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LIFELINES

**Lessons from Natural
Hazards in Canterbury**

**Document
Summaries**

December 2012

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to facilitate double-sided printing*

LIFELINES

Lessons from Natural Hazards in Canterbury

Document Summaries

December 2012

Document Information

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Cover Photo: Early morning fog clearing in Canterbury (Phillip Capper, Wikimedia Commons)

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DISCLAIMER

This report has been compiled from available documented information provided in response to enquiries made to lifeline utilities and other parties who seemed likely to have learnt from direct experience of natural hazards in Canterbury.

Effort has been taken to summarise the source documents accurately. However, the summary material in this report is not a substitute for the source documents. Readers should review the source documents, consider other authoritative best-practice information, and take professional advice, before any investment or other decisions are made. The parties involved in preparing this report do not accept liability for losses arising from use of, or gaps in, the information it contains.

Preface

The Canterbury Earthquake Recovery Authority (CERA) and the Canterbury Lifeline Utilities Group have collaborated to assemble documented infrastructure-related learnings from the recent Canterbury earthquakes and other natural hazard events over the last 15 years (i.e. since publication of *Risks and Realities*¹). The project was led by the Centre for Advanced Engineering (CAE) and was undertaken to promote knowledge sharing by facilitating access to diverse documents on natural hazard learnings, a matter of ongoing relevance and very considerable current interest.

This compendium contains 96 summaries of source documents assembled during 2012. The documents are from a variety of sources including lifeline utilities, international commentators and researchers. Each summary has been checked with original authors.

The project focussed mainly on learnings from the recent Darfield and Christchurch earthquakes but some documents on other natural hazard events such as snowstorms are also included.

¹ Lifeline vulnerability to natural hazards including earthquakes had been given prominence in a comprehensive project undertaken by the Christchurch Engineering Lifelines Group in the first half of the 1990s. The project report *Risks and Realities* records the processes, findings and mitigation steps (risk reduction and readiness) identified at the time.

The summaries, predominantly organised by lifeline sector (electricity, telecommunications, transportation etc.), cover:

- asset-related learnings
- learnings related to organisation performance, i.e.
 - intra-organisational performance
 - inter-organisational performance including relationships with CDEM.

A separate Overview Report outlines the methodologies used and presents a high-level summary of findings including key themes. The Overview also identifies some gaps in source material leading to recommendations for possible future work.

In most cases, the summaries in this compendium are accompanied by the source documents (PDFs or links). However, a few authors, while agreeing to publication of summaries, have requested that their source documents be withheld.

The summaries draw attention to the main learnings in the source documents and are not to be read as a full or definitive account of the authors' views and findings. Readers should refer to the source documents if firm or detailed information is required.

Contents

Document Information	ii
Preface	iii
Bibliography	ix
1 Electricity	1
1.1 Transpower 4 September 2010 Darfield Earthquake Lessons Learned	1
1.2 Transpower 220 February 2011 Christchurch Earthquake Key Findings and Lessons Learned	2
1.3 September 2010 and 22 February 2011 Christchurch Earthquakes from a Transmission Grid Infrastructure Perspective	4
1.4 September 2010 and 22 February 2011 Christchurch Earthquakes from a Transmission Infrastructure Perspective: Asset Structural Performance and Lessons Learned	4
1.5 Orion - Network Asset Management Risk Control Summary	5
1.6 Orion – Wind Storm April 2005	5
1.7 Orion - Snow Storm 2005 Debrief	5
1.8 Orion - Infrastructure Snow Storm Report 2006	6
1.9 Orion – Snow Storm June 2006	6
1.10 Orion Presentation - South Island Emergency Officers Conference 2009	7
1.11 Orion - Christchurch Earthquake 2010, 2011	7
1.12 Key Infrastructure Impacts of the Canterbury Earthquake Series – Electricity	8
1.13 Resilience Lessons: Orion's 2012 and 2011 Earthquake Experience	8
1.14 MainPower Earthquake Recovery September 4th 2010	9
1.15 Business Continuity Earthquake Response	9
1.16 TCLEE Chapter – Electric Power	10
1.17 Performance of Buried High Voltage Power Cables due to Liquefaction	11
1.18 Impact of the Darfield Earthquake on the Electrical Power System Infrastructure	11
1.19 Impact of the Christchurch Earthquakes on the Electrical Power System Infrastructure	12
2 Telecommunications	15
2.1 Earthquake Performance of Telecommunications Infrastructure in Christchurch 2010 / 2011	15
2.2 Christchurch February 22 Earthquake - A Lifelines Presentation	15
2.3 Earthquake Performance of Telecoms Infrastructure in Christchurch	16
2.4 A Telecommunication Provider's Response to the 2011 Christchurch Earthquake	16
2.5 Christchurch Earthquake Report	17

Note: The report *Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance* by the Technical Council for Lifeline Earthquake Engineering (Eidinger, J., & Tang, A. K. Eds, 2012) has been treated on a chapter by chapter basis – see the references to TCLEE in the Contents.

2.6	TCLEE Chapter – Telecommunications	23
2.7	Emergency Telephone Call Services and the February 2011 Christchurch Earthquake	24
2.8	Telecommunication: Promoting Awareness of the Implications of a Wellington Earthquake	25
2.9	Telecommunications Carriers Forum Annual Report 2011	26
3	Potable Water and Wastewater	29
3.1	TCLEE Chapter – Water	29
3.2	TCLEE Chapter – Wastewater	30
3.3	Recent Earthquakes: Implications for U.S. Water Utilities	31
3.4	Liquefaction Impacts on Pipe Networks	33
3.5	Impacts of Liquefaction on Pipe Networks in the 2010 – 2011 Christchurch Earthquakes - PBD Issues and Perspectives	37
3.6	Lateral Spreading and Its Impacts in the 2010-2011 Earthquakes	37
3.7	Liquefaction impacts in Residential Areas in the 2010-2011 Christchurch Earthquakes	38
3.8	Pipe Performance and Experiences during Seismic Events in New Zealand Over the Last 25 Years	38
3.9	Earthquake Damage to Buried Pipelines	39
3.10	Christchurch Earthquakes - Impact on Infrastructure & Services	40
3.11	Canterbury Earthquakes - A Contractor's Perspective	40
3.12	Water Lessons Learnt from the Christchurch Earthquakes	40
3.13	WDC Earthquake Lessons Learned Workshop Outputs	40
3.14	Impact and Recovery of the Kaiapoi Water Supply Network following the September 4th 2010 Darfield Earthquake	44
3.15	Damage to Potable Water Reservoirs in the Darfield Earthquake	45
3.16	Christchurch City Lifelines - Performance of Concrete Potable Water Reservoirs in the February 2011 Christchurch Earthquake	46
3.17	Seismic Performance of Christchurch Wastewater Treatment Plant Oxidation Bunds	46
4	Transportation	49
4.1	NZTA Highways - Christchurch Earthquakes	49
4.2	Performance of Highway Structures during the Darfield and Christchurch Earthquakes of 4 September 2010 and 22 February 2011	49
4.3	February 22nd 2011 Earthquake State Highway Bridges Preliminary Condition Report, Regions 11&12 – Christchurch	50
4.4	Performance of Bridges During the 2010 Darfield Earthquake	50
4.5	Overview of Bridge Performance during the 2011 Christchurch Earthquake	51
4.6	Lateral Spreading Interaction with Bridges during the Canterbury Earthquakes	52
4.7	Seismic Performance of Concrete Bridges during Canterbury Earthquakes	52
4.8	Preliminary Findings on Performance of Bridges in the 2010 Darfield Earthquake	52

4.9	Lessons Learnt from 2011 Christchurch Earthquakes: Analysis and Assessment of Bridges	54
4.10	Observed and Predicted Bridge Damage Following the Recent Canterbury Earthquakes: Toward the Calibration and Refinement of Damage and Loss Estimation Tools	54
4.11	Performance of Bridges in Liquefied Deposits during the 2010-2011 Christchurch (New Zealand) Earthquakes	55
4.12	Forced Vibration Testing of Bridge Damaged in the 2010 Darfield Earthquake	57
4.13	TCLEE Chapter – Roads and Bridges	57
4.14	Christchurch Pavement Resilience Investigation	58
4.15	Christchurch Earthquake Lessons Learnt: KiwiRail Internal Debrief	59
4.16	Business Continuity Christchurch Earthquakes - Christchurch Airport	59
4.17	TCLEE Chapter – Lyttelton Port	60
4.18	TCLEE Chapter – Railway System	60
4.19	The Response of the NZ Transport Sector to the Canterbury Earthquakes	60
5	Liquid Fuels & Gas	63
5.1	TCLEE Chapter – Gas and Liquid Fuels	63
5.2	Mobil Oil New Zealand Ltd - Christchurch Earthquake Response	63
5.3	Observations by BP after Canterbury Quakes	64
5.4	LPG Infrastructure in the Christchurch Earthquakes	64
6	Hospitals	67
6.1	Assessing the Post-Earthquake Functionality of the Hospital System Following the Canterbury Earthquake Sequence in NZ	67
6.2	Impact of the 22nd February 2011 Earthquake on Christchurch Hospital	67
6.3	Response of Regional Health Care System to the 22nd February, 2011, Christchurch Earthquake, NZ	68
7	Solid Waste	69
7.1	TCLEE Chapter – Debris Management	69
7.2	Disaster Waste Management: A Systems Approach	69
7.3	Canterbury Earthquakes - Waste Sector Response	70
7.4	Liquefaction Ejecta Clean-up in Christchurch during the 2010-2011 Earthquake Sequence	70
8	Multi-Sector Reports	73
8.1	Geotechnical Reconnaissance of the 2010 Darfield (Canterbury) Earthquake	73
8.2	Geotechnical Aspects of the 22 nd February 2011 Christchurch Earthquake	74
8.3	Learning from Earthquakes: The Mw 7.1 Darfield (Canterbury), New Zealand Earthquake of September 4 2010	75
8.4	The Value of Lifeline Seismic Risk Mitigation in Christchurch	76

8.5	Recovery of Lifelines Following the 22nd February 2011 Christchurch Earthquake: Successes and Issues	76
8.6	Lifelines Performance and Management Following the 22 February 2011 Christchurch Earthquake, New Zealand - Highlights of Resilience	77
8.7	TCLEE Chapter – Lifeline Interdependence	79
9	Response Coordination	81
9.1	Review of the Civil Defence Emergency Management Response to the 22 February Christchurch Earthquake	81
9.2	Capturing the Learning Points from the Christchurch Earthquakes 2010-2011 – Accomplishments, Suggested Improvements and Transferable Knowledge	83
9.3	Observations, Lessons and Experiences from the Inside	85
9.4	Lifeline Utility Coordinator Experiences and Learnings	86
9.5	Canterbury Earthquake – Lifeline Utility Coordination Review	86
10	Miscellaneous	89
10.1	Infrastructure Recovery Following the Canterbury Earthquakes	89
10.2	The Canterbury Earthquake - The Impact on Farming Organisations	89
10.3	Observed Performance of Industrial Pallet Rack Storage Systems in the Canterbury Earthquakes	89
10.4	Bank of New Zealand: Response in Christchurch	90
10.5	The Recovery of Canterbury's Organisations: A Comparative Analysis of the 4 September 2010, 22 February and 13 June 2011 Earthquakes	90
10.6	Lessons from Liquefaction in the Canterbury Earthquakes for Enhancing the Resilience of the Built Environment	91
10.7	Building Issues for Lifeline Utilities Following Major Earthquakes	91
10.8	Impacts and Emergency Response to 12 th June 2006 South Island Snowstorm	92
10.9	Analysis of the 2008 Flooding in the Hurunui District	92

Bibliography

1. Alexander, D., Crawford, G., Dixon, B., England, K., Falcon, D., Farrell, D., et al. (2009). *Analysis of the 2008 flooding in the Hurunui District*. Christchurch: Geological Sciences University of Canterbury.
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1 ELECTRICITY

1.1 Transpower 4 September 2010 Darfield Earthquake Lessons Learned

(Transpower New Zealand Ltd, 2011a)

This March 2011 report documents main learnings from the Darfield earthquake.

The main points are:

- Although Transpower was in a position to fully supply power within 4 hours of the September 2010 earthquake, restoration of power supply was constrained by the damage to the distribution networks.
- Transpower sub-stations incurred minor non-structural damage (broken windows, fallen ceiling tiles etc) but this did not disrupt service.
- Transmission lines are generally more resilient to seismic events than substation assets.

Design and Installation Issues

- Transpower needs to continue to reduce the risk by replacing or upgrading existing buildings or items of plant not complying with its seismic policy and by supporting the improvement of seismic design and construction standards in the electrical industry.
- Failure of the surge arrester part of the SVC system at Islington (new substation designed to IEEE693 high performance level) was due to a poor detailing of its mountings.
- A number of transformers tripped during the event mainly because of the malfunction of the mercury switches used in some of the on-load tap-changer (OLTC) oil relays, main Buchholz relay and temperature relays. This issue was identified by Transpower some years ago and a programme to replace these old relays with modern seismically rated models commenced prior the 4 September earthquake.
- Continued seismic assessment of infrastructure should be carried out, e.g. equipment restraint for in-service and stored equipment.
- Except for the mercury switched type relays, all other relays, cabinets cabling, wiring, connections and terminations remained stable and secure as did the protection signalling blocking, permissive and intertrip systems.

- It is recommended that the integrity of oil containment systems of any substation likely to be affected by liquefaction be tested.

Dependency on Telecommunications and Fuel

- Generally remote access technologies were also used to allow staff to deliver business services from non-office locations.
- General comments suggested that more satellite phones were required across the industry, as should PSTN network have been affected, and power have remained out longer, then mobile phone network followed by radio phone network would have become non-operational. There was limited access to a number of satellite phones, and poor knowledge of how to contact other satellite phone users.
- It is noted that should radio phones have been required there is a dependency on radio repeater sites and therefore for radio repeater site batteries to hold up until power is restored.
- While Transpower's initial response was relatively unimpaired, the impact of damage to roading infrastructure and ability of Transpower contractors to source fuel when undertaking emergency inspections and repairs was a cause for concern and requires consideration in emergency procedures.

Response Performance

- Fine weather and low network loading post-earthquake helped power restoration.
- Need improved paper management (to avoid paper mess in offices as a result of shaking).
- There is limited flexibility in the law when an emergency occurs. The better alternative would be to amend the regulations to provide disaster safety management as codes of practice cannot over-ride regulations.

Electricity Distribution

- Orion bridge strengthening programme significantly contributed to reduced level of damage to cable network.
- MainPower's seismic restraint programme over the past 15 years following Edgecumbe greatly contributed to lower damage levels.
- MainPower's mutual aid agreement – additional

staff, fault location equipment and portable generators from Marlborough Lines and Electricity Ashburton facilitated quick power restoration to a large part of the Canterbury region.

Main Lessons Learnt

- Transpower assets did not suffer serious damage and system interruption was minimal.
- A number of interconnecting and feeder transformers tripped during the event due to the malfunction of protection switches.
- Distribution infrastructure was affected more significantly than transmission as is consistent with experience overseas.
- Although most Transpower buildings in the affected region were designed prior to Transpower's current seismic policy, they met or exceeded the current performance criteria.
- Only minor impediments to the response/recovery outside of Transpower's control e.g. control of fuel supplies, but they did not seriously affect the response effort.
- Contractors and staff need to consider the safety implications of mobilising in the dark to inspect substations (e.g. liquefaction-induced road hazards and risk of aftershocks).
- A high level of industry cooperation occurred in response/recovery.
- Participation in lifelines exercises was recognised as being extremely valuable in forming relationships that come to fruition in a disaster situation.
- Had the event been during the day, the pressure on mobile phone services would have made mobile telecommunications essentially unavailable. Had the power outages lasted longer, back up batteries would have run out rendering mobile telecommunication service unavailable.
- Fuel availability became a concern early on with no apparent prioritised access to fuel supplies for essential services – a protocol has to be developed. It was also noted that Transpower maintenance contractors do not usually have fuel stored at their facilities available for emergency use.
- The seismic compliance of equipment against Transpower seismic policy should be thoroughly checked when purchasing new equipment or installing equipment in a new configuration, particularly for the equipment that is known to be prone to damage, e.g. cantilevered equipment, transformer mounted surge arresters or bushings.
- Develop better understanding of seismic performance of base isolation devices for computer

racks, through shake-table tests for instance.

- Fuel supply for the vehicle fleet of the maintenance contractors should be ensured by having emergency fuel storage facilities at contractor's sites.
- Regular assessment of individual ability to use fleet link radios and mobile phone should be made.
- Review whether Transpower has a sufficient number of satellite phones.

1.2 Transpower 22 February 2011 Christchurch Earthquake Key Findings and Lessons Learned

(Transpower New Zealand Ltd, 2011b)

This June 2011 report documents main learnings from the Christchurch earthquake.

The main points are:

- This earthquake, as well the 4 September 2010 event, has highlighted the reliance of Transpower transmission network on aged infrastructures.
- This event has also highlighted the potential issue of repairability of some aged equipment after an earthquake due to the lack of readily available spares (such was the case of the 66 kV transformer bushings that broke at Bromley substation).
- The satisfactory performance of Transpower assets during this event does not provide certainty on how well equipment, systems and buildings would perform in another event of a similar or greater magnitude.

Design and Installation Issues

- The seismicity (the frequency or magnitude of earthquake activity) over a region can change following an earthquake. As a result of the 4 September 2010 and 22 February 2011 events, New Zealand structural design standards are likely to be amended to account for an increased seismic hazard in Christchurch region.
- The very short straight connection between the CVT4 and rigid bus at Bromley substation was identified as a possible cause of the failure of the CVT.
- As a general comment, the lack of standardised practice for the installation of flexible conductors and the amount of slack that should be provided

was identified as an issue prior to the Darfield and Christchurch earthquakes.

- The current level of specification allows satisfactory performance of aseismic Buchholz relay during aftershocks and lower magnitude earthquakes but may not prevent false operation during large earthquakes.
- It is however understood that increasing the specified level of acceleration to ensure correct performance of Buchholz relays during rare and large earthquakes will have a detrimental effect on the sensitivity of the devices to actual internal transformer faults.
- Buried cables are vulnerable to soil deformation and their failure significantly impedes prompt restoration of supply. Cable repair process usually requires skilled crews, special equipment and takes significantly longer than overhead lines to repair. Damaged cables may require construction of temporary overhead lines to reroute power supply during the repair works.
- At present there is a lack of comprehensive design and installation practices in the industry to address this risk.

Communications

- A variety of communication mechanisms need to be used to keep in touch with staff. In this event, text messaging was more effective than phone communication due to the phone network being congested. Other methods, such as 0800 What To Do and intranet page were also effective mechanisms, although not as direct as text messaging.
- A variety of communication mechanisms need to be used to keep in touch with field crews. There is limited use of radios at present but this will improve once it is made more explicit in the maintenance contractor's agreements. In addition, an increase in the number of satellite phones will provide a strong alternative should it be required.

Recommendations

General: Transpower needs to continue to reduce the risk by removing or strengthening existing buildings or items of plant not complying with our seismic policy and to support the improvement of seismic design and construction standards in the electrical industry.

Seismic risk assessment: Transpower should ensure that the new values for seismic actions are used when designing future projects in the Christchurch region.

Flexible conductors: Visual inspections should be carried out in all substations to identify any flexible connections between equipment that are obviously too tight. (It is understood that these inspections are under way).

- It is also recommended that flexible connection design and installation guidelines be completed to ensure appropriate slack is provided with consideration to seismic aspects and electrical clearances. A project has been set up to prepare these guidelines.

Equipment replacement: All instrument transformers with insulators held by "finger clamps" should be replaced as this type of clamping is known to perform poorly during earthquakes.

Buchholz relays: Transpower should decide whether it is required for relays not to falsely operate during rare and large earthquake. If that is the case, the specified acceleration levels should be reviewed. The performance of relays should be demonstrated by shake-table tests reproducing the as-installed arrangement of the device.

Transpower should continue to purchase the ETI model relays for new Buchholz relay installations, unless it is decided that relays should remain stable during rare and large earthquake.

High voltage cables: The following actions are recommended to improve Transpower understanding of the risks to its 220 kV underground cable circuits assets:

1. Sponsor a study of the damaged 66 kV cables either uniquely or in conjunction with other utilities (NZ or overseas) or IEEE 693-Consortium. A suggested brief is given in Appendix C. This was provided by Cable Consulting International Mr. Brian Gregory a pre-eminent EHV cable expert who is based in the UK.
2. Leading from Item (1) above, develop technical standards that could be used to mitigate the probability of damage to underground cable circuits during a significant seismic event. Note: It is understood that PG&E and BC Hydro have put in place separate investigation initiatives in this field. We could benefit from coordinating our activities.
3. Place a much greater emphasis on geotechnical studies during the development of 220 kV cable circuits and develop appropriate policies.
4. All optical fibre cables should be installed within separate plastic ducting, i.e. not buried direct – in

Christchurch all these cables have now had to be abandoned and alternative protection communication paths sought.

Communications: Staff contact lists should be regularly updated and should contain mobile phone numbers (company and personal phones) as text messaging was found to be the most effective way of communication.

Transpower should develop a coordinated approach on FleetLink radio and satellite phone for internal communication and communication with maintenance contractors after disruptive events.

1.3 4 September 2010 and 22 February 2011 Christchurch Earthquakes from a Transmission Grid Infrastructure Perspective

(Renton, A. 2011)

This November 2011 presentation to the Auckland Engineering Lifelines Group contains learnings from the Darfield and Christchurch earthquakes.

The main points are:

- Because of previous resilience upgrades the overall transmission grid performed well. Transpower experienced only a small number of equipment breakages and transformer trips in these earthquakes.
- Transpower's network benefited from seismic restraint programme undertaken in the 1990s following the Edgecumbe earthquake.
- Transpower classes essential buildings and facilities as category 4 in terms of AS/NZS 1170.
- The earthquakes were in the 500 to 2,500 year return period zone. Moderate structural damage, repairable equipment failure and reduced security are expected in this zone. The performance of aged infrastructure was above expectations and the grid was returned to service quickly (following safety inspections).
- Transpower needs to continue to use and support the development of international seismic design standards for HV equipment.
- Transpower needs to further identify and mitigate the risk of earthquakes on the transmission network to ensure resilience going forward.

1.4 4 September 2010 and 22 February 2011 Christchurch Earthquakes from a Transmission Infrastructure Perspective: Asset Structural Performance and Lessons Learned

(McGhie, C. & Tudo-Bornarel, C. 2011a)

(McGhie, C. & Tudo-Bornarel, C. 2011b)

This is a combined summary of Transpower's paper and PowerPoint presentation to the June 2011 conference and exhibition of the Electricity Engineers' Association. It contains learnings from the Darfield and Christchurch earthquakes.

