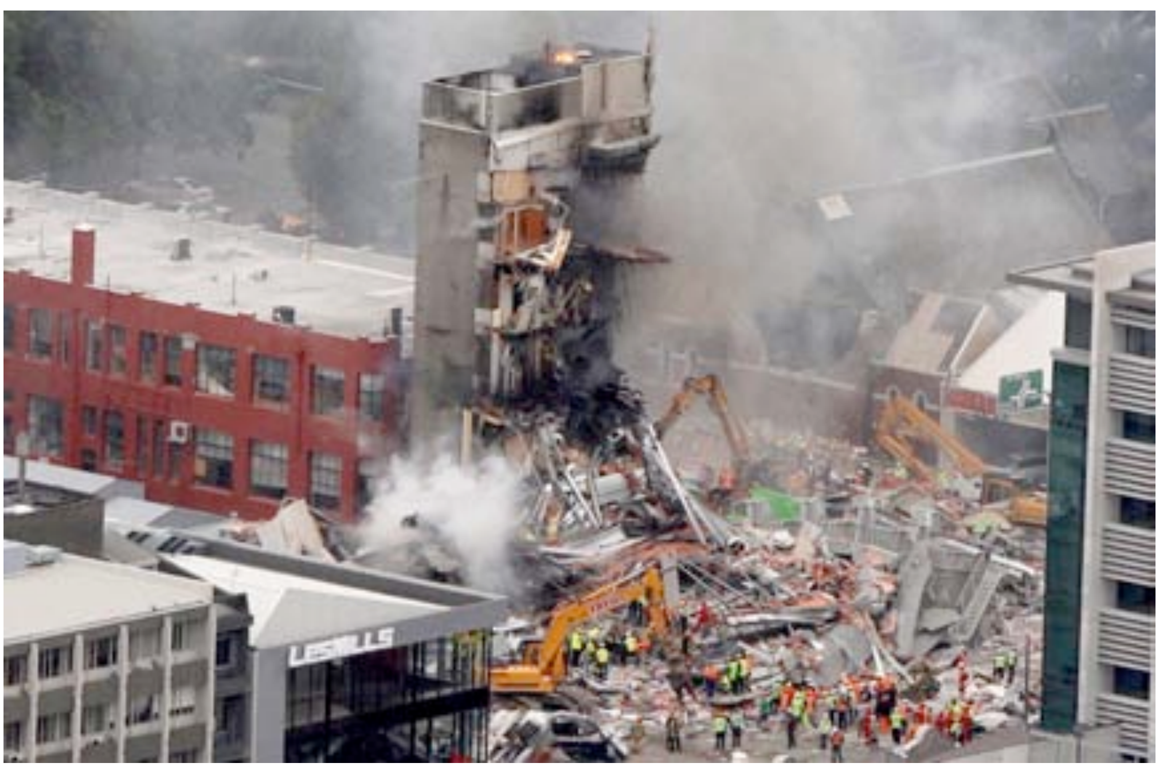


*Figure 16-22. CTV Building*

Figures 16-23 and 16-24 show the heavily damaged portion the tourism office located opposite the Christchurch Cathedral. This structure was originally a URM, and had previously been seismically upgraded (interior steel braced frames); but it was heavily damaged in the February 2011 event. It had been torn down by December 2011.

*Figure 16-23. Damaged Tourism Building, February 2011*

*Figure 16-24. Interior Steel Frame of Damaged Tourism Building, February 2011*

Figure 16-25 shows a severely racked residence located at the north edge of the CBD. A few residences on this street showed similar racking.

*Figure 16-25. Racked Residential Building, February 2011*

# 17.0 Nonstructural

## *17.1 Storage Racks*

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.

Figure 17-1 shows a damaged storage rack at Transpower's Addington warehouse (PGA ~ 0.25g). This rack included two grossly buckled legs, Figures 17-2 and 17-3. Figures 17-4 and 17-5 show damage storage racks at other locations in Christchurch.