The main points are:

- The CDEM Act and the Building Act (and related territorial authority policies) are legislative drivers for Transpower to seismically upgrade / maintain their structures / infrastructure.
- Overall the transmission grid performed well. Transpower experienced only a small number of equipment breakages and transformer trips in the September 2010 and February 2011 earthquakes. System interruption was minimal.
- Damage to Transpower substations included minor cracking of reinforced concrete buildings, non-structural building damage such as broken windows, fallen suspended ceiling tiles and light fittings and settlement damage due to liquefaction. Damage to primary plant included failure of candle-stick equipment (one 220 kV current voltage transformer), transformer mounted equipment (one 220 kV surge arrester and one 66 kV bushing) and damage to an 11 kV switchboard.
- A number of transmission towers were affected by surface rupture, liquefaction induced settlement and/or lateral spreading resulting in tilting towers; suspension insulators being pulled out of alignment; tension / slack in overhead lines; and bent earth peaks. But this did not affect service/ function.
- Length of time taken to put grid back into service was the time taken to do safety inspections (compounded by traffic issues).
- Transformers and heavy plant were restrained, following learnings from the 1987 Edgecumbe earthquake.
- These events highlighted the reliance on existing aged transmission infrastructure.

- Transpower needs to continue to use and support the development of international seismic design standards for HV equipment.
- Further identification and mitigation of earthquake risk to the transmission network is required to ensure resilience going forward.

Summary of lessons learned

- Overall Transpower assets did not suffer serious damage and system interruption was minimal.
- The events highlighted the reliance on existing aged transmission infrastructures. Although most were designed and installed prior to Transpower's current seismic policy, they met or exceeded the current performance criteria.
- The implementation of the lessons learned following the 1987 Edgecumbe earthquake, i.e. the seismic restraint retrofit programme, was demonstrably worthwhile.
- Transpower needs to continue to reduce risk by removing or strengthening existing buildings or items of plant not complying with current seismic policy.

1.5 Orion – Network Asset Management Risk Control Summary

(O'Donnell, J. 2004)

This March 2004 presentation outlines Orion's approach to asset management risk control.

The main points are:

- Orion worked to plan for and mitigate hazard events following their involvement in 1999 *Risks and Realities* report.
- Activities undertaken include network diversification, seismic upgrading.
- Upgrades were based on risk profile, including:
 - risk rating – probability and consequence (MM scale used)
 - priorities assessed
 - action plan established.
- Action plan included attention to substations (including unreinforced masonry distribution substations), pole substations, oil-filled cables.
- Benefits of diversity, spares management and other risk mitigation steps noted.

1.6 Orion – Wind Storm April 2005

(O'Donnell, J. 2005a)

This brief presentation outlines Orion's experience in the major 2005 windstorm.

The main points are:

- Key issue: safety of the public and safety of staff and contractors.
- Overall the event management and network repair went well. Support obtained from another lines company and this also worked well.
- The point at which the event is scaled up needs to be reviewed.
- Contractor and operator hours need to be managed. Adequate food needs to be provided.
- Adequate levels of stock for repair work need to be established.
- Development of text communication strategy would be useful.

1.7 Orion – Snow Storm 2005 Debrief

(O'Donnell, J. 2005b)

This document records an internal Orion debrief following the September 2005 snow storm.

The main points are:

- Better communications with remote areas is necessary.
- Manual job management system caused some mix-ups. Need to better prioritise jobs and staff deployment.
- Send advance parties to assess what is required for repair before sending operations parties (to ensure right personnel and equipment is sent first time).
- Issues arose relating to coordination between Control and Call Centre – Call Centre staff did not always have the right information to pass out.
- Need to develop an emergency dashboard to keep staff informed of developments.
- Need more channels for communication (too much traffic just for one channel). Need enough handheld radios in the event of cell phone network disruption.

- Mobilise the Salvation Army kitchen if the event will run more than 2 days. Different staff like different food options (e.g. linemen like food taken to them, operators like to come in for a hot meal).
- Keep list of individuals requiring specialist equipment / medical requirements updated. Provide accommodation for out of town workers.
- Need to ensure the appropriate people hold the necessary keys.
- Need to communicate to stores / suppliers / warehouses likely material requirements.
- Ensure there are enough vehicles for staff and equipment. Ensure enough fuel available.

1.8 Orion – Infrastructure Snow Storm Report 2006

(O'Donnell, J. 2006)

This July 2006 report to the Canterbury CDEM Group outlines Orion's experiences and learnings from the June 2006 snowstorm.

The main points are:

- A severe snow storm impacted the South Island on 12 June 2006. Electricity supply was lost to thousands of customers. The depth of snow hampered restoration.
- It took about 5 days to restore electricity supply and about 6 further weeks to get the electricity network back to its pre-storm condition.
- Tree damage caused many of the outages, largely from trees outside the regulatory compliance zone. Locating poles on the roadside makes access for restoration easier but creates problems with shelter belts and trees.
- Prior work to replace concrete poles with wooden poles (which are more resistant to snow and ice) and ensuring poles are placed so that the conductors act as mechanical fuses, likely reduced the number of damaged poles and thus restoration time.
- Helicopter reconnaissance is OK for damage assessment but does not provide sufficient detail for restoration planning. Need to allow storm to abate before commencing restoration. Also need to assess damage before restoration starts in order to manage resources.
- Central coordination is essential for setting priorities and managing resources. Repair on a rural feeder basis minimises the chance of missing damage. Good communication is

essential to avoid wasted operational resources (e.g. isolated areas).

- Mutual aid agreements within the electricity industry worked well. Need to brief staff before they go into the field. Manage work hours and worker fatigue.
- Geographic maps online were beneficial for public.
- Telecommunications were affected by loss of power to cell sites.
- 4WD vehicles and chains are necessary for snowy conditions. Need to consider and manage fuel supply in rural areas.
- Workers must have resources to plan and manage own food supply
- Retailer Call Centre needs to have information on damage.
- Public and operators need to be vigilant and assume all wires are live. Education on how to avoid back feed from generators into line.
- There is a need to improve job management systems and training for larger events.

1.9 Orion – Snow Storm June 2006

(O'Donnell, J. 2007)

This March 2007 presentation to an Engineering Lifeline Workshop outlines Orion's experience in the June 2006 snow storm.

The main points are:

- Need to filter early warning information from weather forecasters to avoid false warnings and complacency.
- Three activities of restoration planning – gauge damage, set priorities and communicate (progress, priorities, and limitations) with CDEM, media and customers. Actual snow events are regular enough to not need to practice.
- Initial information transfer and priority setting was too detailed. High level information (constraints and limitations) and priority setting was important. "Let operational people do what they do best."
- Maintaining lines assets up to building entry reduces conflict but is not the standard arrangement within electricity distribution.
- Trees caused 59 per cent of the damage.
- Response constrained by loss of cellphone communication. Cell phones were best for point

to point contact. UHF best for global communication with operational and contract staff. Robust radio network is essential for repair and safety.

- Summary daily update with regional CDEM groups worked well.
- Best use of repair resources is when the storm subsides (H&S issues). Joining broken lines together is faster and more cost effective than replacing poles. Make maximum use of daylight hours. Adding manpower can slow things down temporarily. Access to 4WD vehicles was essential.
- Public communication was managed through central control centre so that operational staff can get on with their work. Providing internet map of damage reduced call centre numbers. Proactive media releases and internet based information is important (don't underestimate restoration time, and emphasise safety issues). Daily communications with other lines companies and daily press release also assisted. Communication lesson – keep it simple and focussed.
- Managers should brief staff in future events (context, conditions, hours of work, PPE, communications, fuel supply etc).
- On average snow storms affect twice as many customers as wind and take 50 per cent longer to restore (this equals three times more customer minutes lost).

1.10 Orion Presentation – South Island Emergency Officers Conference 2009

(O'Donnell, J. 2009)

This July 2009 presentation to the South Island Emergency Officers' Conference outlines Orion's experience in the June 2006 snow storm.

The main points are:

- On average the snow storm affected twice as many customers and took twice as long to restore as a wind storm (which equates to three times more lost customer minutes). Restoration took 4-5 days but recovery took about 1 month for this event.
- Company culture of emergency preparedness based on CDEM's "4 R's" works well. (The "4 R's" are Risk Reduction, Readiness, Response and Recovery.) Risk reduction commenced following Lifeline Group *Risks and Realities* report.
- Centralised control and contractor management worked well, including resource planning, engineering assesses, work planning, stakeholder and public communications. Allow operational staff to perform their normal roles. Need a comprehensive event management system. Keep communication simple and focussed, with regular updates.
- Managers need to provide context to staff/contractors, including work conditions, work hours, PPE required, communications, fuel supply, maximising daylight hours, minimising travel between jobs, setting clear priorities and ensuring self-sufficiency for meals.
- Mutual aid agreement between lines companies was in place (it's a simple, "agreement in principle" form). Adding manpower initially slows response down. Daily communications needed between lines companies working under mutual aid agreements.
- Cell phones best for point to point communication. Minimal backup standards for power to telecommunications sites need to be established.

1.11 Orion – Christchurch Earthquake 2010, 2011

(O'Donnell, J. 2011a)

This November 2011 presentation to the Auckland Engineering Lifelines Group summarises Orion's learnings from the Darfield and Christchurch earthquakes.

The main points are:

- The seismic strengthening recommended in *Risks and Realities* significantly paid off in reducing damage, repair times and costs. (Direct cost of \$6 million with an estimated saving of \$60 excluding indirect costs).
- Having an interconnected network allowed options for power restoration and reduced the time needed for supply restoration.
- Good communication with the public, staff, contractors and stakeholders is extremely important. Strong liaison with CDEM and media was critical
- Do not be pressured into accepting multiple offers especially of inappropriate resource (e.g. linemen verses cable technicians and repairers). Let people perform their normal work where possible.
- Plan for the absent of key personnel and to be able to operate the recovery plan without them.

- Having a National Civil Defence Controller who can make decisive decisions is essential (Orion had to demolish buildings quickly for safety reasons and build temporary overhead power lines).
- Lack of communication and continually changing of rules at cordon checkpoints adversely impacted the service Orion was able to provide.
- Plan for the damage of key infrastructure / buildings that form part of the recovery plan.

Post Script: In June 2012, Orion advised those involved in developing commercial premises that electrical equipment, such as transformers, needs to be easily accessible for safety reasons and to ensure robust electrical supply. Equipment located below ground-level may flood during hazard events creating long delays for power restoration. Locating equipment at street level minimizes flooding risk and improves access for emergency response needs. Fire is a further risk and clear, safe access is required for fire fighting. Orion recommends that commercial building developers make contact with Orion at the start of design work, noting that Orion can assist with assessment and design of electricity requirements.

1.12 Key Infrastructure Impacts of the Canterbury Earthquake Series – Electricity

(O'Donnell, J. 2011b)

This November 2011 presentation summarises Orion's learnings from the Darfield and Christchurch earthquakes.

The main points are:

- Fifteen years of seismic mitigation measures paid off – minimal damage to substations, cables, poles, critical equipment and communication sites.
- Orion's large size helped in the scale-up of work (arrangements with suppliers, mutual aid etc).
- "Plan to plan" (i.e. detailed advance planning to be avoided). Don't be pressured into accepting the wrong resources (this may slow things down).
- Set high level focus/priorities (e.g. top priority is preservation of life).
- Let people perform their normal work.
- Communication was the key to rapid restoration of power. Need to communicate well with staff, public, contractors and stakeholders, including updating contractors on scale of event and resource impact. Having just one point of contact between contractor and Orion worked best.
- Need better job management system (to avoid duplication).
- Determining competency of contractor staff was challenging (especially the different Australian system).
- Radio channels worked well (especially when cell phone down).
- Contractors were not recognised by Civil Defence as an essential service, leading to cordon access difficulties.
- Maintenance programme up to property entry (i.e. beyond industry norms) helped with resilience.

1.13 Resilience Lessons: Orion's 2012 and 2011 Earthquake Experience

(Kestrel Group, 2011)

Orion commissioned this independent review of their earthquake performance following the February 2011 earthquake.

The main points are:

- Orion's approach to emergency planning is to keep documents at a high, principle-focused, level, relying on trained and motivated staff to make sound decisions once the nature and extent of the emergency is known.
- Orion's management approach based around CDEM's "4 R's" helps with role clarity in electricity distribution management.
- Orion has undertaken a systematic seismic risk mitigation programme following the mid-1990s "Risk and Realities" report. Systematic and sustained investment in seismic mitigation was central to rapid and effective electricity restoration. It was also very cost-effective for Orion.
- Orion's emphasis on route diversity for underground cables was advantageous in areas of liquefaction.
- Since the September earthquake, Orion has demonstrated an on-going willingness to seek self-improvement.
- The earthquakes are likely to have shortened the

life of some of the underground and (to a lesser extent) overhead services.

- The question arises: how will earthquake impacts on Orion's performance be accommodated under the Commerce Commission's new price-quality regulatory regime? Looking ahead, a balance will need to be found between longer-term reliability and expenditure on security.
- Maintaining safety is a top priority despite the pressure of work. Time-outs, pauses and regular meetings are valuable and need to be included in response arrangements.
- The inter-dependency between power and telecommunications was highlighted in this event.
- Assistance from CDEM was not required other than for approval of new lines. However, the working relationships around cordon management between CDEM, Police and Army personnel were unsatisfactory (inflexible) to the point that response and recovery objectives were compromised.
- Pro-active communication is most important.

Recommendations:

- Introduction of the Outage Management System (OMS) should recognise the needs of all Orion users.
- Steps should be taken with contractors to facilitate identification and consideration of emergency response matters such as job referral processes.
- Mutual aid agreements should be written up (including issues such as roles and responsibilities for food, accommodation, HSE etc) for the benefit of other electricity distributors in New Zealand.
- HSE issues should be discussed with contractors with a view to improvements (improvements could be documented in Orion processes, the mutual aid agreement or referred to regulators if significant issues are identified).
- Orion should reconsider aspects of its spare parts management taking into account location, likely timing of delivery of new supplies (both from alternative New Zealand sources and overseas suppliers) and storage rack design.
- Orion should take into account the approaches set out in the National Loading Standard A/NZS 1170 Part O in considering future premises.
- Orion should write to the Ministry of Civil Defence & Emergency Management to note its concerns about cordon and demolition management, so

that cordon management takes the needs of infrastructure companies and their contractors more effectively into account in future events.

1.14 MainPower Earthquake Recovery September 4th 2010

(Batten, P. 2010)

This brief presentation outlines MainPower's recovery experience following the September 2010 earthquake.

The main points are:

- Eighteen known cable faults were the result of sideways forces and stretching – damage often over several meters around the ground rip.
- Cables often pulled tight against their terminations due to insufficient slack.
- Traditional cable fault finding and repairs proved to be fruitless. 3.5 km of new cable was laid over 11 cable sections.
- Two ground-level substations required rebuilding.
- There was minimal damage to LV cable – problems may however be an issue later.
- Overhead line network stood up well and was fast to repair. Some poles were leaning and a number of concrete poles sunk due to liquefaction.
- MainPower's seismic restraint programme over the past 15 years following Edgecumbe earthquake greatly contributed to lower damage levels.
- Six portable generators were used for up to 12 days.
- Mutual aid with Marlborough Lines and Electricity Ashburton also assisted.
- Low network load post-earthquake helped reduce the restoration times.

1.15 Business Continuity Earthquake Response

(McDrury, D. 2010)

This brief internal email reports on MainPower's debrief on immediate staff management issues following the September 2010 earthquake.

The main points are:

- The use of the E-Text system would have been useful in being able to text multiple staff cell

phones from one email to check on families. For this to be effective it is necessary to keep contact details of staff and families up to date and training provided to staff to use the system.

- Provide families of staff with a 'back door' number to contact the control room directly. This would allow the call to be diverted to someone else if the person they are attempting to contact is busy.
- Regular updates of staff locations is important to monitor who is at work, whether fatigue issues are possible and whether breaks are being taken. Self-monitoring of hours is better in the first instance.
- Need to stockpile water at easily accessible locations pre-event.

1.16 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Electric Power

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 4 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 4 is on Electric Power.

The main points are:

Experience

- Buried high-voltage distribution cables posed the biggest power outage challenge in Christchurch after the earthquakes due to difficult access and damage from liquefaction. Damage to transmission assets was relatively minor.
- Both Transpower (transmission) and Orion (distribution) had undertaken seismic mitigation prior to the earthquakes. For example, retrofitted seismic upgrades to URM brick substations by Orion using steel supports worked well in both September 2010 and February 2011. Seismic mitigation relating to 66 kV cables across a footbridge proved effective in September but the cables failed in February.
- Transmission towers which had their four foundations tied together experienced no lateral spreading, whereas towers within the same area that did

not have their foundations tied suffered from spreading due to liquefaction and secondary member buckling. There was no loss of service but repairs will be necessary. Transmission, conductor sags and misaligned insulators, and bent tower extensions were experienced, but no loss of supply occurred from these. Damage at substations was minor. Vibration of some mercury switches resulted in false readings, requiring switch resetting.

- A few Orion substations were seriously damaged in February 2011 from liquefaction or rockfall. The Orion headquarters was also damaged.
- Damaged 66 kV and 11 kV Orion cables were the main cause of outages. Damage was generally in areas with lateral spread and/or settlements. These were in areas of moderate liquefaction displacement for the 66 kV cables (one example: direct burial XLPE-type with thermal backfill and direct burial oil-type with thermal backfill), while the 11 kV (direct burial, both PILC and XLPE) cables mainly failed in areas of severe liquefaction. Six per cent of 11 kV failures occurred in areas where there was no liquefaction. New temporary overhead lines and a new substation were quickly built.
- For two of the 66 kV cables the lack of reinforcement allowed permanent ground deformations to concentrate movement at a discontinuity of the thermal backfill, leading to high curvature and failure.

Advice

- Ensure that batteries within battery racks have spacers and are secured to reduce / eliminate the possibility of sliding – no significant adverse effects were recorded as the batteries remained operational, but the experience could have been worse.
- Ensure when a circuit breaker is put into its "not-in-service" position, there is additional bracing to stop their heavy eccentric mass causing it to topple. As well as reducing the potential damage of the circuit breaker, this reduces the risk that movement will damage other nearby assets.
- Ensure that ties to voltage transformers have sufficient slack to reduce the potential for a high "yanking" load to be put on the component.
- Heavy liquefaction caused foundations of one substation to lose bearing capacity, with failure of the foundation and tilting of the building. When upgrading or building a substation the potential for liquefaction needs to be fully considered.
- Rockfall needs to be fully considered as a

potential hazard for infrastructure such as substations and placement of transmission towers. Adequate risk reductions should be put in place where rockfall could occur during a seismic event.

1.17 Performance of Buried High Voltage Power Cables due to Liquefaction

(Eidinger J. M., 2012)

This paper reports on an investigation into the performance of buried cables in liquefaction zones.

The main points are:

- Descriptions (including photographs) of deformed HV cables as they were dug out in liquefaction zones following the earthquakes are included in the paper. For example, the impact of shear on oil-filled cables associated with thermal concrete surrounds is shown – high curvature as the ground moved led to strain on the aluminium cover, tearing it. In another example, high reverse curvature in XLPE cables caused the insulation around the copper core to wrinkle outwards, tearing the outer copper sheath.
- There was no lateral spreading in the six areas surveyed and the cable damage appears to have been due to liquefaction.
- A series of non-linear structural analyses of buried cables was performed to attempt duplication of the field observations. The paper offers the following possible explanation of the forces leading to these cable failures:
 - A combination of travelling waves and local differential settlements create a high bending moment around the horizontal axis of the unreinforced cemented sand / concrete thermal backfill. Before the concrete cracks, the underground cables are intact. When there is an increase in the bending moment there is a resulting induced tensile stress in the concrete. A weak spot in the concrete is found and this results in the concrete cracking. The two ground layers then “slosh” and when they come back together the high forces occur in the thermal concrete causing the cables to buckle sideways. This results in a crushed power cable.

A test programme on full-scale samples is being undertaken at Berkeley, sponsored by Pacific Gas

and Electricity. The samples include four 150 mm PVC or HDPE ducts supported by spacer grids every 1.5 meters within reinforced and unreinforced concrete, about 0.8 to 1.0 meter in cross-section. Initial tests show:

- Unreinforced ducts: when the bending moment on the concrete duct bank exceeds the tensile cracking strength, a large crack forms in the concrete. The ducts maintain their circular cross section sufficiently, preventing crushing of the power cable.
- Reinforced ducts: steel-reinforced duct banks easily absorb the cracking and there is no significant damage.

Conclusions and recommendations:

- Avoid the use of underground cables in liquefaction zones.
- Direct burial in moderately-strong thermal backfill concrete can result in cable failures.
- When buried cables are required in liquefaction zones, a reinforced concrete thermal backfill can control curvatures and prevent knife-edge offsets. Reinforcement (steel or fibre) should be used for such burial situations. Cemented PVC joints can be expected to crack under high bending action when placed in thermal concrete.

1.18 Impact of the Darfield Earthquake on the Electrical Power System Infrastructure

(Watson, N.R. 2010)

This is a summary of a paper from the December 2010 Bulletin of the New Zealand Society for Earthquake Engineering, Vol 43, No. 4.

The main points are:

- The seismic events caused the mercury in Buchholtz relays to move and trip the transformers which resulted in a partial loss of supply in Transpower's network. The Buchholtz devices have now been updated to replace the mercury switches with reed switches as these are less sensitive to seismic events.
- A lesson learnt from the Edgecumbe earthquake was the need to seismically restrain transformers. These were fitted prior to the earthquake and ensured no transformers toppled off their foundations.

- The use of flexible cables rather than solid conductors to make connections between busbars and substation equipment also allows some flexing without breakage.
- Clashing of conductors in both Transpower and lines companies' overhead lines occurred which caused temporary faults.
- Orion acted on many of the recommendations that came out of *Risks and Realities* and were prepared for an event like this. They have been actively pursuing a policy of earthquake (and storm) hardening in their electrical network.
- Pole mounted structures and transformers (Orion) were strengthened to withstand earthquakes. The result was that only a few of Orion's substations were affected by the earthquake.
- MainPower have been working over the last 15 years to upgrade zone substation transformer seismic restraints as this was a lesson learnt from the Edgecumbe earthquake. This resulted in no real damage at zone substations.
- Mutual aid agreements meant that MainPower were able to have access to aid from Marlborough Lines and Electricity Ashburton which allowed for access to equipment, staff and cable jointers.
- Underground cables were damaged due to major ground movement but there is no easy way to prevent this apart from moving to overhead lines. However these are more prone to storm damage and being hit by vehicles.
- The cable repairs were undertaken with the support of local and overseas specialist cable jointers.
- The low voltage network of predominantly polyethylene and polyvinyl chloride (PE and PVC) cables have performed well and suffered fewer faults when compared relative to the observed 11 kV cable networks.
- The major fault with overhead lines were predominantly LV issues such as barge boards being ripped off houses and conductors being torn out of terminals due to the ground shaking. Liquefaction caused several poles to sink.
- Orion's head office was damaged but a hot standby control office had been set up pre-event.
- The loss of chimneys potential would increase the winter electricity demand.
- The risk reduction action taken over the past 15 years reduced the network damage:
 - Seismic strengthening of substations
 - Improvement to key bridge approaches
 - Improvement in design standards
 - Establishment of a backup hot-site for Network Control & Call Centre.
- Other design features such as ringed 11 kV HV cable systems and interconnected low voltage network helped give flexibility in restoring loads. Use of deterministic security standard, and the policy of maintaining lines up to the customer building entry, were also beneficial.

1.19 Impact of the Christchurch Earthquakes on the Electrical Power System Infrastructure

(Massie, A. & Watson, N.R. 2011)

This is a summary of a paper from the December 2011 Bulletin of the New Zealand Society for Earthquake Engineering, Vol 44, No. 4.

The main points are:

- Most cable damage to paper-lead cables (PILCA).
- Fracturing in hill slopes caused some cables to tear.
- 66kV oil-filled cables deemed un-repairable (Bromley – Dallington and Bromley – New Brighton) and replaced with overhead lines as an emergency repair.
- Also helpful to mobilize staff and resources quickly:
 - Mutual aid arrangements in place with other lines companies
 - Arrangements with suppliers & contractors
 - Relationships established.
- Pre-event plans and disaster scenarios were beneficial.
- Communication with public and media important. Dallington Hub was set up for people to use telephones and computers if they couldn't at home.
- Looking after staff was critical – e.g. food, water, washing.
- Bringing help from outside the region reduced the burden on local staff (and their families). Similarly retaining local staff in normal functions helps to reduce the load.

- Looking after medical needs (e.g. Hep A vaccinations for those working in / near ruptured sewer lines).
- Impossible to carry enough spares for this event – good supply chains were imperative.
- The optimal size of temporary generators was found to be 400 kVA – 500 kVA, 415 V. As they: matched kiosk load; no transformation necessary; not dependent upon possible faulty 11 kV cable network.
- Generators are expensive to run and require fuel supply but if fuel is available they are good to use and can enable the ability to expand resources.
- More economically viable to buy rather than lease.
- More redundancy needed between key substations and national grid.
- Loads are changing and temporary overhead lines will have to be replaced.
- Underground cables will need to be planned, not on the shortest route, but in land least likely to deform (>500m from waterway to avoid lateral spreading). Thus care is needed when crossing waterways.
- Review required of the encasing cable practices in weak concrete or hardfill. Ducting protects cable from damage during ground deformation or using extra cables with different cable routes to provide redundancy.

2 TELECOMMUNICATIONS

2.1 Earthquake Performance of Telecommunications Infrastructure in Christchurch 2010/2011

(Foster, C. 2011a)

This 2011 paper reports on the performance of key components of Christchurch's telecommunications network following the 2010 and 2011 earthquakes.

The main points are:

- The Telecom core network continued to operate both through and after each event and the many aftershocks. There were call overloading issues on both the PSTN and mobile networks, but much more significantly on the February 22 event. After the immediate aftermath panic, calling levels returned to manageable levels.
- Many sites had been provisioned to be easily connected to portable engine alternators because it had been recognised from earlier events that the mobile network would be a prime mode of telecommunications for both restoration and normal communications.
- All telephone exchanges have at least a battery back-up for reserve and the larger ones also have generator (engine) in case of mains failure.
- Equipment in the Telecom buildings had been seismically supported and continued to operate because of this.
- The main points of failure of buildings were connections, i.e. where they had been structurally extended since their original construction.
- There were insufficient engines locally to support the continued operations of the field sites providing services (such as broadband) to customers. There were also logistical issues with keeping them operational (refuelling etc).
- It was important that staff rostered to work following the earthquake were given days off to ensure they did not burn out during the highly stressful period.
- Preplanning can only be effectively done to a certain level. It usually needs to include those issues that can take some time to put in place but have a considerable impact on being able to manage and mitigate the effects of the event. In this case having more of the most suitably sized

generators would have been more effective in keeping mobile sites operational initially, especially when their nominal battery reserve is only 2 hours.

- Use a mixture of local and distant people to manage and control the event. The distant management need to be willing to listen to the locals and the locals need to be aware that what might seem the most logical solution may not provide the most effective answer. The locals' families came first.
- Because so many of the basics (water, food, toilets etc) were not readily available, special supply arrangements were required often from outside the region.
- A control bunker (or War Room) was set-up with basic computer and phone connection facilities, audio conferencing, whiteboards and controlled access. It is essential that generator power is available.
- Early liaison is important with key people in support infrastructure especially power distribution and those that control physical access.
- Be prepared to change at short notice the way events are being managed where critical success factors will be compromised if the present approach is continued.
- Gel technology in roadside cabinets appears to be relatively resilient. The resilience of AGM batteries in the mobile network has yet to be determined.

2.2 Christchurch February 22 Earthquake – A Lifelines Presentation

(Chorus, 2011)

This presentation describes issues arising in Chorus's response to the February 2011 earthquake.

The main points are:

- Location of the "War Room" was in the process of being changed following September, from the central city to the eastern suburbs. Focus on keeping mobile network operational.
- Call centre activities moved to other national Telecom sites. 111 services moved.

- Staff put on 'special leave', but effort taken to get staff back into work place within a week.
- Some staff brought in from other locations for specific tasks. Contractors also brought in to increase resources.
- Significant calling congestion, access faults four times greater than September, local cable damage in some areas, core network continued to operate.
- Temporary working spaces for call centre staff difficult to find.
- Power outage a significant concern. Power outage affected rate of restoration – especially in east of city. Approx 80 generators "imported" from other parts of New Zealand. Improvements in availability of timetable information for power restoration compared to September earthquake noted.
- Telecom had a priority contract for structural engineers to check key sites – building checks initiated the following day.
- Chorus had a staff presence in main civil defence EOC for first 2 weeks (12 hours per day).
- Plastic and fibre cabling has had minimal damage. Damage to lead cables (most with paper insulation) in some locations through sheaths cracking and letting in liquefaction water, and being pulled apart.
- Telephone exchange / Telecom House – in red zone, no power, no reticulated water for cooling towers (local bore set up as back-up proved very useful), significant cracks in telecommunications cable tunnel in the street, risk from neighbouring buildings.
- Problems around disconnecting cables / protecting equipment from buildings being demolished. Those cables were often also providing services to other customers who were not affected by demolition etc.

2.3 Earthquake Performance of Telecoms Infrastructure in Christchurch

(Foster, C. 2011b)

This November 2011 presentation to the Auckland Engineering Lifelines Group summarises Chorus's learnings from the Christchurch earthquake.

The main points are:

- Resilience in the network is noted, i.e. duplicate

sites, ring fibre networks, back-up generators and batteries in reserve.

- Immediate impacts arose from by power outages, traffic congestion and cable damage.

Key points for managing disasters:

- High level pre-planning essential. Details can be adjusted during the event to account for specific circumstances.
- Need a mixture of local and national resources, and to ensure that staff have water, food etc.
- Establishing good working relationships with CDEM and electricity suppliers early in the response is essential.
- Be prepared to change approach at short notice. Match the new situation with the required resources, rather than just assuming the current resources are appropriate.
- Use robust technology, such as portable generators and Gel v AGM batteries. Minimise the reliance on plant that requires a water source.

2.4 A Telecommunication Provider's Response to the 2011 Christchurch Earthquake

This summary is from an internal review conducted by a Telecommunication Service Provider following the February 2011 earthquake. The author has approved release of this summary but has requested that the source document be withheld.

The main points are:

Things that worked well

- The organisation's efforts to put in place proactive safeguards and establish a crisis management plan was very effective.
- Very good internal and external corporate relations ensured the organisation's brand was protected. The organisation pulled out all stops to assist its customers and emergency services.
- Great staff commitment to the organisation's survival and to its staff and contractors aided the response.
- HR response was essential in supporting staff and helping them to return to work.
- Crisis management teams were more effective since previous events (indicating good internal learnings processes, stemming from detailed,

clear reporting to the senior management team).

- Risk prevention measures applied to physical assets radically reduced damage and restoration time.

Lessons Learnt

- Check assumptions made when preparing crisis management plans (e.g. having a strong building housing staff is not enough in itself if the event causes surrounding buildings and structures to be dangerous or damaged, thereby preventing access).
- Further thought required into strategies needed where access to office building is impossible (e.g. working from home, implementing remote working technologies; relocation to Work Area Recovery sites; developing geographic diversity for key time-critical functions; work load shedding to other teams). Imposition of cordon required the company to completely change its operating model from centralised to decentralised in a very short time and its business continuity arrangements allowed this to happen and thus minimised the impact to the business.
- Right at the start of the crisis event, set arrangements for crisis communication, set crisis management roles and responsibilities, and determine staff health and safety and welfare response.

- Need to develop relationships in “peace time”, including at senior management level, with local authorities, CDEM and power companies.
- Need to pre-plan for crisis-centres and work area recovery sites – including back-up communications equipment and food and water.

2.5 Christchurch Earthquake Report

This summary is from an internal review conducted by a Telecommunication Service Provider following the February 2011 earthquake. The author has approved release of this summary but has requested that the source document be withheld.

The majority of the lessons were taken direct from the report (see tables on pages 18-23).

Green – Observation relates to something that went well and should be repeated or built on in future

Amber – Observation relates to something that should have been avoided or could be improved in future

! – General observation on events.

Emergency Management Process and Preparedness		
	Observation	Lesson
Green	<p>Experience of September earthquake meant that many effective tactics learned in the previous event were very quickly implemented, e.g.</p> <ul style="list-style-type: none"> • initial media releases • technical change blackout • minimum coverage modelling to prioritise generator deployment • deployment of dedicated H&S lead to CTP 	Ensure these lessons are incorporated as guidance in support documentation.
Green	Exec-level Crisis Management team provided effective governance at the strategic level, and the appropriate decisions were referred to CMT for approval.	Process is well-practiced through annual exercise, good use of support materials such as template agenda.
Green	Engagement with Civil Defence worked well and proved useful to get priority access to transport, to get staff through cordons, and to get information about the activities and priorities of other utilities.	Relationship with civil authorities as a "lifeline utility" is important to cultivate and engagement process needs to be ready.
Amber	Meetings between telco CEOs were useful, could have happened earlier.	Include as guidance in support documentation.
!	A number of alarming and incorrect rumours emerged in the aftermath, particularly during the first week (e.g. Civil Defence had confiscated telco generators)	Need to actively consider the source and the plausibility of information before acting on it or disseminating it.

Health & Safety		
	Observation	Lesson
Green	Checking in on affected staff was accomplished as a priority.	Process and tools could be valuable here, e.g. capability to text staff based on place of work.
Green	Health & Safety rules were communicated to Christchurch staff on Day 1.	Include as guidance in support documentation.
Amber	Some Health & Safety processes not standardized and documented e.g. instructions to staff entering the 'quake zone, process to conduct checks of staff safety, tracking staff travel.	Ensure these processes are documented and included in review and testing schedule.
Amber	Contractors were not always aware of the company's health and safety requirements.	H&S requirements need to be communicated effectively to contractors.

HR / People		
	Observation	Lesson
Green	Extraordinary efforts and co-operation by staff across the business. Staff were motivated not only by loyalty to the company and each other, but also by the sense that they were working to provide an essential service and assist the people of Christchurch.	Benefits of strong company culture and a focus on corporate responsibility. Formal acknowledgement and reward for extraordinary efforts is also important.
Green	Effective response from engineering vendors based on strong personal relationships with our staff.	Benefit of fostering strong relationships and understanding the vendor's capability to deliver beyond BAU supply arrangements.
Amber	Some contact details in the HR database were not up-to-date, which delayed contacting some staff.	Incentives and ongoing effort required to keep staff database current.
Amber	Some out-of-town staff sent into Christchurch in the first week did not have a clear role.	Some planning required before sending people in. Ensure that people entering the regions are adequately briefed on what they will be doing and the authority they have to make decisions.
Amber	Some staff in Sales relief teams had a difficult time dealing with the heightened emotion and stress encountered when dealing with traumatised members of the public.	Make sure this is better considered in future and all staff are prepared for the situation that they will encounter. May need expert advice in developing a plan here.

Network and Technology Facilities		
	Observation	Lesson
Green	Well-equipped workshop and spares storage at key facility was valuable e.g. in setting up microwave equipment before going to site.	Should be considered in the design of key facilities.
Green	Impressive stability of core network infrastructure under high load – several units ran at 100% capacity in the first hours after the earthquake but remained stable.	Stability under high load should be considered in the assessment of network hardware or configuration.
Amber	Some cellsite batteries did not perform to standard. There were two issues: 1) battery life degraded due to age 2) battery spec no longer adequate for site following additional equipment installation	1) Battery replacement program required as part of BAU (kicked off two years ago). 2) Delivery process should evaluate whether battery upgrades are required when power load at site is increased (e.g. site expansions).
Amber	Portable generators with small fuel tanks (2 hour supply) were problematic when deployed in large numbers – refuelling rounds became burdensome.	Recommend investment in modular fuel tanks to expand capacity.
Amber	Initial set of generators available to the region was not adequate to the scale of the power outages. We were fortunate to be able to procure additional generators reactively.	Review number, location and type of portable generators available.
Amber	Difficulties encountered in deploying generators to rooftop sites.	Consider including fixtures to install mobile generators at ground-level in standard design for rooftop sites.
Amber	The requirement from Civil Defence to send bulk SMS targeted to people in impacted areas was difficult and time-consuming to execute using existing capability.	It is preferable to leverage cell broadcast or location-based SMS solution for this purpose if possible. The NZ Government is currently investigating a centralized solution for the “National Warning System”

Marketing & Public Communications		
	Observation	Lesson
Green	Media releases aimed at controlling congestion were effective – messaging encouraged limiting use of data, voice for emergency use only, and use of SMS. “Tips and tricks” were also useful, e.g. suggesting that people record a voicemail message before their batteries run down.	Most of these messages are relevant to any major incident and if prepared in advance can be released very soon after the event.
Green	Pro-active media releases were effective once these began. Reporting of network impacts in terms of coverage areas affected rather than “number of cellsites down” was more meaningful.	Incorporate as guidance in support documentation.
Amber	Some important local media were missed in press releases due to focus on national media. Feedback from local staff was useful in determining which media were most effective in communicating local messages (e.g. which stores are open).	Incorporate as guidance in support documentation.
Amber	Relief offers to customers were well-received but could have been offered more quickly.	Develop reference principles and procedure for domestic and international incidents, to allow a pick and choose of workable relief offers to affected customers, including roamers.
Amber	Descriptions of network impacts were not clear and consistent at first..	The format of network status reports towards the end of the response phase was very good and should be used as a model for future incidents.

Sales Regional HQ, Retail, and Dealer Channels		
	Observation	Lesson
Green	Increased DLAs to staff to assist customers worked well and was appreciated by both staff and customers.	Empower front-line staff to deal with issues immediately then tighten guidance as appropriate.
Green	Effective redeployment of Christchurch Sales staff from closed stores and HQ functions into retail.	Consolidate staff who are available to work in the places they will be most effective. Roles can be flexible during emergency response.
Amber	We anticipated demand for cheaper devices and accessories. However there was unexpectedly high customer demand for smartphones as a means to get online.	Stock management strategy should take this into account.
!	Higher levels of demand for stock were experienced in surrounding regions such as Ashburton, Queenstown and Dunedin. This was driven by displaced people relocating to other centres.	Stock management strategy should take this into account.

Finance & Corporate Affairs		
	Observation	Lesson
Green	Corporate Affairs team linkage into central government was effective and valuable, e.g. in securing fuel supply, and for escalation of issues with local authorities.	Incorporate as guidance in support documentation.
Green	We designated a single liaison contact for aid agencies, emergency services and volunteer groups to ask for assistance (e.g. Prepay top-ups for volunteer forces).	Incorporate as guidance in support documentation.
Amber	Difficulties were experienced in pulling together insurance claim information. Costs and insurance claim information were not adequately tracked from the outset of the event.	Include this as a formal role in the response framework. The person in this role needs to know the technology and understand insurance claim requirements, so ideally a staff member with appropriate training from Finance.
Amber	While new collections activity was ceased on day 1, activity that was already underway continued.	Need a procedure to pull back or undo collections activity in progress as well as ceasing new activity.
Amber	An issue was encountered with standard Prepay top-up rules that are intended to prevent fraud (i.e. maximum daily top-up amounts). Emergency responders and aid agency staff using Prepay phones were hitting this limit.	Need to be aware of this in future incidents. Incorporate in support documentation.

Customer Service		
	Observation	Lesson
Amber	In the first days of response, a small number of external messages were not consistent between service and media relations e.g. details of network impact.	Co-ordinate and align all channels via the Comms Recovery Team
Amber	Free diversions from fixed line to mobile were offered on Day 1, however in some early cases we were unable to deliver this as it depended on the availability of the wholesale operator and their ability to access exchanges in the region.	Ensure the process is understood before making the offer.
!	Call volumes were manageable, they went up but were less than might be expected. The type of queries coming in from customers changed over time, e.g. requests for assistance were common at first, later we received increasing queries from customers anticipating bill shock.	Incorporate in support documentation.

2.6 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Telecommunications

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 5 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 5 is on Telecommunications.

The main points are:

Experience

- Customers have become more reliant on cell phones and wireless services compared to landlines. It is recommended that a stronger emphasis is placed on mobile network earthquake-resilience as a result.
- Pre-event preparation reduced earthquake damage but outages occurred nevertheless.
- Liquefaction extensively affected buried cables, especially near rivers. The damage included cracked sheaths, water leaking into cables and cables being pulled apart. However, the most common service outages arose from loss of

battery power, antenna towers out of alignment and circuit congestion.

- Sustained periods of battery use can degrade their capacity. This can result in shorter up-times during the next event, especially for those batteries that have started to age. Replacing old batteries after a disaster needs to be a priority to ensure sufficient battery uptime for a second event.
- During the first event, initial priority access to generators proved difficult. It is recommended that there needs to be better planning around power generation needs. Quick connect boxes on the outside of facilities, Base Transmission Stations (BTSs) and cabinets helped with power generators being quickly connected once on site.
- Repeat speed dialling by customers contributed to circuit congestion.
- Old fashioned POTS phones proved useful to customers who did not have mains electricity, as these phones can operate using power provided via the POTS lines.
- Coordinating BTS restoration with power restoration timetable proved challenging. Until general power was restored there was also no need to restore FTTN cabinets.
- FTTN broadband can be used as a substitute for POTS service when the damage sustained cannot be repaired quickly (or at all).

Response

- Service providers' responses included switching off 3G while retaining 2G services (3G drains batteries more quickly). Text messaging and voice communication were prioritised over data.
- Cellsites on wheels proved to be a real asset in replacing BTSs that were out of service.
- Contractors offering support were turned down due to difficulties in managing additional resources. Better planning around these resources would help to draw a better picture of potential resources needed.
- A good working relationship with Civil Defence proved essential – especially when there were cordons in place. It was however difficult to keep up with condemned buildings being demolished, in order to know what buildings needed their cables disconnected. There is a need to ensure emergency procedures include plans to deal with cordons and that there are sufficient plans to quickly relocate essential functions (e.g. "war rooms").
- Power restoration timetables with local providers (electricity lines companies) can be difficult to ascertain. Knowing what vulnerabilities exist in the power company's networks would allow for more detailed planning in what facilities and BTSs are most at risk to power outages. This would allow better planning around batteries and back-up power generators.

Advice

- It is recommended that BTSs should have sufficient batteries to cover the time estimated to be required to get a generator to that site while accounting for road congestion in the aftermath of a large event.
- Storage facilities should be strategically located to ensure quick deployment of equipment (such as cabinets and BTSs). Storage facilities should include mobile power generators, fuel, Cellsites on Wheels, Switching on Wheels and spare parts for at least 75 – 80 per cent of the calculated damage in the area. Plan alternative routes to BTSs and storage facilities in case primary routes are not available.
- Quick access to structural engineers is needed to assess building safety.
- Ensure any BTSs placed on top of buildings are seismically stable. Several stations were impacted due to either the building collapsing or needing to be demolished. BTSs on top of buildings that are dangerous to enter can result in access and electricity supply challenges.

- Ensure plans are in place if important sites are in vulnerable positions. Many phone companies needed to work quickly to transfer functionality to other facilities.
- Ensure sufficient plans are in place to provide fuel to generators. There also needs to be planning around refuelling schedules to ensure sufficient resources.
- Have in place redundancies for loss of water to cooling towers.
- Run tests including different scenarios covering the logistics of mobilizing large numbers of generators including moving equipment into the region from outside the area.

2.7 Emergency Telephone Call Services and the February 2011 Christchurch Earthquake

(Fenwick, T. 2011)

This report outlines the performance of the 111 emergency calling system immediately after the February 2011 earthquake. Commercially sensitive data has been withheld.

The report notes that:

The telecommunications sector generally performed well following the February 2011 Christchurch earthquake. Telecommunication service providers (TSPs) took strong steps to restore services, and most services were back (or close) to normal within a week or so (except in the CBD where immediate restoration was not possible – nor was it a priority given cessation of most CBD activity).

The ability to make calls immediately after the earthquake, including 111 and other priority calls, was impacted by electricity outages, cable failures in liquefaction areas and congestion. Cordless phones immediately ceased to work where electricity failed. Some physical damage to telecommunications assets also occurred but the effects were secondary – congestion largely resulted from the sudden substantial increase in call attempts rather than to equipment failure. Battery life at cabinets and cell towers also quickly became a constraint on telecommunications performance and significant losses of cellular coverage arose.

It is not possible to assess the extent to which calls may have failed due to impacts in the access

networks. Further, an unknown number of 111 calls failed to complete due to interconnection and exchange congestion in the immediate post-earthquake period despite buffer capacity and overflow arrangements. This is not to say that the emergencies leading to these calls were not notified to emergency services. Most of the callers would have succeeded with redialling / retries or by using other telephones (e.g. landlines), or the emergency could have been notified by another person at the site.

Twenty further unsuccessful (abandoned) calls were followed up by 111 call centre operators and Police applying the standard failed-call process.

ICAP¹ call takers experienced a very sharp increase in 111 call volumes immediately following the earthquake (the Christchurch impact briefly took national volumes to a level approximately three times normal). 111 calls that would normally have been received in Christchurch were diverted Wellington. The ICAP warm site at Palmerston North was opened the next day to reinstate diversity.

Emergency Service Providers (ESPs) considered that TSPs generally performed well following the earthquake. Reports received noted that ICAP continued to perform its normal functions. 111 call retries due to congestion within telecommunications system and links prior to handover to Telecom were however not visible to the ESPs.

The steps taken by TSPs to improve services in the immediate post-earthquake days included deployment of over 200 portable generators. Significant logistical challenges arose in keeping generators refuelled. Access restrictions and building demolition programmes also needed to be actively managed. Special measures were required to keep key TSP assets at the badly damaged TVNZ building operational.

The Christchurch experience is instructive but it is difficult to draw definitive conclusions from a single event. Physical damage to telecommunications equipment (especially core infrastructure) was very light. Although road conditions were challenging, roads generally remained open facilitating generator deployment and refuelling. These favourable conditions might not be repeated in other emergencies.

This and other comparable events demonstrate the very high reliance on cellular networks in emergen-

cies. Congestion may reach high levels as callers, including those involved in the emergency response, make coincident demands on suddenly fragile infrastructure.

Telecommunications networks are typically designed to meet normal traffic demand with a surplus to deal with sudden peaks. A totally fail-safe, unlimited capacity 111 system is unattainable. Judgements need to be made about cost-effectiveness, both of incremental improvements and of any more fundamental changes to the 111 system that might be suggested. One ESP (the Fire Service) noted that, as businesses, TSPs cannot be expected to cover all contingencies. Of course the same is true of the ESPs themselves (average wait times to Ambulance and Fire rose briefly immediately after the earthquake).