*Figure 17-1. Damaged Storage Rack, Addington Warehouse*


*Figure 17-2. Damaged Column Leg, Addington Warehouse*


*Figure 17-3. Damaged Column Leg, Addington Warehouse*

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.

In 2007, a design guide for storage racks was issued in New Zealand (ref. Beattie and Deam). This design guide was developed in New Zealand because, in part, of a concern about the safety of high level storage racking systems used in places with public access, as well as confusion about the need to satisfy the requirements of the New Zealand Building Code (NZBC). This guide allows that 100% of the weight (including contents) be assumed in seismic calculations in the cross-aisle direction, but just 54% of the weight in the long direction for multiple (3 or more) bays. The 54% factor is based on the idea that not all racks will be simultaneously loaded on multiple bay racks (this might be a fallacy in some situations) and an allowance for items "sliding" in the racks as a way to "eliminate" mass due to sliding effects (this might be a fallacy). The input seismic hazard is set to correspond with a 250-year return period motion (assumes the rack's lifespan is 25 years, so as to have a 10% chance of exceedance within the lifespan of the rack; note that by relying on these types of probability statements, the rack will be under designed any time it is exposed to a large earthquake on a fairly active fault, so this would not be recommended practice in the USA or for any owner concerned about performance of its facilities after an actual earthquake or magnitude greater than about 6 on a nearby fault. Wisely, the New Zealand guideline limits "ductility" in the cross aisle (braced direction) direction to 1.25; or 2 in the down-aisle direction, presuming the lateral resistance is offered by a moment frame action (subject to verification of the actual connector's capacity to resist post-yield loading). In the down-aisle direction, the guide would suggest V = 0.095W for a typical rack in Christchurch; in the cross aisle direction, the guide would suggest V = 0.37W.

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.


*Figure 17-4. Collapsed Storage Racks, September 2010*

*Figure 17-5. Storage Rack Leg, Incipient Failure, September 2010*

## 17.2 Base Isolation Devices

Base isolation units using inverted pendulums were installed at Transpower's regional control center. Horizontal ground motions at this site were about PGA = 0.25g to 0.30g. The base isolated racks were installed on a raised floor, 300 mm ( 12 inches) tall in the computer room on the ground floor of the Islington Regional Operating Center, located about 0.5 km from the Islington substation.

Four double-base Iso-Base platforms (from Worksafe Technology) with 6 dishes each were installed. The equipment racks were strapped to the platforms. The dishes were not bolted to the raised floor, and lateral actions are resisted by friction only.

For three of the platforms, two cabinets each were installed above each platform; all the cabinets were bolted together and strapped to the platform below (Figure 17-6). For these three platforms, 3 of the 18 balls jumped out during the earthquake. The bottom platform moves sideways about 50 mm (2 inches). However, the racks remained as a block and were sitting on their base frame.

On the fourth platform, only one cabinet was installed on the platform, resulting in a torsional-eccentric arrangement. This cabinet and the platform below jumped off the isolation dishes, ending up rotated about 15 to 20 degrees from its original position, Figure 17-7. Figure 17-8 shows the disassembled system, to highlight the dishes below.

The solid state computers in the racks did not suffer any damage and were operating perfectly during and after the earthquake. Had the rack in Figure 15-5 toppled, the cables from above might have been at risk; on the other hand, perhaps the cables from above assisted in restraining the rack, such that it did not topple.

The equipment in the rack in Figure 17-7 had to be shutdown after the earthquake in order to re-install the rack on its base isolation system. The photo in Figure 17-8 is believed to be taken during the re-installation process. RE-installation of the balls under the equipment in Figure 17-6 did not entail having t shut down the equipment.

About 90 of these devices are installed in the Transpower system, country-wide. The four devices seen in Figures 17-6 to 17-8 are the only such devices in the Christchurch area.

The Worksafe product literature for this devices states that it is qualified to PGA = 0.5g (shake table tested), even with only one cabinet atop the platform.

Other shake table tests of this hardware have shown that if exposed to a sufficiently large displacement demand, the top platform jumps off the lower dishes (as it did in Figure 5-4), with the resulting cabinet resting upright on the surrounding floor. It seems apparent from this actual earthquake that these isolator devices can provide some measure of protection for moderate earthquakes (three successes on the other side of this room), but possibly not for earthquakes with displacement demands (including torsional motion) in excess of dish capacity.

From an owner's point of view, the concept of base isolation is to reduce the input motions to the equipment so that they have a greater chance of remaining functional during and immediately after the design basis earthquake, Should the displacement limits of the base isolation unit be exceeded, higher mode effects (impacts) occur, quite likely negating any reductions provided by the first mode base isolation period. With today's solid state electronics, an owner should seriously consider direct anchorage of the equipment to a competent floor slab below, as this is quite likely lower cost than the base isolation units, and can provide substantial margin in larger-than-planned-for earthquakes, and avoids dealing with the additional flexibility needed to all attached cables.

*Figure 17-6. Triple Base Isolation Units – Slid 50 mm, Lost 3 of 18 Balls*

*Figure 17-7. Base Isolation System as Found, Immediately Post-Earthquake*

*Figure 17-8. Base Isolation System, Disassembled*

## 17.3 Other Non Structural Items

Figure 17-9 shows fallen bottles.

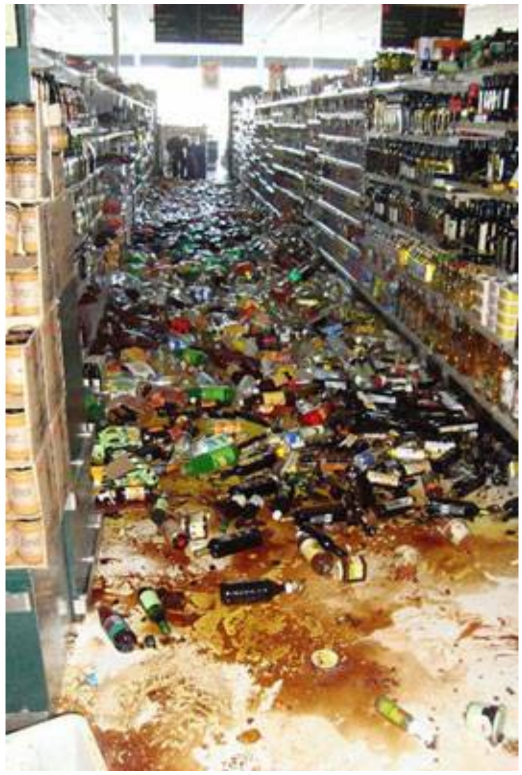

*Figure 17-9. Toppled Bottles at Market*

Figure 17-10 shows damage to a suspended ceiling; this damage was rather common at locations with PGA > 0.3g. No people were known to be seriously injured due to lightweight ceiling panel failures; there were no fatalities. Figure 17-11 shows the two television monitors that fell out of their enclosures in Figure 17-10.

*Figure 17-10. Suspended Ceiling (credit John Mackenzie) September 2010*

*Figure 17-11. Fallen Television Monitors (credit John Mackenzie) September 2010*

Figure 17-12 shows a toppled cabinet. This cabinet was lightly anchored. It was located at the top floor of a modern building.

*Figure 17-12. Toppled Cabinet (credit John Mackenzie) September 2010*

Figure 17-13 shows stacks of books located in a shop in the CBD. Perhaps 1% of the books toppled / slid to the floor in the February 2011 event. Typical recorded ground motions in the CBD were on the order of horizontal PGA = 0.5g. Figure 17-14 shows buckling of two tables in this same shop, suggesting that the high vertical acceleration, coupled with the heavy loads, were too much for these two tables (out of perhaps 40 tables).

*Figure 17-13. Stacks of Books, February 2011*

*Figure 17-14. Stacks of Books, February 2011*

Figure 17-15 shows the state of dishes and glasses in a ground floor restarant in the CBD. The dishes and glasses are as they were left on Feburary 2011 event, apparently without attempt to clean up fallen items. This type of scene was repeated at many different locations throughout the CBD.