Development of the emergency call system will always be a work in progress as technology opens new opportunities and challenges, and as community expectations change. A broadening of the dialogue between TSPs and ESPs, and the community at large, is required. The Fire Service, for example, noted that *"if ESPs know what limits and risks TSP services have in CDEM events we can more effectively plan our own telecommunications processes"*.

Strong governance arrangements will be needed for improvements requiring coordination across the 111 system as a whole to be made effectively.

2.8 Telecommunication: Promoting Awareness of the Implications of a Wellington Earthquake

(Telecommunications Emergency Forum, 2012)

This brief report, prepared for the Wellington Lifelines Group by the Secretary of the Telecommunications Emergency Forum, includes a summary of learnings relating to telecommunication performance.

The report notes that immediately after the Christchurch earthquakes:

- Cellular performance suffered for some hours due to extreme congestion (exacerbated as batteries ran down after a few hours). Congestion resulted from calling spikes (spikes also occurred following significant aftershocks). Some cell towers and other assets were damaged but the service

¹ Initial Call Answering Platform, a Telecom operated facility for supplying emergency calling services to fulfil Telecommunications Service Obligations (TSO).

impact from damage was secondary (i.e. congestion was primarily due to increased calling rather than reduced capacity). In urban and suburban areas, coverage from cell-sites generally overlaps reducing the impact of loss of individual sites. Cellular providers took steps to stabilise networks and ration available bandwidth (e.g. curtailing data to protect voice and text communications).

- Cordless PSTN phones ceased to work where electricity failed. Numerous faults occurred in the local access copper network. Roadside cabinets were generally undamaged.
- Some microwave dishes were misaligned and many PSTN copper and lead-covered cables were damaged. Fibre held up well.
- Main nodes / exchanges (where back-up electricity supplies are available) and connections to other parts of New Zealand held up well.
- Radio services held up well. Radio services are used by the emergency services and many infrastructure providers and their contractors (radio links to the rest of New Zealand were also uninterrupted).

In the hours / days following the February 22nd earthquake:

- Cellular performance temporarily declined where electricity was unavailable as batteries at cell sites depleted (batteries generally last around 4 to 12 hours depending on the importance of the site and the volume of call traffic).
- Cellular performance then improved to usable, and then to near-normal levels as generators and mobile sites were deployed (around 200 mobile generators were used).
- Generator refuelling presented major logistical challenges due to road conditions and congestion.
- Landline availability declined a little (in areas without mains supply) as batteries at roadside cabinets depleted.
- Performance then improved progressively as generators were deployed, numerous telephone cable faults were repaired (a slow, labour-intensive process) and electricity was restored at customer premises.
- Systems in the core network also improved progressively. On-site generators at key nodes functioned as planned – these generally have fuel sufficient for many days.
- TSPs collaborated to maintain services by sharing assets (including smaller generators),

information and sites. TSPs kept each other informed as opportunities (access windows) arose to service, and progressively relocate equipment at the damaged (and now demolished) TVNZ Building in Gloucester Street where many TSPs had key communication links. More generally, building demolition and site access restrictions threatened fragile telecommunication services in the CBD and other areas where damage was widespread.

- The main Telecom exchange in Hereford Street benefitted from back-up access to on-site artesian water for air conditioning.

2.9 Telecommunications Carriers Forum Annual Report 2011

(NZ Telecommunications Forum, 2011)

This is a brief extract from the Telecommunications Carriers' Forum's 2011 Annual Report (pages 14 to 17)

The Annual Report notes that:

- The Telecommunications Emergency Forum, convened directly after the February 2011 earthquake, was successful in sharing information and resources between competitors. Telecommunication companies worked collaboratively, including with Civil Defence, through the mechanisms that the Forum provides. This helped rapid response and reduced customer outages.
- Farmside's mobile satellite platform supported Urban and Land Search and Rescue activities (independent of disruption of land-based systems).
- Providing for staff was very important for telecommunications companies including: housing, counselling and support, safety, paid leave and home security. Multiple modes of communication with staff were also important (text, email, Facebook, twitter, webpage).
- Some companies also provided additional support services (e.g. bandwidth) to support key corporate and government organisations.
- Working with businesses to provide backup services for their data was important. Many also offered free services, waived regular fees, provided free equipment, and worked with other industry providers to get their customers connected quickly.

Telecommunication providers are thinking about:

- Satellite contingency planning for business reliant on broadband
- Investing in additional core network infrastructure.
- Monitoring staff working long hours under stressful conditions.
- Appointing a dedicated recovery leader to align recovery needs with business strategy.
- Back-up power supplies.
- The need for preparedness across the country (e.g. re-routing through other centres).
- The need for close personal and business relationships both inside and outside the affected area.

3 POTABLE WATER AND WASTEWATER

3.1 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Water

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 6 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 6 is on Water.

The main points are:

Experience

- Due mostly to widespread liquefaction there was sustained damage to a great number of buried water pipes and water wells.
- 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 from the wells due to power outages.
- However, despite a PGA equal to 0.7g to 0.9g, HDPE pipe at Lyttelton sustained no damage. During the February and June 2011 earthquakes, no damage was sustained to new HDPE pipes installed after the first earthquake, in an area heavily affected by liquefaction. Large diameter PVC pipes also performed well. Small diameter PVC pipes performed poorly. “Repair-in-kind” repairs failed again.
- 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.
- Although the main water tank for the CBD (36,000,000 litres) sustained substantial damage which resulted in its contents emptying, there was no inundation or life safety threat to nearby residences.

- 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.
- Supply from some wells was impacted where mains electricity was lost and where generators were not in place.

Response

- The immediate earthquake response was focused on restoring potable water. The secondary response was on the wastewater collection and treatment plants.
- The distribution of potable water to customers with broken water mains was an important part of the post-earthquake response. Distribution was normally required in areas of heavy liquefaction. It is important that Civil Defence and others coordinating the response have adequate plans in place to quickly supply this potable water.
- Because of Christchurch’s very high water quality from the aquifers, there is normally no water treatment. After each earthquake health officials issued warnings requesting everyone to boil their water as they were worried about contamination. Portable chlorination stations were installed at various locations throughout the city.
- Often repairs were made to be functional rather than be sustainable in the long term. Except in a very few cases, short repair lengths were inserted instead of replacing old fragile pipes with new seismic-resistant pipes (considered nice to do but not realistic in the immediacy of post-earthquake restoration efforts).
- After the second event, tracking of the damage became much more detailed, GIS databases were updated with many more attributes than simply the repair location. This will help with long-term asset management and should help develop a more resilient network.

Advice

- Inspections and damage assessments need to be made quickly so that the level of effort for response can be quantified.
- 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.

- Water tanks on hillsides need to be built to sustain landslides.
- 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 regular basis. When upgrading the network over the long-term (20-50 years) consideration needs to be given to both the aging of pipes due to corrosion or leaks and pipes that are seismically vulnerable. *Further guidelines are contained in the Chapter on capital works programmes that address these issues.*

3.2 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Wastewater

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 7 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 7 is on Wastewater.

The main points are:

Experience

- The wastewater infrastructure was so badly damaged after the February 2011 earthquake that for several months households were asked to conserve water to reduce the risk of the sewage ponds overloading.
- Dry well lift stations and dry well pumping stations were lifted due to extensive liquefaction. This lift exceeded 1 meter at some stations. Inflexible connections at pumping stations caused break-ages.
- While some pumping stations suffered no damage from the seismic activity, inlet and outlet pipes were damaged. One station floated when sewage was sucked into trucks.
- Pipes may be vulnerable where they are too rigidly supported on bridges (e.g. settlement of one abutment can lead to failure).
- The 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 pipes in Christchurch and Kaiapoi. Instead

fusion butt-welded HDPE or clamped electric-welded HDPE or ductile iron pipes with chained joints are recommended for consideration.

- There was no damage to rod-hung cable support trays and pipes at the Bromley Waster Water Treatment Plant (WWTP) despite shaking with $PGA = 0.5g$.
- The WWTP has an underground corridor (called a gallery) constructed of reinforced concrete, used for housing piping and conduits. The gallery was damaged and separated at the construction joints. Water and sand flowed into the gallery through the drainage pipe system and the joint separations.
- The WWTP had to be able to deal with an influx of debris and sand which infiltrated the wastewater collection pipe system, putting pressure on the already-distressed filtering tanks. Sewage can bypass the treatment plant to the ponds, but the ponds cannot be bypassed to send sewage directly to the outfall.
- Sloshing forces were the likely cause of many aeration pipe breaks at the WWTP.

Response and Advice

- The extent of pipeline damage to the sewer system equalled or exceeded that of the water system but took 3 to 10 times as long to repair owing to the depth of gravity sewers. Crews had to dewater the sewer, install sheet piles (or trench shields) before the pipe could be either repaired or replaced (this is because they were often 3 meters deep).
- Interior inspection of sewer pipes was hampered by having so many of them clogged with sand.
- Crew worked to flush sewer pipes with a water jetting method. This cleaned the pipes enabling cameras to be deployed to inspect the pipes. At locations where large sewer pipe breaks had 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 fell into the sinkholes. The process was modified to reduce the possibility of creating sinkholes by monitoring the rate of progress of the jetting holes, when the rate significantly slows the crews stopped the jetting and report a location of potential significant damage.
- The repair strategy was to first restore the larger downstream sewer mains then continue working upstream. In this way CCC could take as much sewage as possible to the WWTP and also contain as much sand as possible in the pumping

station wet wells, thus removing a significant sand load from the WWTP.

- Slow moving effluent in pipes caused the biggest headache for both the city council and health authorities because of leakage into backyards, rivers and the sea.
- Portable toilets proved essential in providing temporary service to customers – generally one per two houses. Another approach was to install small tanks on berms or in the front of properties without sewer service, where the sewer mains couldn't be repaired. This allowed use of the household internal toilets, showers and washing machines. Finally chemical toilets were deployed to some residents to replace the usage of portaloos.
- HDPE pipe was useful in establishing temporary sewage bypasses over bridges.
- It is noted that relative to other lifelines, sewer systems have often been neglected with regards to seismic vulnerability assessments and mitigation. Liquefaction has a major impact on the network's performance and had a very large impact on people's daily lives.
- There needs to be adequate preparation for storing silt if liquefaction is a possibility.

3.3 Recent Earthquakes: Implications for U.S. Water Utilities

(Davis, C. & Eidinger, J. 2012)

This paper draws on experience from the Christchurch earthquakes and makes recommendations for consideration by US water authorities.

The main points are:

Experience

- Water pipes and wells in Christchurch had not been designed for earthquakes although some seismic upgrades to reservoirs had been undertaken.
- The bulk of the earthquake damage to water systems was due to failure of hundreds to thousands of smaller diameter distribution pipes in zones of infirm ground. Liquefaction caused water pipe breaks. Landslides and road-fill slumps damaged pipes in hill areas. AC pipes were the most vulnerable to settlement or lateral spreading.

- One water storage tank had damage to the roof in September, likely due to uplift forces by water sloshing. More damage occurred to tanks in February.
- Difficulties arose in water well performance after the February earthquake in liquefaction zones. Soil settlements due to liquefaction resulted in broken well casing pipes. Some wells did not have generators (for emergency response phase). Fortunately there were no / few fires.
- For common distribution pipes and service laterals (from under 1" to 8" diameter), HDPE pipe (either fusion butt welded or electro-welded with clamped joints) appeared to have excellent earthquake performance.
- Christchurch City Council had installed some HDPE pipe in its water distribution system after the first earthquake. In the subsequent earthquakes, no HDPE pipe was damaged, while nearby older pipes were damaged.

Response

- Water was the number one restoration priority, wastewater was second.
- Shallow pipe burial depths simplified immediate repair efforts (most consumers had water within 10 days, the last about 6 weeks).
- Deep sewer pipes (9-10 feet) complicated repair. Dewatering and shoring was required.
- Christchurch utilised small water tankers to provide potable water in liquefied zones. When plans are being made for these tankers, consideration should be given to who will operate them, how they will obtain petrol and where / how the tankers will refill with potable water.
- Water quality was managed through boil water alerts and mobile chlorination stations. Boil water notices were removed after 14 days.
- Most immediate repairs were replacing "like for like". Where HDPE was used instead of "like for like", less damage occurred.

Advice and Recommendations

- The report recommends the adoption of performance goals. Goals may include the seismic performance of upgraded assets, how long is acceptable for customers to be without water after an earthquake as well as measures around mitigation and preparedness. This would provide a "yardstick" as to what constitutes acceptable water system performance. Targets should be discussed with all involved parties.

- The following two recommendations are amongst a group addressed to the US Water Research Foundation:

- A cost-effective pipe replacement strategy should be developed that factors in on-going aging pipeline replacement as well as earthquakes. A seismic design guideline for water pipes (ALA 2005) is currently available, but it addresses only seismic issues. This guideline, supplemented with attention to pipe aging/corrosion and on-going lessons learned, should be updated.
- A review of the various post-earthquake restoration targets and strategies, addressing forecast benefits, and actual costs, would be useful to utilities to help them select their own strategies.

- The report also notes that:

- Seismic upgrades are more likely to be cost effective if the hazard occurs on a regular basis.
- Non-gravity sewer systems should be considered as an option.
- Emergency response plans should have provisions for major increase in work crews after an earthquake. These can be from either outside contractors and/or mutual aid. For practical purposes, the work crews should not increase by more than 100 per cent unless the utility has the ability to manage a much larger workforce.
- Backup power generators with sufficient fuel supplies for critical well supplies will reduce the need for electric power restoration.
- 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.
- Fire spread was not a problem and existing fire prediction models may need to be updated. This will affect the strategy for water supply design / resilience levels.

Detailed recommendations are made in the paper for pipe renewal, water tank design and water well design. Extracts from the relevant sections follow (see the full report for further information).

Seismic Design for Pipes

Distribution pipes. Pipes (diameter 12 inch 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 in the next 5 to 10 years. 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, does not need any special seismic design – important exception: the author recommends that pipes supplying essential facilities such as hospitals and evacuation centres be able to be isolated from other areas where damages may be sustained.

Transmission pipes. Pipes (diameter 30 inch and larger) that have leaked and been repaired more than 2 times over the past 7 years, per 1 km length, and are in soils prone to liquefaction, landslide or faulting, deserve replacement in the next 5 years. 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 to 2,500 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 requires proper design of any slip joints in order to accommodate seismic ground shaking effects; or avoid the use of slip joints.

Storage Tank Sites

For sites exposed to permanent ground deformation in the design basis earthquake, the following is recommended:

- Avoid using the site. If this is not feasible, then consider the following mitigation measures:
 - All attached pipes must be able to absorb the estimated ground settlements or lateral spreads. A variety of flexible pipe hardware can be used, which will be most effective if the pipe is above ground (or in an underground vault) to allow the pipe to move without soil resistance.
 - Steel tanks might be able to take as much as a few inches of ground settlements, without rupture of the tank.
 - Concrete tanks (pre-stressed or reinforced) appear to be more fragile than steel tanks, and ground settlements of 2 to 3 inches appear to be enough to crack the tank.

For new tank installations in high seismic zones, we

recommend site-specific subsurface investigations to establish the potential for permanent ground movements. If the site is thought to have potential movements, use steel tanks (not concrete tanks) unless the hazard is mitigated. If the tank site requires pile foundations (for example, a site atop young bay muds, etc.), then the pile-pile cap detail must be designed to accommodate the design basis earthquake, inclusive of soil-structure interaction effects, with ductility demands low enough to assure no leakage in the tank.

Avoid placing tanks at sites prone to surface fault offset from normal or reverse faulting movements, as it will be hard to design for these movements.

If other mitigation schemes are impractical or not cost-effective, and if a suitable water drainage system is included to avoid life-threatening inundation impacts to nearby residents, and if the tank is sacrificial (not needed) post-earthquake, then a tank can be placed in faulting, landslide or liquefaction zones.

Water Wells

Where possible wells should be situated outside of zones subject to seismically induced permanent ground deformation. These can include areas prone to liquefaction, landslides or fault crossing etc.

For wells located in zones prone to liquefaction, a prudent design approach would be to design the casing pipe (top 40 feet) to be able to resist all imposed loads due to

liquefaction. The geotechnical parameters needed for this type of design can be adopted from ALA (2005), but specific geotechnical site investigations are recommended. If the well casing can survive the effects of liquefaction (including seismically induced settlements), and if the attached discharge pipes are provided with suitable flexible connections, most such wells should remain functional once power is restored. Backup power generators with sufficient fuel supplies for critical well supplies will eliminate the need for electric power restoration.

3.4 Liquefaction Impacts on Pipe Networks

(Cubrinovski, M., Hughes, M., Bradley, B., McCahon, I., McDonald, Y., Simpson, H., et al. 2011)

This 2011 paper, prepared with funding from the Natural Hazards Research Platform, provides advice, solutions and recommendations to the Christchurch City Council on geotechnical, liquefaction and seismic issues relevant for potable water and wastewater pipe systems, documents and evaluates the performance of the systems and develops procedures towards improved seismic resilience.

The main points in this paper are:

- Submains suffered a higher percentage of damage than watermains for any given type of material
- Polyethelene (PE) submains suffered, on average, five to six times less damage than galvanised iron (GI) pipes
- For all potable water pipe materials except PE pipes, there is a clear increase in the affected length (percentage of damage) with increasing liquefaction severity
- The depth of the wastewater network caused difficulties for observations and repairs.

The paper includes recommendations on seismic resistance materials and how to improve construction and design processes.

Soil Liquefaction and Lateral Spreading

- Liquefaction at a given site does not increase liquefaction resistance of soils and does not prevent re-liquefaction at a site in subsequent earthquakes. The types of soils that were most affected by liquefaction were non-plastic sands, silty sands, sandy silts, and silt-sand-gravel mixtures.
- Starting from the Colombo Street Bridge, practically all downstream bridges on the Avon River were severely impacted by lateral spreading. Rotation movements of abutments, damage to foundation piles and subsidence of approaches to bridges and in some cases, structural damage were the most typical spreading-induced damage.
- “When evaluating lateral spreading one should carefully consider ground elevation (direction of sloping), river geometry (meandering, loops, cut banks, point bar deposits), presence of weak-

ened zones (old river channels, fills, etc.) and geotechnical conditions, next develop lateral spreading zoning and probable range of spreading displacements and their distribution, and then anticipate loads and deformation of [pipelines] having in mind [their] particular layout relative to the direction of lateral spreading.”

Performance of the Potable Water and Wastewater Systems

- “PE submain pipes suffered, on average, five to six times less damage than GI pipes.”
- “Comparing the damage to watermains and submains, it appears that for each pipe material the damage to the submains was larger than the damage to the mains. The total damaged length of submains was smaller, however, because over 80% of the submains were comprised of the well performing PE pipes.”
- Although damage is associated to a certain pipe material, the “failures” include (and probably are dominated at least for the PE pipes) by failures of particular components (joints, connections, fire hydrant details, crossovers, laterals) rather than material failures. *It is critically important therefore to discriminate between different types of failure and carry out more rigorous analysis.*”
- Inspections of and repairs to the wastewater network were much more difficult than to the potable water system because of the depth at which the pipes are installed (often exceeding 2.5 meters) and, once the need for repairs had been identified, dewatering and trench support was necessary before repairs could take place.
- Detailed information on damage to the wastewater system was not available at the time the paper was written. Further studies and analysis are required.

CCC Issues and Considerations

- “A significant effect on the gravity pipe network has been the movement of pipe sections relative to each other, the surrounding ground and/or structures. This movement is evidenced by changes in grade, varying grades along a pipe length, or joint dislocation either within the pipe length, or at connections to structures.” The effects included:
 - Reduce capacity particularly in gravity lines,
 - Inconsistencies in the invert level
 - Partial or complete blockage of mains or laterals
 - Joint damage or movement allowing silt and

groundwater infiltration or discharge of wastewater to groundwater

- Depressions in carriageways caused by infiltration of subgrade materials into the gravity system.
- Portions of Christchurch’s gravity reticulation network are installed at depths exceeding 2.5m resulting in delays and high reinstatement costs.

Note: The following material (“Construction Alternatives” and “Design Alternatives”) summarises:

- *recommendations*, applicable to all Christchurch zones, and
- *best practices*, applicable dependent on liquefaction resistance in the particular area as identified on a Liquefaction Resistance Index map in the paper.

Research is continuing in many of the areas listed. Readers should refer to the full paper for details.

Construction Alternatives

1. Pipe Haunching or Surround / Backfill Details

- Imported gravel backfill under roads to reduce the potential for trench settlement also “increases resistance to liquefaction damage by forming a zone of non-liquefiable soil above the pipe, providing a zone of much more permeable ground to relieve excess pore pressures immediately under and around the pipe and higher strength material along the trench.”
- Alternative methods and materials for pipe haunching, surround and backfill have been investigated. Recommended solutions included:
 - Detailing a “soft ground” or “raft” foundation wrapped in geotextile with strength class C, installed to TNZ F/2
 - Continue using M/4: AP40 or AP20 as pipe haunching or surrounding
 - Continue using M/4 AP40 or AP65 as trench backfill
 - Tightening bedding or haunching compaction requirements.

“Best practice” solutions include, in relation to flexible gravity pipes, wrapping haunching or surrounds in geotextile, strength class C, installed to TNZ F/2.

2. Polyethylene Pipe Construction

- Recommendations for improved seismic resistance in pressure networks using polyethylene material include:

- Providing quality records including methodologies and weld records to support welder competence
- Ensuring welder competence, e.g. by requiring current qualifications
- Improving weld construction through amendments to construction specifications including equipment and processes
- Providing commentaries and graphical plots of electrofusion peel de-cohesion test results to confirm weld competence and allow tracking of material or welder related performance issues
- Updating polyethylene weld test requirements ensuring testing is relevant to pipe size and use

3. Material Selection

- Recommendations for material selection take into account increasing pipe stiffness, specifying ductile materials and improving the material specifications for connections between pipes and for fittings. Specific recommendations include:
 - For gravity applications, use of PVC-U pipe, SN16 for 100 and 150 diameter and SN8 for 225 and above to improve pipe resistance to becoming oval or buckling under seismic loading
 - For wastewater pressure applications, use polyethylene pipe as it has experienced no known failures under seismic loading
 - Increase the minimum PN for polyethylene pipe in wastewater pressure applications to PN10 to improve resistance to seismic loading
- Best practice solutions include use of polyethylene for potable water.

4. Joint Details

- For pipe joints it is recommended to:
 - Wrap PVC-U gravity pipe joints, including on laterals, in geotextile with strength class C to prevent ingress of silt where joints open up under seismic loading
 - Install long socket connectors to manholes on PVC-U gravity reticulation to increase the potential to accommodate longitudinal joint movement
 - Improve socket lengths and so joint movement capacity on PVC-U pipes by specifying minimum socket lengths and marking two witness marks (one as a reference mark) through CCC PVC-U material approval

Design Alternatives

1. Providing for Future Events

- “Improved resilience can be provided through increasing the capability of the network to withstand seismic events by allowing for future settlement, by providing a system that will not be as affected by liquefaction or land movement e.g. pressure systems, by adding redundancy into the network, by using more robust materials and by designing to reduce the recovery time involved in repairs or replacement.”