*Figure 17-15. Tabletop Dishes and Glassware, CBD, February 2011*

Figure 17-16 shows collapsed racks (no anchors, no bracing) with heavy paper records; these were located on the top floor of concrete building, at a site with PGA = 0.5g.

*Figure 17-16. Collapsed Storage Racks, February 2011*

Figure 17-17 shows the buckled struts between the upper and lower concrete mats of the only base isolated building in Chirstchurch (women's Hospital). This damage did not impact the function of the utilities; but shows the need to think through the vertical movement that does occur (often ignored by building codes) in steel-laminate-type rubber bearing isolation systems.

*Figure 17-17. Damaged Vertical Struts, February 2011*

# 18.0 Debris Management

The simple truth of a destructive disaster in an urban area always leaves behind a huge pile of trash - all different kinds of trash. The trash hinders both services restoration and recovery in a timely manner. It is not an easy problem to solve as the trash usually includes hazardous material that requires special disposal processes, otherwise the consequence will be detrimental to health and pollute the environment. The clean up will cost more than disposing the hazardous material properly in the beginning.

The February 22 2011 earthquake impacted an area with a mix of old and modern structures. The number of buildings partially or completely collapsed was much higher than the September 4 2010 earthquake. Both commercial buildings and residential buildings were affected. The trash generated includes building materials, household appliances, computers and printers, cars, food items, and many more. In order to dispose these materials require a huge amount of resources and spaces.

There will be many lessons that we can all learn from how it is being handled and the difficulties that encountered during the execution phase of the disposal process. Man factors will also affect the decisions how to carry out the disposal processes including financial matters, particularly when insurance is involved.

## *18.1 Description of Debris and Hazardous Waste Management Policy*

A policy was quickly established to provide guidance of managing the debris resulted from the February 2011 earthquake. The policy goals[7] are:

- Protect public and worker health and safety,
- Enable rapid and affordable recovery of Christchurch,
- Avoid or mitigate the harmful effects of waste,
- Maximize the efficient use of resources,
- Sensitivity in the handling of buildings and vehicles where fatalities have occurred,
- Identify and protect heritage items, and
- Establish transparent and equitable processes

Where fatalities had occurred the buildings and contents had to be stored at the Burwood Landfill site for future investigation by the coroner. There were fourteen of these buildings.

Removal and return of personal belongings to owner was allowed when it was safe to do so. Unauthorized removal of personal belongings would be prosecuted as theft.

[7] Verbal and written information provided by Tom Moore.

Contractors were screened and approved by the national controller prior to performing demolition and removal of debris. Only contractors approved to handle hazardous materials were allowed to remove and dispose such materials. All contractors must operate in accordance with all legal requirements and industry standards, including obligations and liabilities.

Quality control and inspections were carried out by the authority to ensure all requirements were met.

## *18.2 Overview of Performance*

Overall debris and hazardous waste management was executed efficiently. However, when insured properties that were in the grey area of serious enough to be demolished or not serious enough to be repaired created much delay. Resolving the insurance contractual issues, inspection and report by structural engineers (inspectors), and owner's opinion took time. Therefore in CBD many buildings were not scheduled to be demolished until a decision was in place. The delay might impact the future of Christchurch CBD as many businesses were relocating in near by towns.

The priority was to perform rescue and then removal of casualties before waste and debris clean up started. Due to insurance of many damaged properties, identification process demanded proper documentations to ensure owners could make claims. This process required lots of resources and a good documentation process.

Before beginning of clean up, the work was set in four phases. Phase 1 was rescue, phase 2 was body recovery, phase 3 was establishing exit way safety of damaged buildings, and phase 4 was establishing safety in general. It took about 2 weeks to get to phase 4 and clean up began. Phase 5 was to start demolition and recovery. Demolition was in progress as of April 8 2010, recovery was still a long way away mainly due to the indecision of what to do with many buildings, such as the Grand Chancellor Hotel. At the time of TCLEE investigation, there were four contractors bidding for the demolition of this hotel. Many owners had to pay for debris removal. It would tough to recover cost that was not insured. The area that would be secured for investigation was the CTV building location where majority of life was lost.