Best practice solutions are suggested as follows:

- Allow, in designing gravity line grades, for liquefaction settlement as determined by the LRI zone and associated settlements table
- Carry out detailed geotechnical investigations of sites to determine the liquefaction potential and therefore likely settlement or lateral spread and subsequent movement
- Apply the guidelines from NTC 33 clauses 32-37, detailing what the geotechnical investigation for pump station sites should address
- Consider alternative depths or wastewater reticulation systems instead of large scale gravity networks serviced by substantial lift pump stations.

2. Differential Movement Risk Areas

- “Network analysis suggests that the water reticulation experienced greater damage rates at the hill/plain interface by comparison to similar reticulation in other areas. This area may require special consideration to ensure there is sufficient ductility in the reticulation and the reticulation performance is still being analysed.”

3. Lateral Spread Risk Areas

- Liquefaction encourages lateral spreading in those areas where the land is sloping or is not confined (e.g. adjacent to rivers). To counter this effect on damage to reticulation it is recommended that:
 - Designs consider ease of repair, e.g. fittings between structures and pipes should be placed above ground
 - Flexibility in the pipes be improved through use of polyethylene and through designing adequate compensatory flexibility in connections to structures etc.

4. Sewer Depths and Grades

- There are a number of ways to reduce the depth of gravity sewers in selected areas and as a

larger scale solution. Recommended solutions include:

- Installing collector sewers over existing deep (over 2.5m) sewers, where depth permits. This is to prevent future repairs on laterals and junctions
- Apply depth restrictions of 3.5m to gravity sewers to prevent possibility of repairs at depth
- Apply depth restrictions of 2.5m for the connection of laterals to gravity sewers to prevent the possibility of repairs to depth.

5. Material Selection

- Ductility of materials within and between pipes and robust connections between pipes and fittings or structures are fundamental to maintaining a functioning network after an earthquake event. Material choices to counter the seismic load on pipes, which can occur in all directions, include:
 - Avoiding brittle piping materials
 - Detailing long socket connectors to manholes on PVC-U gravity reticulation to provide increased longitudinal joint movement.

6. Foundation Treatments

- “Liquefaction substantially reduces the strength of the pipe foundation materials. Foundation treatments designed to counter this include the use of “soft ground” or “raft” foundation options for pipes laid in areas where foundation bearing pressures are less than 50kPa.”

7. Redundant Infrastructure

- Treatment options for large volumes of damaged infrastructure in the ground still require further consideration, however recommended solutions include:
 - “Removal, because these pipes form voids which can undermine the foundations of pavements and adjacent services and can disrupt groundwater flows”
 - “Treatment is dependent on the proximity to all services, the pipe’s position in the road cross-section and the size of the pipe. If grouting, ensure it is continuous along the pipe length. Low strength concrete (3MPa) is preferred to prevent future issues where the pipe may require removal”
 - “Obsolete asbestos cement (AC) pipes should preferably not be left in the ground due to contamination problems”

Summary and Conclusions

Potable Watermains

- “For all pipe materials except PE pipes, there is a clear increase in the affected length (percentage of damage) with increasing liquefaction severity.”
- “For steel (S), asbestos cement (AC) and other material pipes, the percentage of damaged pipes in areas of severe liquefaction was very high, between 15% and 22%.”
- “PVC pipes suffered two to four times less damage than S, AC and other material pipes.”
- “The level of pipe damage in no liquefaction and not-inspected areas are similar, indicating that ground displacements/performance were similar in these areas (with general absence of liquefaction manifestation). This fact together with the findings that the percentage of damage was linked to and increased with liquefaction severity provide an independent verification of the good quality and reliability of the generated liquefaction map.”

Potable Submains

- “GI pipes performed poorly with 17% damaged length in areas of low to moderate liquefaction and 26% damaged pipes in areas of severe liquefaction.”
- “PE pipes suffered, on average, five to six times less damage than GI pipes.”
- “Comparing the damage of watermains and submains, it appears that for each pipe material the damage to the submains was larger than the damage to the mains. It is important to understand what features/details contributed to this outcome. The total damaged length of submains was smaller however because over 80% of the submains were comprised of the well performing PE pipes.”
- “Even though in the simplest form of the analysis the damage is always associated with certain pipe material, the nominally defined “failures” include (and probably are dominated at least for the PE pipes) by failures of particular components (joints, connections, fire hydrant details, crossovers, laterals) rather than pipe failures.
It is critically important therefore to discriminate between different types of failure and carry out a more rigorous second stage analysis, which will help us to identify key weaknesses and also “good design/construction details/characteristics” of the pre-earthquake potable water system.”
- “Having in mind the severity of ground shaking and failures caused by the earthquakes, as well

as the reasonably quick restoration of potable water services throughout the city, one may argue that, by and large, the potable water system performed satisfactorily under the extreme seismic events.”

Wastewater

- “By and large, the performance of the wastewater system was poor and not satisfactory (below desirable level/standard) despite the acknowledgement of the extreme severity of the earthquakes and liquefaction-induced ground failures.”
- “Detailed information on the damage to the wastewater system was still not available because of the extensive damage and very difficult accessibility due to the large embedment depth.”
- “Further studies and analyses of the wastewater network are required and strongly recommended.”

3.5 Impacts of Liquefaction on Pipe Networks in the 2010 – 2011 Christchurch Earthquakes – PBD Issues and Perspectives

(Cubrinovski, M., Hughes, M., McDonald, Y., Henderson, B., McCahon, I., Orense, R., et al. 2012)

This is a summary of a paper presented on to the May 2012 International Conference on Performance-Based Design in Earthquake Geotechnical Engineering, Taormina.

The main points are:

- The wastewater system was hard hit by earthquakes with loss of grade in the gravity pipes, numerous breakages of pipes/joints, and infiltration of huge amounts of liquefied silt into the pipes. Nearly 40% of the network pipes had limited or no service approximately one month after the February earthquake.
- PVC and PE pipes performed very well in the potable water system, suffering several times less damage than other material pipes (i.e. asbestos cement, galvanized iron and steel pipes).
- In both networks, there is a strong correlation of damage to liquefaction severity for all pipe materials (except PE in the potable watermain system).
- Nearly 80% of the damaged watermains were in liquefied areas.

- In comparing damage of watermains and submains, it appears that for each pipe material, submains experienced a higher percentage of damage. The total damaged length of submains was smaller, however, because over 80 percent of the submainss were comprised of well-performing PE pipes.
- It is important to emphasize that even though in these preliminary analyses the damage is always associated with a certain pipe material, the nominally defined ‘failures’ include (and probably are dominated at least for the PE pipes) by failures of particular components (joints, connections, fire hydrant details, crossovers, laterals) rather than actual failures of the material (pipe breaks).
- The paper sets out Christchurch City Council’s performance objectives for recovery of both potable water and wastewater systems based on the observations and experiences of the 2010 – 2011 earthquakes. This criterion may be a useful comparison for other water utilities which have similar risks and can be viewed in Table 3 on page 11.

3.6 Lateral Spreading and Its Impacts in the 2010-2011 Earthquakes

(Cubrinovski, M., Robinson, K., Taylor, M., Hughes, M. & Orense, R. 2012)

This paper appeared in the New Zealand Journal of Geology and Geophysics, September 2012. It summarises the effects of lateral spreading following the 2010-2011 earthquakes. Many valuable photographs, charts and diagrams appear at the end of the paper.

The main points are:

- Lateral spreading caused damage to a large number of bridges, where the results were induced rotational movements of abutments, damage to foundation piles, and subsidence of approaches to bridges. In some cases this caused structural damage.
- The spreading induced lateral displacement of the banks towards the river. This was resisted by the stiff and strong upper structure of the bridges (girders and deck), causing a pinning effect and rotation of the abutments as the foundation piles could not resist the large lateral movement of the foundation soils. Additional stress was imposed on the top of the piles because of the large

abutment rotation which resulted in further damage.

- In cases when the lateral spreading was very large, it was accompanied by slumping of the approaches which produced large vertical offsets between the approaches and the bridge itself.
- Preliminary GIS analyses of the performance of the potable water system show clear link between the damage to the network and occurrence / severity of liquefaction.
- Approximately 80% of the water mains breaks (repairs) occurred in areas affected by liquefaction, and nearly 60% of the damage was in areas of moderate to severe liquefaction where lateral spreading was the key contributing factor to the damage.
- The impacts of lateral spreading were even more pronounced on the wastewater system because its network of pipes is laid at larger depths (2.0-3.5 m), and hence is more susceptible to damage and also more difficult to access for repair/reinstatement.
- The typical types of failure to both water and wastewater networks was the loss of grade, breakage of brittle pipes and the failure of joints or connections (laterals).

3.7 Liquefaction impacts in Residential Areas in the 2010-2011 Christchurch Earthquakes

(Cubrinovski, M., Henderson, D. & Bradley, B. 2012)

This 2012 paper, in part prepared with funding from the Natural Hazards Research Platform, summarizes the characteristics of liquefaction and discusses its impacts on residential houses and buried pipe networks.

The main points are:

- Typical damage to the wastewater network included loss of grade in gravity pipes, breakage of pipes/joints and infiltration of liquefied silt into pipes (often accompanied by depression of carriageways, undulation of road surface and relative movement of manholes), and failure of joints and connections (particularly numerous failures of laterals).
- The potable water system was proven to be much more resilient than the wastewater network.
- Preliminary GIS analyses using the pipe network damage data and liquefaction observation maps show a clear link between the damage to the pipe network and liquefaction severity.
- The GIS analyses also revealed that PE pipes and PVC pipes suffered significantly less damage (three to five times less on average) than AC, steel, GI and other material pipes.
- There is a clear link between the severity of liquefaction and observed damage to the potable water network with nearly 80% of the damaged pipes being in liquefied areas, and 50% in areas of moderate to severe liquefaction.
- The Christchurch experience clearly shows that special consideration should be given to an improved design of the waste water system, which is more vulnerable to liquefaction and more difficult to recover/repair due its large depth of embedment.

3.8 Pipe Performance and Experiences during Seismic Events in New Zealand Over the Last 25 Years

(O'Callaghan, F.W./ Iplex Industries 2012)

This is a summary of a paper delivered to a conference of the American Society of Civil Engineers, August, 2012.

The paper notes that:

- Nothing is earthquake proof – the ground movement happens anyway, particularly in liquefaction and lateral spread zones – anything can, and will, break at the weakest link. No pipeline material survived undamaged in Christchurch where the ground movement exceeded the yield or break limit of the pipe material.
- Pipes must be designed with flexible joints to accommodate movement or deliberately selected “weak” points such as at bridge and structure connections, to manage the location of seismic breakage. Continuously welded pipelines, without designed ability to accommodate compression and expansion movement, or lacking designed “weak” points, performed badly in severe liquefaction and lateral spread zones, and are difficult to repair on a large scale, if the repair system requires heat or electricity.
- Ductile, flexible pipes with rubber ring joints generally performed well in Christchurch.

- Other New Zealand councils should identify and focus limited pipe upgrade budgets in their liquefaction zones first.
 - Real risk (not estimated or perceived risk) for seismic insurance evaluation of pipelines is quite different in non-liquefaction zones (much lower), compared with high liquefaction risk or lateral spread zones (much higher or extreme).
 - There is ample evidence that the extent of pipeline damage is very closely related to liquefaction occurrence.
 - Pipe movement observed in liquefaction and lateral spread zones was consistent with Seismic “P” wave axial movement. The mode of pipe or joint failure in liquefaction and lateral spread zones was closely linked to the angular direction of the pipe asset with the seismic epicentre.
 - Do not use gravity based pipeline designs in liquefaction risk zones – the grades will change and disable the pipe system, regardless of pipe material, with every seismic event.
 - Design to accommodate movement, allow compression (most damaging), expansion, and grade changes, rotation and axial movement, and lateral spread.
 - Use materials and designs which are easy to repair in the future. Ease of pipe repair, in the rain, mud and wet, with low skill installers, without electricity, roads, bridges, is a vital factor.
 - Design to avoid or manage assumed or certain pipe failure sites (fault crossings, liquefaction sites, lateral spread sites, ground displacement areas).
 - A dedicated resource is needed of technically skilled pipeline specialists, to be available to quickly and fully use future opportunities to research first hand information on actual pipe performance in future events.
- the water supply and sewage pipelines, particularly in areas that do not have a high risk of lateral spreading.
- The older, brittle, pipe materials e.g. ceramic (earthenware), cast iron, AC and small diameter concrete pipes have performed poorly in areas affected by liquefaction. Lateral spreading and pipe stream crossings were a cause of failure.
 - Connections to pumping stations must be flexible and fixable.
 - Avoid laying infrastructure (pipes, manholes, pumping stations) in lateral spreading zones. Brittle pipe with rigid joints has the greatest number of failures. Deeper and bigger pipes are less susceptible to earthquake damage.
 - Pipe manufacturing quality may impact performance. Installation affects performance as well – e.g. insertion depths of spigot and socket pipes and angular deflection at joints.
 - Corrosion (cast and ductile iron, AC pipes) and chemical breakdown (PVC, PE) can reduce strength of materials.
 - Consider building weak links that can be easily repaired (indestructible pipe systems are almost impossible to build and are costly).
 - High vulnerability pipes include:
 - Ceramic pipes with mortar joints.
 - Brick and stone barrels generally with lime mortar jointing.
 - Old reinforced concrete pipes with rigid, lead joints.
 - Ceramic pipes with rubber ring joints.
 - Cast iron (CI) pipes with rigid, run-lead joints.
 - Unreinforced concrete pipes with rubber ring joints.
 - Asbestos cement (AC) pipes of \leq DN 150.
 - Old, small diameter reinforced concrete pipes with rubber ring joints.
 - Screwed steel pipes (generally \leq DN 50).
 - Steel pipes with lead joints.
 - CI pipes with rubber ring joints.
 - AC pipes with rubber ring joints, \geq DN 200.
 - Least vulnerable pipes:
 - DI pipes with locking rings e.g. Tyton-Lok.
 - PE 80B or PE 100 pipes with end-load bearing mechanical joints.
 - CLS pipes full strength welded joints.

3.9 Earthquake Damage to Buried Pipelines

(Black, J. 2012)

This summary is from a paper delivered to the INGENIUM Conference in June 2012.

The following are the main points:

- Ductile pipes (e.g. modern PVC-U and others) with rubber ring joints provide an acceptable and cost effective option for most repairs and renewal/replacement works for all but the most critical of

- DI pipes, with seismic joints.
- PE pipes with butt or full strength electro-fusion joints (Pipes of PE 80B & PE 100).
- It is important to learn from pipe failures (e.g. investigate pipe failures as repairs are done).
- A measured approach to priority for repair and replacement of damaged pipes needs to be made, e.g. taking into account the nature and location of the damage and damage to street pavement as well as the existing condition and remaining life of the pipe.

3.10 Christchurch Earthquakes – Impact on Infrastructure & Services

(Christchurch City Council, 2011)

This November 2011 presentation to the Auckland Engineering Lifelines Group summarises a range of Christchurch City Council's infrastructure learnings from the earthquakes.

The main points are:

- In an emergency good information is rarely available. Need to obtain information on the extent of the damage.
- The road transport network is the most vital first response infrastructure. Liquefaction cannot easily be prevented within the road corridor.
- Have emergency service agreements and response plans in place and review them regularly.
- Don't underestimate the value of institutional knowledge.
- Set key priorities with Civil Defence. Think ahead and use all available resources – must be strategic from day 1.
- Communication is critical.
- Analogue phones have the advantage that they are independent of mains power.
- While the Christchurch City Council being prepared helps a little, everyone being prepared can help a lot.
- Plan and model worst case scenarios for major, acute network failures and have alternatives.
- Create a platform to deliver the recovery phase of the work.

3.11 Canterbury Earthquakes – A Contractor's Perspective

(Gibson, T. 2011)

This November 2011 presentation to the Auckland Engineering Lifelines Group summarises City Care's infrastructure learnings from the earthquakes.

The main points are:

- Need a detailed picture of the extent of damage.
- Public health needs particular care and attention (water and sewerage).
- Have an emergency management structure prepared and be well linked into the CDEM EOC.
- Have alternative access to resources such as accommodation and management tools, i.e. computers, phones and maps.
- Develop a planning culture within management to be able to deal with changing in events. Planning must be flexible.
- Look after staff outside of work and ensure that their basic needs are met. Develop networks for staff support and replacement. Maintenance of health and safety standards is challenging.
- Access to the following is most helpful: high pressure blasting trucks, combination sucker trucks, CCTV cameras, pipe welding equipment and pipe bursting equipment.
- Maintaining information technology connections including GIS capabilities, communication links to providers and clients, access to satellite phones, radio phone and other equipment as well as the ability to store data.
- Understand when a fix is not working – i.e. where permanent fixtures were not holding, temporary fixes were quite often the only course of action. It is important to determine this quickly.

3.12 Water Lessons Learnt from the Christchurch Earthquakes

(Free, P. 2011)

This November 2011 presentation to the National Lifelines Forum summarises GHD's water-related learnings arising from the earthquake emergency response.

The presentation covers:

- Careful consideration is needed on the topographical location of settlement areas. Consideration must be given to flooding and liquefaction etc, as these have physiological impact as well as a physical impact. Large emergencies are rarely single-cause events, they involve multiple smaller emergencies clustered around the initial event, e.g. loss of power or fire, localised flooding, civil unrest etc.
- Backup needed for critical assets. Stocks of spare parts, replacement pipe etc, are not needed if robust arrangements with suppliers are in place (although holding some critical long-delivery lead-time items may be useful). Arranging or having access to engineering workshop facilities for running repairs is important. Develop closer ties with neighbouring authorities as they will be most useful contacts in an emergency.
- A good accurate (and accessible) map of information is essential showing what's working, what has been assessed, what is at partial or low service and where there is no service. This type of information needs to be available to decision-makers with regular updates, especially in the early days of an emergency.
- Keep multiple hard copies of key operational plans in different locations. Also duplication equipment should be sourced and available early in an emergency.
- Having a combination of 4WD (and 2WD) vehicles in the fleet is essential. Often commercial decisions are made about the usefulness and need vs cost of 4WD vehicles but they give great flexibility in many types of emergencies.
- Keep priority messages simple. And keep the target goals changing to drive progress. Be careful to not change focus too regularly due to outside influences and if necessary create a separate team to deal with side-line issues, often politically or media driven.
- Pre-agreed repair techniques are useful as they minimise rework at a later date and help with materials supply. They also give comfort to works staff and supervisors as they can get on with the job and not have to worry about misalignment with BAU repair techniques and procedures compared to emergency repairs.
- Environment standards and some H&S normal standards may not be applicable during an emergency as they are designed for a totally different environment.
- Valving control practices should be in place. This should include easy to understand position

marking techniques to ensure workers are safe from accident when working on mains, pumps etc.

- Emergency water sources need to be available quickly. Need a lot of low volume distribution points for suburban areas that do not have mains water. However these sources should be made as safe as possible as there is huge reliance on these key facilities.
- Identify and empower those who can make quick decisions. And allow for new management structures and personal to evolve, all people (for various reasons) aren't necessarily able to lead teams in an emergency compared to normal times.
- Availability of temporary / portable disinfection plants are essential. In an emergency extra care is required to ensure water is safe.

Outside help (staff resources) from other areas is useful, as these people don't have the family issues that local staff will have and will be able to work longer hours due to lack of family commitments. Also emergencies require a much large number of people. Doubling (or more) of normal staff numbers may be necessary depending on the type and size of emergency.

- Make time to help/discuss or give time to team members who are struggling, sooner or later even the toughest people struggle in a large emergency. When all else fails, keep calm and carry on.

3.13 WDC Earthquake Lessons Learned Workshop Outputs

(Waimakariri District Council, 2011)

Waimakariri District Council (WDC) held a series of internal workshops to gather lessons from the September 2010 earthquake. Sessions focussed on what went well and areas of improvement during the response phase, which was defined as the first 2-4 weeks after the event. The response from the February 2011 earthquake (which had a lesser impact in WDC's area) provided a good comparison of suitable arrangements for less significant but more frequent events. The majority of the lessons below were extracted directly from the workshop write-up.

Water Learnings

- No repairs required on PE rider mains. PE should

be used for rider mains unless there is a good reason not to.

- PVC was easier to lay in short lengths, particularly where there are many other services in the ground.
- Performance of PVC laterals was OK, not many repairs required.
- There was significant benefit of having headworks on either side of the river. The river crossing is now valved resulting in increased resilience.
- AC pipes did not perform well but no material would have withstood the earthquake.
- PVC failures observed were only at joints. Recommend use of restrained joints or extended push fit joints on critical mains.
- PVC in Pines Kairaki may have performed better if it was D class. No D class PVC was seen to pull apart however ground movement in Pines and Kairaki could have been the differentiating factor.
- Eliminate the use of glued fittings in high seismic risk and liquefaction areas.
- PE should be used for all riders and where possible directionality drilled. This may be difficult where there are a number of other services and it may be easier to lay short lengths of PVC.
- Critical mains should be more uniform in diameter to ensure more resilience. Lead times for delivery of unusual diameter mains were too long. It is proposed that all critical mains are laid in PE.
- PVC riders were less resilient. Repairs on small diameter PVC were easier to perform than on large diameter PVC.
- Experience has shown that PE can fail due to weld defects. Therefore performance is dependent on both the joints and the quality of the welds. Where welding repairs are necessary, the right conditions must exist such as dry uncontaminated surfaces.
- PE will stretch and deform under earthquake stress. The longevity of the deformed PE is unknown and while service may continue, the damage may not be detected for some time.
- When selecting what pipe diameter to use, ensure there are sufficient resources available to maintain and repair the pipe in the result of a disaster.
- There were occurrences where unoccupied properties did not have water reinstated, but when the owners returned they wanted water.

Further consideration needs to be given to the management of water supply to unoccupied properties.

- While water was restored using patching, overland and relay methods, there was a view that the overlanding method could have been utilised much earlier and would have enabled quicker restoration times.
- Main diameter pipes need to be larger in size than their rider main to assist in providing a quicker restoration of service.
- Water valves need to be located on the main and not just on the rider. Buried valves are of no benefit. Valves in the road are a potential health and safety issue although traffic volumes in the district were generally low.

Wastewater Learnings

- Sand as backfill for sewer works did not perform well, a heavier more granular material should be used.
- Asking residents not to use toilets made CCTV work easier. It would have been beneficial to prolong the period of no toilet use.
- Need to develop and have a plan to co-ordinate mains cleaning to reduce the number of sites revisited. A lot of mains needed to be re-cleaned when laterals come back into service as more silt was flushed into them.
- Early work is necessary after an event to prevent silt from broken laterals (at significantly damaged properties) entering the system. It was difficult to determine what properties would not be reoccupied.
- Marking lateral locations with Council pegs would have helped identify them.
- There was a problem using penetrating radar as it was not accurate enough. The merits of using other unproven techniques during an earthquake response therefore needs to be seriously considered.
- It is necessary to ensure that there are hard copies of plans available as back-ups. Services had moved due to ground shift and were not always the same location as shown on the plan.
- Having access to laterals and mains on the road and not in back gardens makes access easier and allows sucker trucks to be utilised.
- Sending manhole lifting crews through first and marking/spraying the lids of manholes that require cleaning, worked well.