Parking areas were used to pile debris before hauling to landfill sites by trucks. By April 8 2011 about 250 tons of building steel were recovered from damaged and demolished buildings. The cost of street sweeping was estimated to be $400,000 NZD.

Due to resources shortage in the Christchurch area, outside contractors were used and that created a degree of complexity. The difficulty was to merge the outside and local resources in a harmonious working environment.

*Figure 18-1. Volume of debris such as shown in this picture was everywhere in the earthquake impacted area.*

*Figure 18-2. Heavy machineries were used to handle the debris.*

*Figure 18-3. Heritage building in Christchurch – Cathedral Square*

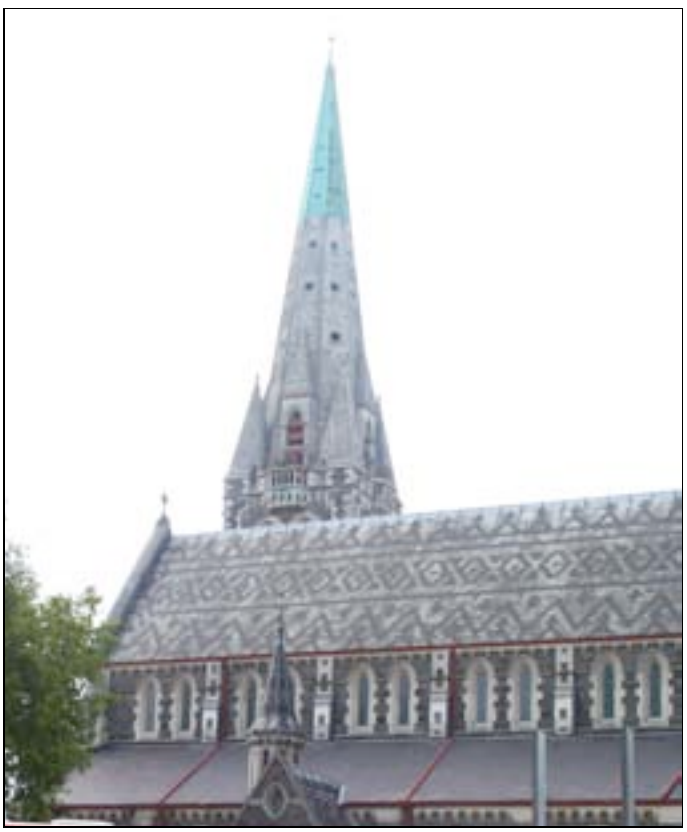

*Figure 18-4. The original cathedral*


*Figure 18-5. Spoiled food in eateries – food items that were exposed for a long time. Many restaurants within the cordoned area of CBD had the same problem.*

Handling of perishable goods such as milk, meat, etc. was one of the hazardous materials and a special process was required to prevent any environmental impact.

The estimate on 8th April 2011 was about another 9 months before the clean up would be completed.

## 18.3 Major Observations and Recommendations

Waste and Debris Management in a post disaster situation is a critical task in terms of supporting lifeline and general recovery effort. A coordinated effort must be established in order to ensure a timely restoration of services and clean up of impacted areas to rebuild and to return to normalcy.

The major effort is in recycling of materials that cab be reused. Careful handling of hazardous material is also high on the list of priorities.

It will be more effective if major appliance manufacturers can help to recycle damaged products. Some of the older products may have materials that are classified as hazardous today can be easily handled by the manufacturers.

Removal of personal material that has sentimental values must be process with care and a process of returning them to the owners.

## 18.4 Acknowledgements

The author is indebt to Sonia Giovinazzi who coordinated the meeting with Tom Moore to collect the relevant information. The information provided by Tom Moore and Charlotte Brown is valuable for future post disasters dealing with debris.

## 18.5 References

Waste management as a "Lifeline"? A New Zealand case study analysis by Charlotte Brown, Mark Milke, and Erica Seville, Department of Civil and Natural Resource Engineering, University of Canterbury, New Zealand.

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