Agreements

- Having the Council pay for materials and delivering them direct to contractors worked very well.
- Having water staff make sure the contractors knew what needed to be done worked very well. It was felt that one Water Unit staff member to 3 gangs was a good ratio.
- Water Unit management of contractors worked really well, it meant that staff with local knowledge could remain fresher and continue to be involved for longer.
- Outside contractors managed themselves and the response could not have been achieved without their contribution.
- Difficult to secure good resource, not enough staff and too much work. On the other hand, Council had more offers of help than they could take up but it was difficult to determine which resources were capable and competent. Would have been beneficial to have a Resource Manager to control and manage the quality of contractors / gangs.
- Needed to know the cost of emergency works to enable better asset management decisions to be made. Step back to assess the pros and cons of different options (including total cost) before proceeding.
- Maintain a list of equipment held by each potential supplier. This would allow access to quicker sourcing and relevant information to determine feasibility of certain jobs and the costs involved.
- There was difficulty in providing toilets for the disabled and elderly. Wooden platforms were produced to be used with portapotties. There needs to be documented arrangements for sourcing and distribution alternative toilet facilities.
- Ensure a succession plan is in place for roles that are essential during an event, such as communications officer who was absent from WDC when the event occurred.
- Door knocking by contractors worked well but was time consuming. It would have been better to have a dedicated council staff member undertaking this role.
- The water unit need a dedicated emergency radio channel separate from Civil Defence. The channel was shared by all council units and some contractors. It is recommended to have a dedicated Civil Defence spectrum and then separate channels for each function.
- Need to ensure that all council and contractor vehicles have radios. Those using the radios need to be provided with adequate training.
- The utility managers had too many tasks to do at certain times but team leaders were not provided with adequate scope or authority to lighten the load. Potentially zone managers could lighten the load on key individuals.
- Ensure only one point of entry exists for service requests for the call center, EOC and Water Unit combined. Two parallel systems were in play resulting in no central point for faults / breaks.
- Public phone calls should not be transferred to EOC for specific answers – this ties up vital phone lines and is too time consuming. A more robust call handling process would have helped to resolve these issues. Need to involve Customer Services in the development of the job management process.
- It was useful to take down the public's details and then call them back later to ensure their issue had been resolved. Software may be able to assist further with this.

Communication

- Leaflet deliveries informing the public of what was taking place worked well.
- Ad hoc break times were very useful in sharing informal ideas between parties and allowing crews to share and pick up lessons learnt – meant certain mistakes were not repeated.
- Aerial reconnaissance worked well, helped to speed up communicate and develop the bigger picture. This reduced the amount of rumours and misinformation concerning the severity of damage.
- Need to ensure strong emergency relationships with other utilities in the area such as electricity.
- Better early communication is needed between the Water Unit and Roading Manager. It was felt roads needed to be closed earlier in the response to protect the health and safety of workers and this was not responded to quickly enough.
- Improved communication was needed with the Planning and Intelligence team in the CDEM EOC.
- The EOC structure was not well understood across the Council, there is a need to provide better training and information to all personnel involved (regarding both the structure and the processes inside).
- Field managers should be assigned one EOC contact point to limit queries and time required.

The contact point needs to be a role, not a person. This is to ensure effective handover within the EOC.

Staff Arrangements

- Contractors liked returning to the hub for food. If food and break times weren't organised many contractors wouldn't have stopped for food, which is a health and safety issue.
- Providing contractors with geographical work areas worked well, not using existing service request system meant that contractors could be given dedicated areas and didn't have to move around between jobs. Contractors got satisfaction in seeing one specific area improve.
- Providing contractors with diversity in work was important to maintain morale. Worked really well with the sewer gangs where balance of the good and bad jobs was given.
- Having a full set of plans was a real benefit. Contractors were generally happy with the quality of the Plans (A3). Being able to view the plans electronically was also very useful. Paper plans need to be laminated, with copies stored outside HQ.
- Use of GIS in the EOC received good feedback. GIS used as an electronic pin board, plotting data from phone calls, red and green properties. It was very useful to have access to recent aerials (within the last year).
- WDC recommends moving towards a web-based GIS viewer that will allow all staff to access base network maps and print them.
- Ensure any software used in mapping is not overly specialised and there is a pool of talent to call on for assistance to operate the software.
- Not all contractors could break at the specified time. Would have been good to ensure hot food is available at all times.
- Time consuming for staff to remove work clothing so they could come in for food, drive through/ soup kitchen concept. Runners were used to take food out to gangs working further from the hub.
- Contractors had difficulty obtaining fuel. Large queues at fuel stations. Dedicated lanes or stickers for priority service would have been beneficial. It was found there were very short queues at stations where petrol had run out but diesel still existed.
- Contractors had to leave jobs to get fuel when they could, there would be benefit in a fuel tanker supplying contractors.

- Universal fuel cards would have added resilience as not reliant on one supplier.
- Would have been beneficial to have a small number of gangs attending to reactive jobs, leaving the majority to focus on dedicated areas.
- Use of GIS in the EOC could have been streamlined, linking incoming asset information with existing attribute data, e.g. rating database. It would have been good to be able to interrogate attribute data particularly the valuation number as this is the only truly individual attribute per property. Creating basemaps pre-event would have helped.
- GPS units should be tested pre-event to ensure they are accurate. Training is required on how to use these devices properly.
- Review number of vehicles likely to be needed. Consider emergency hire agreement with rental company to provide suitable vehicles during an emergency (4x4 and trucks).
- Ensure planning of spare computers and establishment of pre-agreements are in place so that suitable supply is on hand.
- Keep better records of broken assets (photos etc) to provide an audit trail for insurance purposes. The photo bank for water was pretty good, less reliable for wastewater and storm water, needed particularly for rising mains.

3.14 Impact and Recovery of the Kaiapoi Water Supply Network following the September 4th 2010 Darfield Earthquake

(Knight, S., Giovinazzi, S. & Liu, M. 2012)

This is a summary of a paper presented to the 15th World Conference on Earthquake Engineering 2012, Lisbon.

The main points are:

- A back-up diesel generator was essential in getting the main headworks operational within six hours of the of the September 4th earthquake. The headworks enabled potable water to be circulated into the Kaiapoi township pipe network and for the process of finding breakages to begin.
- While damage to the water pipe network was spread throughout Kaiapoi, a significantly higher number of repairs were required near the Kaipaoi River.

- Asbestos Cement (AC) pipes required a comparatively larger number of repairs in areas where no land deformation was recorded, compared to PVC and PE pipes. The same comparison can be found in areas of minor or severe liquefaction relative to the number of AC pipes in those areas.
- The repair rate for AC pipes was the highest at 3.36 repairs per kilometre.
- PVC pipes were more exposed to minor liquefaction comparative to major or severe liquefaction, but the majority of repairs were required in areas that experienced moderate to major liquefaction. This could suggest general good performance of PVC pipes when subjected to minor land deformation, with performance becoming more significantly affected in areas where land deformation was greater.
- The repair rate for PVC was substantially better than AC pipes at 0.59 repairs per kilometre.
- PE pipes had similar exposure to minor liquefaction but required only one repair in these areas, and therefore relatively, showed the best performance in Kaiapoi.
- Information regarding which repairs were being made and what new breakages were being discovered was updated daily. This enabled the plan to be constantly updated, helping utility managers to understand the overall picture of the restoration, set intervention priorities and make decisions regarding where resources should be directed.
- While managing the emergency, the local Council did not have an established procedure and/or available tool for assessing and quantifying repair needs. Therefore it is recommended that improvements be made in enabling Councils to make the following assessments during a crisis:
 - The number of customers without water
 - The number of customers with water reconnected after each set of repairs
 - How different repair strategies could have speed up the functionality restoration process.

3.15 Damage to Potable Water Reservoirs in the Darfield Earthquake

(Davey, R.A. 2010)

This is a summary of a New Zealand Society for Earthquake Engineering paper on water reservoir

performance following the September 2010 earthquake.

The main points are:

- Inspections of 54 water reservoirs were undertaken. These were concrete, steel and timber tanks of which five had collapsed and four were severely damaged.

Concrete

- Most were robustly constructed with attention to seismic detailing, only two had serious damage.
- One was damaged at the junction of the roof and the wall because the concrete nib at the top of the wall could not withstand the inertia load applied by the roof.
- The other concrete tank suffered from a partial collapse of the roof due to the buoyancy forces from the earthquake-generated convection wave. This caused the slabs to be lifted off supporting walls and to be fractured when they impacted down again.
- This highlights the importance of avoiding or allowing for uplift pressures that are caused by such convection waves. This lesson is one that can be investigated further as to why these practices were not implemented prior to the earthquake and how improvements could have reduced the effect on this concrete tank.

Steel

- Six were inspected, four failed at their anchor bolts.
- The two that didn't fail were smaller and had a greater number of large anchor bolts.
- The failures raise a question regarding the criteria used for the design of the anchor bolts on these tanks. Further investigation is needed to confirm this lesson.

Timber

- Four were inspected; one was functional, two were damaged with leaking present and the fourth collapsed. Timber tanks rely on a base-isolation response which did occur in the earthquake, however the wall displacements caused liners to rupture and reservoirs to leak.
- Need to examine how these were built and whether there is a significant design feature present which made them fail.

3.16 Christchurch City Lifelines – Performance of Concrete Potable Water Reservoirs in the February 2011 Christchurch Earthquake

(Billings, I., & Charman, N. 2011)

This is a summary of a 2012 New Zealand Society for Earthquake Engineering conference paper on concrete water reservoir performance following the February 2011 earthquake.

The following are the main points:

- Of 43 Christchurch City Council reservoirs, two were declared inoperable (Hunstbury No.1 and McCormacks Bay No.2) in the February earthquake. A number of others were also damaged requiring repair works (the extent of damage was minor in many cases). The City lost 40% of its potable water supply following the earthquake.
- Reinstatement works, varying from minor crack injection and patch repair through to reconstruction and retrofit, were developed appropriate to the extent of damage. CCC prioritised reservoir repair to maximise water supply available for the 2011-2012 summer demand and this required, in some instances, staging and deferring of reinstatement works.
- It is estimated that some reservoirs may have experienced much higher shaking than originally designed for.
- Damage to Hunstbury No.1 reservoir is believed to have been caused by movement in an underlying shear zone. This reservoir has now been replaced by two smaller tanks, one either side of the estimated extent of the shear zone.
- Particular issues are noted in the paper:
 - Roof-to-wall and wall-to-base/foundation connection vulnerabilities have been identified. Roof-to-wall dowel connections performed poorly
 - Leakage through wall construction joints – double protection system for water-tightness is recommended
 - A potential deficiency in resistance to sliding has been identified
 - Insufficient freeboard to roofs identified during seismic analyses of some reservoirs
 - Avoid joints in floor slabs. Interconnected walls, foundations and continuous internal

base-slabs increase overall robustness and reservoir performance

- Thin walls with single layer reinforcing are not robust
- Foundation competency is important
- It is likely that a number of reservoirs throughout New Zealand have similar roof-to-wall and wall-to-base vulnerabilities.
- Repair and retrofit requirements for all reservoirs are noted in the papers.

3.17 Seismic Performance of Christchurch Wastewater Treatment Plant Oxidation Bunds

(Christison, M., Young, R., & Gibson, M., 2012)

This summary is from a paper delivered to the INGENIUM Conference in June 2012.

The paper describes the geotechnical investigations, observations and seismic assessment of the Wastewater Treatment Plant oxidation bunds. It outlines the repair methodologies adopted and likely performance in further seismic events.

- A risk based assessment of damage to the bunds was carried out, taking into consideration the risks of overtopping of the bund crest, piping instability and deterioration of pipework and breach of the bund. Mitigation measures were then developed for different bund sections to yield more homogeneous and enhanced resistance to earthquakes up to the proposed design level.
- The preferred mitigation treatments included vibro-compaction, mechanically stabilised earth and compacted fill. It was recognised that following a design or stronger earthquake, the bunds may deform, although breach of the bunds should not occur. Such an approach balances the functional requirements of the ponds with budget and other project constraints.
- To mitigate the risk of overtopping between ponds, approximately 400m of sheet piling was installed through the worst sections to prevent further damage in subsequent events.
- There was damage to the piped connections between the ponds, leading to a reduced capability to control flows through the ponds, which under extreme circumstances this has the potential for overtopping of the bunds.

- Discharge of oxidation pond effluent over the bund crest occurred (due to subsidence to crest level and/or excessive lateral spreading) resulting in rapid localised erosion.
- During the repair and redesign phase it was recognized that all unnecessary penetrations (old disused buried pipes) through bunds should be removed to mitigate the risk of pipe failure.
- Ensure any new or existing pipes are enhanced or designed to accommodate potential bund movement.
- For the more intermediate / high risk areas vibro-compaction with geogrids were adopted
- During construction there is an elevated risk of bund breach, especially if significant.

4 TRANSPORTATION

4.1 NZTA Highways – Christchurch Earthquakes

(Stratton, B. 2011)

This November 2011 presentation to the Auckland Engineering Lifelines Group summarises NZTA's learnings from the earthquakes.

The main points are:

- The primary source of damage to bridges in Christchurch was liquefaction-induced subsidence and lateral spreading.
- Seismic retrofit undertaken prevented more critical damage. Seventeen bridges had been retrofitted at a cost of \$2 million.
- NZTA's previous bridge screening program assisted in identifying which inspections were a priority. Key bridges inspected within 5 hours. Forty-five bridges were inspected over 6 days.
- Unstable rock on Port Hills affected transport routes. Netting deployed from helicopters was useful in securing unstable rocks above critical roads. Where site access was possible, fences were used to capture falling rocks. Shipping containers were also used.
- Reliable communication was vitally important to the recovery operations.
- Current design standards for structures seem to be appropriate and there are no current plans to deviate from these standards as a result of the Christchurch earthquakes.
- There needs to be a coordinated approach when reinstating utilities as roading often forms the top layer.
- After an earthquake traffic patterns may change. Constant monitoring is required to ensure that the roading system is as efficient as possible.

4.2 Performance of Highway Structures during the Darfield and Christchurch Earthquakes of 4 September 2010 and 22 February 2011

(Wood, J. H., Chapman, H. E., & Brabhakaran, P. 2010)

This is a summary of a report by Opus to the New Zealand Transport Agency, February 2012.

The main points are:

- The authors were asked by the New Zealand Transport Agency to visit bridges in the area affected by the earthquakes to identify how the bridges had been impacted. Twenty-seven bridges were inspected and simple static analyses were carried out. Statistic analyses were carried out to assess the strength and performance of the critical components of each of the bridges. The report contains considerable, bridge-specific, performance information.
- Liquefaction and lateral spreading were the principal causes of damage to bridges. Bridges with abutments in liquefaction-prone soils and with slender piles were particularly vulnerable.
- Soil/structure interaction is likely to have dissipated energy.
- It seems certain that the retrofitted Chaney's Road, Port Hills Road and Hortane Valley Overpass bridges benefitted from the linkage bars and shear keys that were installed between 2003 and 2004.
- There are no indications that current design standards need to be revised except for reinforcing the importance of considering liquefaction and lateral spreading.
- Quality detailing and maintenance are critical to bridge performance.
- Consideration needs to be given to providing robust inter-span linkages on some bridges.
- Detailed monitoring and investigation into the bridges to detect existing and on-going damage would be beneficial.

4.3 February 22nd 2011 Earthquake State Highway Bridges Preliminary Condition Report, Regions 11&12 – Christchurch

(Opus New Zealand. 2012)

This is a summary of a preliminary report on bridge condition by Opus to the New Zealand Transport Agency, February 2012.

The main points are:

- Contractors commenced drive-over inspections of the State Highway network (in accordance with pre-arranged contingency plan) immediately after the earthquake.
- Most of the damage was along SH 74.
- Cell phone reception was intermittent in the immediate post-earthquake period. Most of the information was conveyed via radio.

Three bridges were identified for closure or restricted use:

Anzac Drive Bridge

- The bridge sustained considerable damage. There was significant rotation of the abutments and minor rotation of the piers due to the lateral spreading of the approaches. Capping / spalling of the pier capping beams and pier columns was also observed.

Horotane Valley Overpasses

- Differential settlement of the twin structures that form the substructure was observed. Both structures are supported by pad-footings.

SH73 Heathcote River (Opawa) Bridge

- The extent of damage was not clear in this preliminary review. Speed restriction and monitoring were recommended.
- Bridges were also identified for further investigation and analysis:
 - SH1S – Chaney's Road Overpass: Liquefaction could result in possible displacement and tilting of the piers
 - SH74 – Styx Railway Overbridge No. 1: Shear failure of pier columns
 - SH74 – Heathcote River Bridge: Pier column base plastic hinging/shear failure
 - SH74 – Railway Overbridge: Pier base and top plastic hinging/shear failure

- SH74 – Port Hills Road Underpass 1 & 2: Pier base/footing plastic hinging/shear failure. Excavation to top of selected pier bases will be required
- SH74 – Horotane Valley Overpass 1 & 2: Pier base/footing plastic hinging/shear failure. Excavation to top of selected pier bases will be required
- SH74 – Tunnel Admin Bridge. Unseating of spans/shear failure of pier columns.

4.4 Performance of Bridges During the 2010 Darfield Earthquake

(Wotherspoon, L. M., Palermo, A., Heux, M. L., Brunea, M., & Anagnostopoulou, M., 2012)

This summarises a paper that appeared in Bridge Maintenance, Safety Management, Resilience and Sustainability, Biondini & Frangopol (Eds), 2012.

The main points are:

- "Highway bridges generally performed well, with only one case of closure for more than a day where the approach subsided and cracked"
- Pedestrian bridges suffered higher rates of severe structural damage due to their lower design requirements. The lateral spreading close to riverbanks caused much of the damage, resulting in replacement rather than repairs.
- Bridges near the epicentre suffered no damage at locations where no liquefaction was observed.
- The majority of damage took place near the coast where the water table is higher and the soil is more susceptible to liquefaction. All of the pedestrian bridges that were damaged were in this area.
- A short unreinforced masonry bridge failed due to large longitudinal compression force from the spreading of the river banks. As it was unable to resist the pressures from the riverbanks, the arch failed in a three hinge mechanism.
- Both approaches to the Bridge St Bridge located in South Brighton, a three span superstructure constructed from precast concrete I-beams with elastomeric bearing and single column bents with hammerhead bent caps, suffered from severe lateral spreading forcing the bottom of the abutment to back-rotate 5 degrees towards the midstream. Despite this, much of the rotation was accommodated by the elastomeric bearing pad, which deformed to a stream of approximately

30%, resulting in very little rotation to the superstructure and very minor damage (only damage was at the south end expansion joint). The pier columns did also exhibit flexural cracking just below the low tide mark, which does not indicate any severe damage but not provide an opportunity for erosion during high tide.

- It would appear NZTA retrofit programme since *Risks and Realities* has been very successful. One of the first steps was to install inter-span linkages and shear keys to prevent unseating. These brackets worked well on the Port Hills overpass on SH 74 and Horotane Valley overpass, 150m from the Port Hills Bridge.
- One of the key Christchurch lifeline bridges on Ferrymead Road was expected to suffer from liquefaction and lateral spreading after September, but the new retrofitted abutments accommodated the lateral spreading and the bridge performed well.

4.5 Overview of Bridge Performance during the 2011 Christchurch Earthquake

(Palermo, A., Kivell, A., Wotherspoon, L., Hogan, L., Yashinsky, M., Bruneau, M., et al. 2012)

This summarises a paper that appeared in Bridge Maintenance, Safety Management, Resilience and Sustainability, Biondini & Frangopol (Eds), 2012.

The main points are:

- Monolithic construction and axial strength of older designed bridges meant that they were able to resist axial demands placed on them.

Antigua Street Footbridge

- Cross bracing members on the Antigua Street footbridge failed due to the hogging used.
- The shear failure of the concrete wingwalls caused the supports to the timber footbridge beams to fail. These supports had very little anchorage into the concrete wingwalls and would not have required much momentum to fail.

Bridge of Remembrance

- Damage was due to settlement of the approach fill, lateral spreading soil pressures resulting in deflection and rotation of the wingwalls and possibly the abutments.

Moorhouse Overbridge

- Insertion of steel rod linkages in the deck at the expansion joint at only one side of the bridge reduced irregularity in the structure's transverse response.
- This structure also had widely space transverse reinforcement, making it susceptible to shear failure.

Ferrymead Bridge

- The bridge sustained damage due to lateral spreading.

Bridge Street Bridge

- The flow of soil (from liquefaction) against the wingwall, abutment and through the piles resulted in abutment back-rotation due to the restraint provided at the top of the abutments by the superstructure.
- The crack patterns observed on the piles indicate that the piles subjected to bi-directional bending during the earthquake due to the rotation of the abutments and the transverse translation.

Gayhurst Bridge

- Lateral spreading exerted a lateral force on the pier base, causing a large moment at the stiff pier deck interface, inducing cracking of the pier.

Pages Road Bridge

- Because of the bridge's robust design, the overall performance of the bridge was good.

In Summary

- Few state highway bridges were severely damaged during either the Darfield or Christchurch events. This is because of the recent seismic retrofit programme which aimed to reduce the seismic risk. Of the more successful of these was the installation of tie-rods and steel brackets acting as the transverse shear key between pier to deck and deck to abutments.
- Integral cast in place bridge method appeared to work well on both the Port Hills Overbridge and the Horotane Overbridge.
- On these bridges 60% of the bolts that attached the soffit of the precast concrete beams to the abutment shear extension had sheared off. If these pans had not been tied together and the seats not extended it is quite likely the spans would have collapsed.
- Pipes were damaged due to different settlements between the bridges and the surrounding soil. This indicated the pipe connections were not appropriately designed to accommodate deck to pipe or abutment to pipe relative displacements.

4.6 Lateral Spreading Interaction with Bridges during the Canterbury Earthquakes

(Camnasio, E., Heux, M. L., Palermo, A., & Wotherspoon, L. 2012)

This summarises a paper that appeared in Bridge Maintenance, Safety Management, Resilience and Sustainability, Biondini & Frangopol (Eds), 2012.

- The paper comments on the effects that lateral spreading can have on bridges in terms of abutment rotation and plastic hinging of the piles. Two significant case studies relating to Pages Road Bridge and ANZAC Drive Bridge are included, and a further case study relating to the Dallington Pedestrian Bridge is presented as an example of the global performance of a bridge subjected to lateral spreading.
- The paper concludes that the compressive force caused by the soil spreading and settlement placed a high displacement demand at the abutments and a large force demand at deck level, often leading to rotation of the abutments and pile foundation systems and to development of plastic hinges at pier deck connection.
- Services and third party structures near bridges were also damaged, with the ground at the approaches shifting downwards and leaving bridges raised above the surroundings.
- In order to model numerically the interaction between the soil and the structure during liquefaction, a three-layer soil model has been adopted. Displacement push-over analyses were carried out on pile-abutment sub-assemblies and on a global bridge structure, chosen among the damaged bridges in Christchurch. The results provided a better understanding of the damage that likely occurred to the piles below the ground surface at Pages Road and ANZAC Drive Bridges.
- The analyses showed that plastic hinging usually develops at the interfaces between liquefied and non-liquefied layers or at pile-abutment connection.
- A global analysis of the Dallington Pedestrian Bridge was undertaken. The analysis compared well with the observations made at the site and led to the provision of recommendations for the selection of certain parameters required when determining the lateral force that acts on a bridge due to lateral spreading.

4.7 Seismic Performance of Concrete Bridges during Canterbury Earthquakes

(Palermo, A., Wotherspoon, L., Hogan, L., Heux, M. L., & Camnasio, E. 2011)

This is a summary of a paper that appeared in Structural Concrete, April 2011.

The main points are:

- Large demands were placed on pile foundations of bridges
- Settlement and lateral spreading of approaches caused serviceability and operation issues.
- Monolithic structures are stiff and sturdy and performed well.
- No significant damage occurred at retrofitted bridges where tie rods and steel brackets acting as the transverse shear keys at the pier–deck and deck–abutment junctions respectively had been installed.
- Pipe connections were not appropriately designed to accommodate deck-to-pipe, or abutment-to-pipe relative displacements.
- The main issues arose with stiff pipes, such as sewage and water pipes, as they are fully fixed to the deck and usually run through the abutments. On the other hand, the flexibility of power and/or telephone cables was able to accommodate larger displacement demands.

4.8 Preliminary Findings on Performance of Bridges in the 2010 Darfield Earthquake

(Palermo, A., Heux, M. L., Bruneau, M., Anagnostopoulou, M., Wotherspoon, L., & Hogan, L. 2010)

This is a summary of a paper from the December 2010 Bulletin of the New Zealand Society for Earthquake Engineering, Vol 43, No. 4.

The main points are:

- Bridges performed well overall because:
 - They have small to moderate length spans; such spans are recognised to generally exhibit a more sturdy seismic response due largely to their symmetry and limited reactive mass.

- Bridges were generally designed to resist forces substantially larger than the demands imparted by this particular earthquake.
- Pedestrian bridges were affected because they could not resist the high demands induced by lateral spreading of the riverbanks due to soil liquefaction.
- Fourteen of the fifteen bridges that were damaged were in liquefaction affected areas.
- Lateral spreading is the primary action on bridges leading to damage.
- Bearing damage: a different damage type was the deformation of rubber isolation bearing pads due to large lateral movement between the deck and the abutment/pier, e.g. South Brighton Bridge.
- External piers on the flood zone suffered more cracks than those in the current normal river flow. This is caused by the river scouring increasing the height and therefore reducing the stiffness of the central piers, inducing more load on the shorter and stiffer external piers.
- The current design of abutments reduced failure significantly. Those that failed were built under the old design codes. In lateral spreading banks abutments are to be made with a shallow beam with a small number of deep piles. Those that failed had deep abutments or closely-spaced abutment piles.
- Many new bridges are built with tie-rods between the deck and the abutment. In two cases these failed significantly. The first was due to the tension activated response on the bridge that caused the coupling beam to experience significant concrete spalling. In this case the tie rods were fully activated. In the second instance the tie rods were activated by the longitudinal push action of the soil. This caused a five degree rotation of the abutment and a gap to form between the tie-rod bearing plate and the coupling beam.
- Seven out of eight road bridges were closed due to damage. This was due to lateral spreading which caused the slope to move across and downwards towards the river.
- In some cases the bridge approach spans partially or totally failed. There were examples where the liquefaction of the site surrounding the bridge settled by a few inches.
- Global lateral torsional buckling, plastic hinging at mid-span, longitudinal rocking of towers (and consequential opening-up of existing hinges that consisted of in-contact horizontal wood splices) and plastic hinging near abutments all occurred on pedestrian bridges because of lateral spreading. The horizontal inward movement of riverbanks induced an additional and unexpected longitudinal compressive force through the superstructure, resulting in the above events.
- Pedestrian bridges that were near collapse did not have any form of lateral isolation between the superstructure and the abutments / piers, resulting in major damage between these and the bridge deck.
- Significant lateral spreading occurred on two pedestrian bridges damaging the abutments. Of all the pedestrian bridges these were the only two with a concrete main superstructure element.
- Porritt Park pedestrian bridge experienced large rotation and translation on the south abutment. This abutment sits on six small piles and it is likely that these piles did not extend very deep. As such, they provided minimal lateral stiffness to the system and exacerbated the problem through increasing the surface area the soil wedge interacted with.
- When the riverbanks suffered from lateral spreading the bridge structure itself acted as a prop across the river. This compressive strut in effect provided resistance to lateral spreading and altered the soil cracking pattern. In some cases the longitudinal compressive force transferring through the bridge was greater than the axial capacity of the deck or other structural components and lead to failure of the bridge structures.
- The effect of the above on the soil was that the spreading of the slope around the abutment lead to soil gapping from differential movement, passive soil wedge failure, and large cracks forming on the approach running parallel to the longitudinal bridge axis.
- No bridge that was retrofitted under the Transfund NZ seismic retrofitting program was structurally damaged.
- Retrofitting was carried out on the Dallington pedestrian bridge by Orion as it carried a cable across the Avon River. Raked wing piles were placed on the abutment and driven down into the stronger soil. Retrofitting was also carried out on the approach to the bridge to reduce the level of deformation that the 66kV cables would be placed under during an earthquake.

4.9 Lessons Learnt from 2011 Christchurch Earthquakes: Analysis and Assessment of Bridges

(Palermo, A., Wotherspoon, L., Wood, J., Chapman, H., Scott, A., Hogan, L., et al. 2011)

This is a summary of a paper from the December 2011 Bulletin of the New Zealand Society for Earthquake Engineering, Vol 44, No. 4.

The main points are:

- Pipelines crossing bridges were damaged predominantly where there was soil-bridge interaction in areas of lateral spreading. Pipe connections were not appropriately designed to accommodate deck-to-pipe, or abutment-to-pipe relative displacements. Design guidelines for abutment/pile liquefaction/lateral spreading should be more widely implemented in order to reduce this type of damage.
- The monolithic construction and axial strength of bridges meant older designs were able to resist the axial demands placed on the structure due to lateral spreading, even though they were not specifically designed for these loads.
- Even modest structures (like the Dallington pedestrian bridge) can have strategic importance if they carry lifeline utility services, therefore consideration must be given to the priority of these structures and how they may be designed appropriately.
- There was extensive damage to services at bridge abutments where stiff service assets existed (e.g. like wastewater pipes). Flexible services like telecommunications were less susceptible (but still sustained damage in some cases).
- Broken pipelines at bridges caused secondary damage (e.g. discharging raw sewage into waterways).
- Bridge damage caused significant traffic disruption; therefore emergency management plans must include contingencies for these scenarios.
- Previous works to seismically strengthen bridges had been largely successful.
- The seismic strengthening work that started in 2000 was effective in reducing the scale of the damage. At the time of the earthquakes strengthening had been completed on seven bridges.

4.10 Observed and Predicted Bridge Damage Following the Recent Canterbury Earthquakes: Toward the Calibration and Refinement of Damage and Loss Estimation Tools

(Brando, M., Lin, S. L., Giovinazzi, S., & Palermo, A. 2012)

This summarises a paper that appeared in Bridge Maintenance, Safety Management, Resilience and Sustainability, Biondini & Frangopol (Eds), 2012.

The main points are:

- “In spite of the expected damage threshold level being much lower than the estimated bridge response accelerations of the earthquakes, only a few bridges suffered significant visible structural damage as a result of ground shaking.”
- As a result of the damage sustained to bridges throughout Christchurch there was significant economic loss and social impacts which occurred as a result of temporary or medium term closures. Given the size of the event the performance of the bridges was satisfactory in terms of the magnitude of the damage sustained, but this must be weighed against the loss sustained in the community. This is where the use of tools such as earthquake loss estimation can be effectively used in the emergency response and planning.
- As a result of lessons learnt from the Canterbury earthquakes, it is essential that the use of available ELE tools and platforms (such as RiskScape Platform in NZ and MAEviz in the US) become part of normal practice for mitigating and managing earthquake risk.
- “The preliminary study of the loss assessment on Christchurch bridges using the 22nd February 2011 Christchurch earthquake scenario, confirms the viability of existing ELE components and procedures to be implemented in New Zealand bridge infrastructure”

4.11 Performance of Bridges in Liquefied Deposits during the 2010-2011 Christchurch (New Zealand) Earthquakes

(Cubrinovski, M., Haskell, J., Winkley, A., Robinson, K., & Wotherspoon, L. 2013)

This summarises a paper that appeared in the ASCE Journal of Performance of Constructed Facilities, Special Issue 2013.

The main points are:

- Short span bridges on pile foundations have very stiff superstructure (deck) which led to a characteristic deformation mechanism for all bridges involving lateral spreading – deck pinning – abutment back rotation with consequent damage to the abutment piles and slumping of the approaches.
- Despite experiencing higher ground force acceleration and being closer to the fault than many other bridges which sustained significant damage during the February earthquake, bridges along the Heathcote River sustained less damage in comparison. This may be for two reasons. First the lateral spreading displacements along the Heathcote River were smaller than other rivers and secondly the bridges on the Heathcote River have shorter spans/lengths.

South Brighton Bridge

- The South Brighton Bridge is a three span design, constructed from reinforced concrete. The superstructure consists of cast in situ reinforced concrete deck on precast “I” beams. The bridge is supported through elastomeric bearing on two octagonal ‘hammerhead’ RC piers and seat-type RC abutments. The bridge sits on 44 precast concrete piles, ten beneath each abutment and twelve beneath each pier. The bridge is situated in the wetlands area where thickness of recent soil is around 40m. Each approach sits on uncontrolled fill material. The bridge has been built on a 25 degree skew to the river bank.
- Substantial lateral spreading was experienced at the site during both September and February earthquakes. Large ground distortion and slumping was evident at both of the bridges’ approaches, with large vertical offset between the pile supported deck and embankment approaches. In conjunction with the stiffness of the superstructure, the skewed design of the bridge constrained the movement of the approaches

resulting in permanent horizontal displacement of the approaches in opposite directions and lateral offsetting between the deck and approaches of approximately 20cm. The significant offsets between the approaches and bridge deck caused the water main pipes running beneath the deck to rupture.

- The damage observed at the South Brighton Bridge was typical for all bridges that were affected by lateral spreading. The rigid beam deck superstructure practically prevented any displacement in the longitudinal direction of the bridge which resulted in deck-pinning and consequent back-rotation of the abutments about the beam-abutment point of collision, because the foundation piles could not resist the spreading movement of the foundation soils towards the river.
- The back-rotation motion of abutments on the South Brighton Bridge caused damage to the top of the abutment piles and as a result these piles have been laterally displaced towards the river. The displacement of these piles in conjunction with the rotation constraints imposed by the rigid pile-abutment connection caused the bending of the piles which resulted in tensile cracks on the river side and the concrete crushing / spalling on the land side of the piles.
- As there was no serious damage to the South Brighton Bridge superstructure (aside from some dislocated bearings), temporary repairs were able to be made offsets between the deck and approaches were able to be refilled and the bridge was quickly back in service.

Anzac Bridge

- The Anzac Bridge is a 48 meter three span bridge with a roundabout located at the northern approach. The superstructure is a precast concrete hollow-core (double) deck with precast concrete beams and is supported by situ concrete piers and abutments. The piers sit on reinforced concrete piles, 1.5m diameter and 20m long with 8 mm permanent steel casing. Each abutment is supported by 16 “H” piles with 1.5m spacing. The soil at the south end is about 2m sandy soil, uniform fine to medium dense sand up to 12m and slightly coarser / denser sand thereafter.
- Massive liquefaction ejecta and substantial lateral spreading was evident in the area of the Anzac Bridge during the February earthquake. Complex lateral spreading was observed at the roundabout on the northern approach.
- The substantial lateral spreading at the site caused deck-pinning and back-rotation of the

abutments on the Anzac Bridge. The effect had permanent lateral displacement of three elements:

1. Lateral displacement at the bottom of the abutment (top of the H-piles) due to the back-rotation of the abutment
 2. Lateral offset of the precast concrete underpass
 3. Lateral offset of the surrounding soil at the interface between the paved track and reinforced concrete underpass
- The pedestrian underpass at the Anzac Bridge site is built on independent 1.2 m in diameter reinforced 6 meter piles. Due to their limited length the piles “practically floated in the liquefied soil”.
 - The spreading-induced damage at the bridge caused a large offset between the deck and the approaches (infill was completed in the repairs). The compression deformation of the pavement at the approach / deck interface was also spreading-induced, resulting in the back-rotation of the abutments. There was visible cracking of the interior beam-pier connection and concrete spalling due to excessive compression on the exterior beam-pier connection. Despite the damage the bridge remained in service after each earthquake and was a vital link (including being used by heavy vehicles).

Dallington (Gayhurst) Bridge

- This bridge has a continuous reinforced concrete deck, reinforced concrete piers and reinforced concrete abutment walls with wing walls. The bridge is 26.8 meters long with three spans without any expansion joints. The piers and abutments are supported on reinforced 350 mm x 10.4m piles. Seven piles at 4D spacing are used beneath the piers, while six piles at 6D spacing support each abutment. The north approach has 2.5m of brown sandy silt and silt with peat, a grey fine sand reaches up to a depth of 15m, sandy silt is found between 15 and 20 meters, and from then onwards is fine sand. The bearing stratum for the piles is in the underlying dense sand between 13 and 16 meters deep.
- The north approach to the Dallington Bridge shows substantial damage, as that side of the river experienced much higher lateral spreading displacement (between 0.6 and 0.75m). The large settlement and slumping of the northern approach resulted in subsidence reaching about 1 meter. Conversely the southern approach showed neither significant damage nor vertical offset at the bridges interface where spreading

displacement of the cut bank was less than 5cm.

- The stiff deck of the Dallington Bridge resisted the spreading of the banks resulting in back-rotation of the abutment walls. An effect of the lateral movement of the abutment wall towards the river was the buckling of the water pipes running beneath the deck.
- Much higher penetration resistance at 13-16 meters deep was measured at the south side of the bridge, which is consistent with the observed absence of any significant land damage or signs of lateral spreading at the south approach of the bridge.

Summary and Conclusion

- Except for a relatively thin crust (1-2m thickness) the foundation soils at the three bridge sites completely liquefied up to 8-9 m or even 12 m. The liquefaction was accompanied by substantial lateral spreading that resulted in permanent horizontal displacements of the unconstrained river banks. The bridges experienced extreme seismic activity including substantial liquefaction in the foundation soils accompanied by very large kinematic loads due to spreading and inertial loads due to strong ground shaking.
- The key factor in the development of the characteristic deformation mechanism of the bridges was the stiff and strong superstructure in the longitudinal direction.
- Pronounced slumping of the approaches occurred due to liquefaction in the underlying soil that resulted in large settlement and vertical offsets between the approaches and the pile-supported deck of the bridge.
- There was limited, but no serious damage to the bridge superstructures. After temporary repair and infill at the approaches, all three bridges were back in service and operational immediately after every earthquake event. Overall, the performance of more recently constructed bridges allowing movement of the superstructure relative to the piers/abutments and older integral (jointless) bridges was similar. The same deformation pattern developed for both types of bridges though the differences in the kinematic constraints were reflected in the amount of permanent tilt of the abutments and consequent superstructure damage. The skew in the bridge geometry also contributed to permanent lateral offsets between the approaches/abutment and the bridge deck.

4.12 Forced Vibration Testing of Bridge Damaged in the 2010 Darfield Earthquake

(Hogan, L. S., Wotherspoon, L. M., Beskhyroun, S., & Ingham, J. M. 2012)

This summarises a paper that appeared in Bridge Maintenance, Safety Management, Resilience and Sustainability, Biondini & Frangopol (Eds), 2012.

The main points are:

- The Davis Road Bridge is a single span bridge consisting of six double hollow core precast concrete beams with six square precast concrete piles and a 2.0 meter long friction slab at each abutment.
- During the earthquake, lateral spreading caused the western approach to the Davis Road Bridge to subside approximately 0.5 m. The subsidence of the approach effectively removed the stiffness provided by the abutment and provided a unique opportunity to directly measure the influence of this resistance on the system.
- The span was subjected to shaking along both axes from a large eccentric mass shaker and a benchmark system identification was made of the bridge in the damaged state. Soil was then recompacted, and the road repaved. Once the approach was reinstated, another round of shaking was performed, and differences in mode shapes and natural periods were compared between the damaged and reinstated states.
- Comparing mode shapes from the two different approach states, both exhibit similar responses. The mode shape of the bridge with both approaches intact is slightly more dominated by the translation response as can be seen by the larger modal amplitude a mid-span and the small difference in modal amplitude between the two abutments. The natural period of the bridge with both approaches intact is 4% lower than the bridge with approach soil removed.
- The piles supporting the north-western abutment have a longer unsupported length due to lateral spreading and therefore exhibit a more flexible response. While this flexibility would be reduced with the addition of the approach soil due to the contribution of the friction slab, this additional stiffness was counteracted by the increase in gap depth due to shaking from the Christchurch earthquake.
- Comparing mode shapes from both the bridge with and without the north-western approach, the

modal response of the bridge with the approach fill is much more uniform. This is as a result of the passive resistance of the abutment and frictional resistance of friction slab providing the dominant stiffness contribution in this direction.

- The change in transverse response was relatively small due to the increase in unsupported pile length during testing of the bridge with both approaches intact. This increased pile length was due to further lateral spreading from the Christchurch earthquake and subsequent aftershocks which occurred between tests.
- Overall the longitudinal response was altered by 15% between the approach free and both approaches intact states. Mode shapes were altered based upon the level of passive resistance engaged at the abutment.

4.13 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Roads and Bridges

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 11 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 11 is on roads and bridges.

The main points are:

- Many of the approximately 800 bridges in Christchurch were subject to ground shaking higher than design level in the February 2011 earthquake, but only a small number were significantly damaged.
- Most damage to bridges occurred at the abutments due to liquefaction and lateral spreading. Liquefaction significantly contributed to the damage observed by the majority of bridges that failed near rivers.
- At almost all damaged bridges with pipes attached, the pipes were broken.
- Liquefaction and other forms of ground deformation caused widespread damage to roads.
- After the earthquake, traffic patterns on the city road and highway systems in the Christchurch and vicinity areas changed significantly with more congestion observed.

- Tunnels serving Lyttleton suffered little damage.
- Usage restrictions were imposed on some bridges and the road tunnel.
- Temporary tie-back measures were used in at least one instance to arrest further lateral movement of bridge piles.

Moorhouse Overbridge

- The columns have a hexagonal cross-section and are slightly tapered and flare at the top. The column has 1-1/8 inch diameter smooth longitudinal rebars and smooth 5/8 inch transverse ties at 12 inch spacing. The Moorhouse Avenue Bridge suffered significant damage. 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 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. Evidence of liquefaction failure of the foundation soil was observed at the bridge site. After the earthquake, temporary repair measure of bracing of the damaged column bents at the expansion joints taken.

Boathouse Bridge

- This single span pedestrian bridge had damage to the abutments at both ends (severe shear cracks due to lateral spreading movement of the river bank). The approaching pavement buckled due to pounding movement of the bridge's deck superstructure.

Fitzgerald Avenue Bridge

- A 2-span girder on wall pier bridge that had been retrofitted with steel seat width extender brackets at the abutments and wall piers suffered severe damage due to lateral spread movement of the river embankment soil.

Port Hills Overbridge SH 74

- This 6-span slab voided single column bent concrete bridge 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. The bridge suffered sustained flexural crack and spalling of concrete on the middle column as well as buckling of the longitudinal rebar at the base.

Horotane Velly Road Overbridge SH 74

- This 3-span T-girder concrete bridge with retrofitted span tie-links and shear keys with seat width extension suffered from cracks at the abutments and many bolts of the seat width extension brackets were sheared off.

The above is a sample. The full chapter includes comments on other Christchurch bridges.

4.14 Christchurch Pavement Resilience Investigation

(Pidwerbesky, B., & Waters, J. 2012)

This summary is from a paper delivered to the INGENIUM Conference in June 2012.

The following are the main points:

- Most pavements performed well. Most damage was due to subsurface movement.
- The most resilient pavements in seismic events, considering factors such as level of service after the event(s), survivability of the pavement and economics of repair, are thin-surfaced unbound granular and foamed bitumen stabilized pavements.
- The aggregate in unbound granular pavements could be contaminated with up to 30% liquefaction material without adversely affecting its performance.
- A thicker, stiff structural asphalt and concrete pavement could, in theory, constrain the upward movement of liquefaction material but there is no evidence that thickness makes a difference in practice, and would be more expensive to repair. Such pavements would not withstand lateral movement. Roads constructed in this way would be expensive to repair.
- The only means of repairing asphalt bulges (due to liquefaction) is to remove the asphalt and the underlying material, and replace with new construction.
- The selected surfacing treatment should be as per normal using normal surfacing treatment selection criteria, but the rebuild designs need better adhesion of the surfacing to the pavement.
- Pavements designs must be sustainable, maximising the utilisation of recycled materials in the pavement construction including the pavement materials themselves. Preventing contamination of subsurface layers (e.g. by use of geotextiles) would reduce cost of repair (as materials could be reused).

- Where possible contaminated materials should be modified in situ (to avoid trucking of large volumes of aggregate causing further damage to roads). Coal tar materials should be re-laid on the top of pavement fabric where full reconstruction is undertaken.
- A life cycle cost analysis should be carried out to ensure that the lowest cost engineering solution is used. The residual lives and expected lives will be critical components of these calculations and must be based on the tables developed for the purpose.

4.15 Christchurch Earthquake Lessons Learnt: KiwiRail Internal Debrief

This summary is from an internal review following the February 2011 earthquake. The author has approved release of this summary but has requested that the source document be withheld.

Lessons for KiwiRail noted in the review include:

- The need to establish relationships with helicopter services. Immediately post-event, helicopters are potentially helpful to determine the status of trains if cell phone and radio network coverage is lost. It would be useful to have seismic sensors automatically notify KiwiRail Train Control of the size of the event.
- The need to have in place procedures for sending staff to remote locations, protocols for complete loss of communication (where to meet etc) and control centre bringing together different KiwiRail groups (it would have been useful to have a combined control centre with KiwiRail Network, Freight, Mechanical and Passenger Services to coordinate activities).
- Administration support should be resourced separately from those managing the emergency. Water, food and Civil Defence equipment should be stored at the control centre.
- Need to establish relationships with Civil Defence before an emergency occurs. A designated rail representative should be included in local CDEM once activated.
- Direct contact with Environment Canterbury facilitated resource consent issues relating to emergency sourcing of gravel and ballast.
- Establish a list of approved building inspection consultants in locations close to KR buildings and depots who could be called upon to carry out certified building inspections.
- Fuel is crucial in the response and recovery. Consider planning for emergency fuel (diesel and petrol) in event of emergency.
- Diary all major discussions, decision and milestones at the local level to provide audit trail and evidence of actions taken.
- Emergency contact lists need to be kept up to date and made available both locally and to HR.
- Coordination of resources is critical to determine the best outcome and manage fatigue (although there were many offers of assistance, they were not immediately required).
- There was a perception that outsiders did not understand what was going on, and as life had changed for many this created high on-going stress levels for some.
- There was a perception that people had become more “tunnel visioned” (as a coping mechanism) and perhaps were not so aware of peripheral issues – hence an increase in risk.
- Some performance indicators showed a decline in performance in the second quarter after the main quake (between 1 and 4 months after). Provision of external resources in the medium term would have allowed those affected to take a break from the situation.

4.16 Business Continuity Christchurch Earthquakes – Christchurch Airport

(Robertson, F. 2011)

This November 2011 presentation to the Auckland Engineering Lifelines Group summarises Chorus's learnings from the Christchurch earthquakes.

The main points are:

- Constant training is necessary to ensure an adequate response.
- Recommend “Go Bag” with emergency resources, equipment designated to the position not the person, backups for each position
- Constantly update the contact key (for key personnel in particular).
- Debrief soon after the event so the important points are still at the forefront of people's minds.
- Even when the airport is open and operating, do not rush to declare the crisis state over.
- Do not underestimate the effect of trauma on staff.
- Set priorities early in the response.

- Develop categories for different levels of response for future events.
- The 4 R's (Readiness, Response, Recovery, and Review) were an essential framework.
- Expect the unexpected.

4.17 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Lyttelton Port

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 9 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 9 is on Lyttelton Port.

The main points are:

Experience

- The port suffered significant damage in the earthquakes but critical services resumed very quickly, reflecting preparatory mitigation measures and quick remediation.
- Damage resulted primarily from deep seated slides in loose hydraulic or dumped fills overlying silty bay muds. The slide movements damaged the wharf structures.
- Despite the earthquake damage, the port has experienced a significant increase in container volumes. This is partly due to local industries growing (e.g. dairy), but also to additional goods being brought in to help rebuild Christchurch.
- The loss of Z Berth and the cool storage has had a significant impact on the local fishing industry. This has resulted in loss of business for the port and for other local businesses. Replacement facilities are planned at the port.
- Oil piping and tanks were undamaged in the earthquakes. Most of the pipes were above ground, had little or no anchorage and had been designed so that there was flexibility in the bends.

Response and Advice

- Pre-planning after the first event for port improvements facilitated access to machinery including large cranes for use in restoration after the second earthquake.

- Having a process for emergency consents allowed the port to move quickly in applying for consent to reclaim land to restore the ports functionality. Hard debris from damage within Christchurch city has proved useful in achieving this.
- Ballasted shipping containers proved useful in protecting against rockfall.

4.18 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Railway System

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 12 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 12 is on the railway system.

The main points are:

- The driver of a locomotive at the time that the February earthquake took place said that the front wheels "seemed to lose traction". He applied the emergency brake which brought the locomotive to a stop.
- Wrinkles in the tracks occurred after being repaired, suggesting the effects of post-earthquake fault creep. Considerable track re-ballasting was needed following after-shocks.
- Six bridges were extensively damaged. Most of the damage was due to settlement and lateral spreading of liquefied ground.
- No derailments occurred.
- The location of aftershocks was monitored to assess possible risks to bridges. This facilitated quick deployment of bridge inspectors and repair crews.

4.19 The Response of the NZ Transport Sector to the Canterbury Earthquakes

(Brunsdon, D. 2011a)

This summary is from a paper delivered to the Australian Trusted Information Sharing Network Transport Sector Group Forum in November 2011.

The following are the main points and learnings from the presentation:

- A Transport Response Plan sets out national operational arrangements to aid the rapid, coordinated and effective response of transport to significant emergencies. The Transport Response Team, chaired by the Ministry of Transport, facilitates information flows and provides advice on response matters.
- A good level of co-operation was noted within the petroleum industry. It was helpful that fuel stocks were high in Lyttelton and Timaru.
- Interdependencies: Telecommunications need electricity. Many generators were used, requiring continuous fuel supply. Road access difficulties significantly impeded fuel delivery.
- Many key facilities were within the CBD red zone; its closure caused issues. These included the electricity distribution control room, Telecom's main facility and the broadcasting hub building. There were many rooftops where cell sites were located.
- The port was significantly damaged but was able to continue operation.
- The main highways were largely unaffected. However local roads were extensively damaged.

Key Learnings

- Criticality of access and power:
 - Fortunate that there was only limited disruption to regional access (this would not be the case for most other parts of NZ)
 - Electricity transmission and distribution providers maintained supply to most areas
- The importance of progressive mitigation programmes:
 - Network-wide planning for redundancy

- Specific asset restraint
- The importance of relationships and connectedness:
 - Regionally: through engineering lifelines groups and civil defence emergency management groups
 - Nationally: via the National Engineering Lifelines Committee and the transport emergency management cluster. Government's Domestic and External Security Coordination arrangements also address national issues
- The value of having a strong resilience culture within key organisations:
 - Technical / Management: looking for mitigation and preparedness opportunities
 - Governance: supporting resilience investments
 - Balancing planned and adaptive capabilities

Three Aspects of Infrastructure Resilience

- Robust physical assets with key network routes and facilities having appropriate redundancy.
- Effective co-ordination arrangements (pre- and post-event); and
- Realistic end-user expectations and appropriate measures of back-up arrangements.

The Resilient Organisations Research Programme has identified crucial factors for both resilience and recovery. These are:

- Integrative and alert situation awareness
- Grounded and inspiring leadership
- Structured and responsive decision making
- Disciplined and innovative culture.

5 LIQUID FUELS & GAS

5.1 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Gas and Liquid Fuels

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 8 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 8 is on LPG and liquid fuels.

The main points are:

Gas (LPG)

Experience

- Durable pipelines and gas services, coupled with careful preparations served Christchurch well. Features included diesel generators at feeders and dispersion of feeders throughout the system. Planning for rapid shut down and restoration of services included arrangements with independent contractors for emergencies.
- Gas to the CBD was completely shut-off after the February earthquake. This had to be done manually. Because traffic was a hindrance, bicycles were used in many instances to negotiate traffic and gain access to valve locations.
- There was no damage to any of the MDPE mains in the system, including in areas where liquefaction was experienced.
- The Christchurch gas network illustrates several interdependencies among lifeline systems, such as water to operate the gas vaporizers and for fire suppression, electricity for water heating, and cell phone service to enhance communication among crews restoring the system.
- Difficulties were experienced with hand-held radios. There was topographical interference with some radio transmissions. Most cell phone service was restored by the following day, and cell phone communication was used extensively among the crews during restoration of service.

Response and Advice

- To protect against gas leakage, all Rockgas

pipelines supplying damaged portions of the CBD were cut and capped.

- No services were energized until the customers were contacted.
- When re-pressurization for the gas lines commenced, a 1 hour test was run to ensure the pressure could be held. The process worked as follows:
 - Isolate pipeline sections
 - Shut all customer services
 - Put a gauge on one service
 - Ensure the system is holding pressure before accepting.

The process was repeated across the entire network

- Loss of water interrupted operation of the hot water vaporizers, but residual pressure was available in storage tanks enabling gas to flow. Refuelling storage tanks was suspended until water was restored to operate the sprinkler system for fire suppression.
- 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. Procedures should be set up to handle this risk.
- Backup generators need to be tested regularly to ensure they are in working order.

Liquid Fuels

- There was no damage at any of the liquid fuel tanks, which are at-grade steel and have seismic designs. They all have steel roofs (i.e. no floating roofs) and most tanks were near empty (under 20%) at the time of the largest earthquake.
- The 4 inch pipeline over the Port Hills was dented by rockfall but did not leak.
- Canopies at several service stations were badly damaged.

5.2 Mobil Oil New Zealand Ltd – Christchurch Earthquake Response

(Rea, J. 2011)

This November 2011 presentation to the Auckland Engineering Lifelines Group summarises Mobil's learnings from the February 2011 earthquake.

The main points are:

- Response is based around the PEAR principle; People, Environment, Assets and Reputation.
- Key issues include allocating petroleum supply to meet key user needs (in cooperation with CDEM), managing public expectations (queuing can raise difficult situations in forecourts) and containing petroleum to eliminate environmental hazards.
- Commitment to fibreglass service station tanks worked out as all assets retained integrity despite the severe and continuing earthquake activity.
- There is a need to ensure effective and robust back up for essential supplies – power, water, gas and road infrastructure.
- Consideration needed to liquefaction effect on equipment in future design work.
- Continuous improvement should feature prompt sharing of lessons both within the organisation and between lifeline utilities, assignment of responsibilities for improvement actions, regular follow-up on processes with improvement actions, and regular tests for Business Continuity Planning and Enterprise Resource Planning.
- Good relationships with regulators, MCDEM, lifeline utilities and other critical contractors proved useful.

5.3 Observations by BP after Canterbury Quakes

(Harrison, K. 2012)

This summary of observations and lessons arising from the Canterbury earthquakes, from BP's perspective was drawn from personal correspondence (email, 13 July 2012) and is included with permission of the author.

The main points are:

- All parts of the supply chain need to be restored for sustainable “return to normal” operations.

Restoration of supply chain components may occur out of sequence or be held up due to any part of the supply chain being broken or unavailable.

- Building relationships with key infrastructure providers and Civil Defence facilitates effective response. CDEM needs to be proactive in granting access to roading routes where dangerous goods vehicles are normally restricted or prohibited.
- Expect panic buying of fuel after a natural disaster and expect fuel shortages if the supply chain relies on supply from other ports for any length of time.
- Don't underestimate that people will put in heroic efforts during a response at their own risk. Fresh personnel need to be deployed as soon as possible to allow staff to deal with personal circumstances (this also goes for incident response teams). Provide on-going support to staff and opportunities for breaks.
- Personal preparation at home and work needs greater emphasis.
- The little things count, e.g. providing coffee before fuel was a morale booster in the eastern suburbs. Coffee was made available where possible at service stations where fuel systems were out of commission. This was appreciated by communities which had no other access to hot food and drink.
- The downstream components of the oil industry did not operate as an entity, although this did not seem to impede communications or restoration of services. The previous conversations about the need for an oil sector coordinating entity need to be reviewed to see if this is really required.
- Consideration into how to translate these lessons to other more geographically challenging locations (such as Wellington) needs to be considered.

5.4 LPG Infrastructure in the Christchurch Earthquakes

This summary is from a presentation to the 2011 National Lifelines Forum, prepared by RockGas following the February 2011 earthquake. The author has approved release of this summary but has requested that the source document be withheld.

The main points are:

Rockgas supplies LPG in Christchurch, by cylinders,

bulk tanks and a reticulated network. This summary relates mainly to the February 2011 earthquake.

- Main feeder plant had a minor gas leak and was therefore isolated. PE pipe performed very well. Tank installations also performed well.
- CDEM requested that supply to the CBD be discontinued. Decision taken to shut down entire reticulated network.
- Cellular phones and electricity supply failed. Back-up communications with contractor didn't work well (previous testing not thorough enough).
- Assistance obtained from out-of-town company sources.
- No standard arrangements appear to exist for relaxation of HSNO certification for temporary cylinder supplies in emergency conditions.
- Building demolitions proceeded without gas isolations, reflecting a lack of awareness of presence of piped gas in South Island. Last minute isolation requests were problematic – demolition crews become aware of presence of LPG only once work had begun or immediately prior in more than one occasion. These requests need to happen in a timelier manner.
- A critical customer list was developed immediately after the earthquake.
- HSE issues with staff and contractors required management.
- Gas demand dropped off – not yet fully recovered.
- Re-livening plan drawn up and risk analysis completed. Re-livening commenced from north-west side of the city.

6 HOSPITALS

6.1 Assessing the Post-Earthquake Functionality of the Hospital System Following the Canterbury Earthquake Sequence in NZ

(Giovinazzi, S., Mitrani-Reiser, J., Kirsch, T., Jacques, C., McIntosh, J., & Wilson, T. 2012)

This 2012 paper, prepared with funding from the Natural Hazards Research Platform, summarises earthquake impacts on the main Christchurch hospital.

The main points are:

- Preliminary results show how non-structural damage to health facilities and loss/reduced functionality of the city lifelines was far more disruptive to the provision of healthcare than the minor structural damage to buildings. The earthquake-induced impacts on health facilities and the loss of functionality of city lifelines reduced the capacity of the healthcare network to operate and further strained a health care system already under pressure.
- The ability to cope with the damage was due to the ingenuity and hard work of maintenance and clinical staff.
- The Canterbury healthcare system has exhibited high adaptive capacity and the strong integration with the wider New Zealand healthcare system has enabled a high standard of healthcare to be maintained.
- Hospital planning activities should focus on identifying non-structural and functional vulnerabilities within all critical service areas and mitigating their possible impact with engineering interventions, redundancy systems or alternative resources.

6.2 Impact of the 22nd February 2011 Earthquake on Christchurch Hospital

(McIntosh, J., Jacques, C., Mitrani-Reiser, J., Kirsch, T., Giovinazzi, S., & Wilson, T. 2012)

This is a summary of a 2012 New Zealand Society for Earthquake Engineering conference paper on hospital impacts following the February 2011 earthquake.

The following are the main points:

- Minimal disruption occurred due to structural damage at Christchurch Hospital buildings. Damage was minimized through regular building shapes (with no abrupt discontinuities or large overhangs), separation joints, CWH base isolation, and seismic upgrade of older buildings.
- the effects of damage to non-structural building components and equipment, as well as breakdowns in public services (lifelines), transportation, re-supply, and other organizational aspects, were far more disruptive to the functioning of Christchurch Hospital than the minor structural damage observed in buildings and facilities. The non-structural damage included the failures of many components: windows, non-load bearing ceilings, partition walls, floor coverings, medical equipment, and building contents.
- Suspended ceiling tiles (particularly plaster tiles with tongue and groove joints) caused falling hazard. Tiles were originally diagonally braced to the wall but at some stage bracing was replaced by less effective vertical tiles.
- Non-structural components such as wallboard partitions suffered damage. This caused disruption during repair (no loss of functionality).
- Minor disruption occurred due to elevator shut-down (seismic trip switches).
- Pumps and chillers jumped off their mounts (despite being installed in accordance with seismic mounting standards NZS4219:2007). Chiller piping collapsed.
- Damage to internal and external roof coverings and roof top water tanks on Riverside building caused water ingress and subsequent evacuation of 2 floors. Evacuation took 35 minutes due to lack of horizontal egress.
- Loss of power was a major obstacle. Some back-up generators were damaged or malfunctioned. In addition, shortages to the main low-voltage switchboard caused small fires, damaging the main electrical panel and further complicating the power restoration efforts.
- Damage to water systems was a major problem. Fire sprinklers could not be pressurised for up to a week and emergency water supplies were insufficient and not potable (silt in boreholes). To prevent this situation from occurring in any future disasters, a half million-litre capacity tank system

has been installed to provide emergency water for crucial systems, including the fire sprinklers.

- Building suction was damaged but this was repaired within 30 minutes.
- Laundry was done off-site.
- There was no loss or shortage of lab supplies, radiological supplies, or other diagnostic supplies. The pharmacy had adequate supplies.
- Due to the lack of horizontal egress and the presence of only a single stairwell, the decision was made to permanently change the use of those floors from clinical wards to administrative space.
- All the regional hospitals participated in the redistribution of capacity from damaged healthcare facilities in Christchurch in the form of accepting transferred elderly care and/or maternity patients in the days after the earthquake.

6.3 Response of Regional Health Care System to the 22nd February, 2011, Christchurch Earthquake, NZ

(Mitrani-Reiser, J., Kirsch, T., Jacques, C., Giovinnazzi, S., McIntosh, J., & Wilson, T. 2012)

This 2011 paper, prepared with funding from the Natural Hazards Research Platform, summarizes earthquake impacts on the main Christchurch hospital.

The main points are:

- Rectangular buildings predominate at the hospital, with no L- or T- shaped structures, no abrupt discontinuities along building heights, and no large overhangs. These features, along with the presence of separation joints in most buildings and base isolation of the CWH, likely mitigated structural damage.
- Older buildings that had been seismically upgraded suffered only cosmetic damage.

- Many other factors affect hospital functionality, such as lifelines, transportation and support agencies. Damaged non-structural components of a hospital system are typically the most disruptive factor following an earthquake as well as organisational issues.
- The failures of suspended ceilings, particularly the plaster tiles constructed with tongue-and-groove joints, proved to be one of the most disruptive non-structural failures. Removal of original diagonal ties on tiles also contributed to the damage.
- Non-load bearing wallboard partitions were also heavily damaged throughout the hospital.
- Most disruption arose during the repair phase.
- Staircase damage (due to rigid connections to floors) caused disruption.
- Seismic switches on elevators meant they were out of action for a period.
- Rooftop pumps and chillers fell off their mounts. Water tank failure caused evacuation of two floors with no horizontal egress – evacuation was via damaged stairwells with no lights.
- Despite regular testing, some backup generators failed or were damaged. Some filters clogged because of silt in tanks (disturbed by earthquake).
- Emergency water supply was tested – wells had silt in them (from earthquake) and initially could not be pumped easily. Well water was also not potable. The fire system could not be pressurised either.
- Supplies and non-clinical services were mostly undamaged. The kitchen, laundry, pharmacy, lab all remained functional (some services were transferred to other sites as required, e.g. laundry due to lack of water).
- Hospitals around New Zealand assisted by taking patients and providing staff.
- Hospital planning activities should focus on identifying non-structural and functional vulnerabilities within all critical service areas and mitigating their possible impact with engineering interventions, redundancy systems or alternative resources.

7 SOLID WASTE

7.1 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Debris Management

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 18 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 18 is on debris management.

The main points are:

- Post-disaster debris and rubbish normally includes hazardous material and therefore normally requires special disposal processes.
- Some materials can be reused. It is therefore important to have procedures in place to maximize the efficient reuse of resources.
- Sensitive procedures are needed relating to handling material, buildings and vehicles where fatalities have occurred.
- Heritage items need to be identified and protected – this means also having somewhere to store them.
- Contractors were screened and approved by the National CDEM Controller prior to performing demolition and removal of debris. Only contractors approved to handle hazardous materials were allowed to remove and dispose of such materials. All contractors were required to operate in accordance with legal requirements and industry standards.
- Waste and debris management in a post-disaster situation is critical in terms of supporting lifeline and general recovery. A coordinated effort is required to ensure timely restoration of services and clean-up, thereby aiding rebuilding and to return to normalcy.

7.2 Disaster Waste Management: A Systems Approach

(Brown, C. 2012)

This is a summary of a PhD thesis submitted to the University of Canterbury in 2012.

The main points are:

- Waste needs to be included in Civil Defence and Emergency Planning. In particular, it is recommended that waste management utility operators are included as Lifeline Utilities under the CDEM Act.
- Urban Search and Rescue should consider training construction personnel to assist in search and rescue activities.
- More pro-active public consultation regarding waste related issues would be beneficial.
- The majority of waste management activities during the response and recovery have been privately funded. Consideration of public funding of waste management during the response phases should be considered – particularly where waste is blocking access ways, posing a public health hazard or a social nuisance.
- Greater clarification is needed in terms of cost share for demolition works between EQC and private insurers (and the Crown where land areas have been purchased by the Crown).
- Under the current private funding mechanism for demolition, opportunities for resource efficiency and prioritised planning were not fully utilised. The central city demolition programme managed by CERA allowed for some planning, however, private property owners commanded most of the resources and thus dictated the programme of works, arguably slowing the opening of the central city. Centralised coordination of such a large number of projects in such a confined area was needed, at the very least, to manage traffic and health and safety issues.
- If a centralised management approach to demolition is taken then consideration of appropriate procurement strategies for contractors and debris disposal facility services is needed. The author recommends time and cost contracts in a resource-constrained environment. Also, considera-

tion needs to be given to the timing of renegotiation of contracts let during the response phase.

- Where additional waste management facilities are required to handle the increased volumes of waste, the author recommends that these be run publically or, at the very least, as a private-public partnership. This is so that the risk can be appropriately shared in this highly uncertain environment.
- Authorities should carefully consider whether new disposal / waste management facilities are required before consenting new operations (particularly privately run operations). Bonds under the RMA should be considered to protect against potential environmental damage.
- Guidance needs to be provided on how the RMA (given the discretionary nature of the legislation) should be applied in a disaster situation. A decision-making framework is recommended to protect the environment (physical, economic and social) and decision makers.
- The feasibility of recycling post-disaster should be considered. This particularly relates to whether on-site or off-site separation is preferable. Off-site separation may be more cost effective given the reduced time for demolition compared to on-site separation, and the greater health and safety risks associated with on-site separation arising from on-going aftershocks.
- Asbestos was a major health and safety concern for the public. Better consultation should be carried out in the future regarding asbestos-related risks and mitigation measures.
- Currently there are very few regulatory mechanisms by which demolition and debris management activities can be monitored. This makes management of risks difficult. Consideration into this is required.

7.3 Canterbury Earthquakes – Waste Sector Response

(Brown, C. 2011)

This summary is from a presentation to the 2011 National Lifelines Forum.

The main points are:

- Municipal waste service providers should be included as a Lifeline Utilities under the CDEM Act.
- Need to have plans in place for managing bottlenecks (one waste site in particular became critical to waste disposal).

- Need to have plans in place to store material that may relate to investigations after the event.
- Need to be aware that putrescibles will rot when forgotten (there were putrescible wastes rotting in the city centre while the cordon was up).
- If it is likely that liquefaction silt could arise in an earthquake, need to have adequate plans for a disposal site.

7.4 Liquefaction Ejecta Clean-up in Christchurch during the 2010-2011 Earthquake Sequence

(Villemure, M., Wilson, T. M., Bristow, D., Gallagher, M., Giovinazzi, S., & Brown, C. 2012)

This is a summary of a 2012 New Zealand Society for Earthquake Engineering conference paper on liquefaction ejecta cleanup following the February 2011 earthquake.

The main points are:

- Liquefaction ejecta caused significant damage / disruption (by blockage) to storm water and wastewater infrastructure. Ejecta also disrupted road networks. Ejecta were also a potential health hazard due to mild wastewater contamination and from dust nuisance. Ejecta, in general, was disruptive to people living in affected areas. Thus, speedy removal was essential.
- Planning for community collection of natural disaster debris needs to be undertaken.
- Strategies for managing large numbers of volunteers (food, H&S, equipment, works allocations etc.) need to be developed. The response could have been more rapid and efficient if there had been better provisions for managing volunteers in CDEM plans. Strategies for integrating contracting and volunteer services (including reconnaissance and work planning) need to be developed. Project managers were needed to coordinate volunteers.
- Clean-up managers noted the importance of a clear strategy which was underpinned by clear communication and coordination between council, contractors, volunteers, the public and other stakeholders, such as Civil Defence and lifelines.
- All organisations stated that local knowledge, trust, contacts and existing informal relationships

significantly enhanced the effectiveness of the clean-up management (notable improvement between September 2010 and February 2011).

- Coordination was significantly enhanced when a job dispatch and mobile workforce management system were in place.
- CIMS was used effectively to communicate between the different clean-up organisations and with the public. Social media (in particular Facebook) was also very effective.
- Light and heavy earth moving equipment is needed for large-scale removal of deposits. Fine ejecta sediment is ideally collected when slightly moist. Pre-selected disposal sites facilitate effective debris removal.
- Public communication is key. Volunteerism lifts community spirits and should be encouraged.
- The lessons from liquefaction may be applicable to other events where clean-up is required, such as volcanic ash.

8 MULTI-SECTOR REPORTS

8.1 Geotechnical Reconnaissance of the 2010 Darfield (Canterbury) Earthquake

(Cubrinovski M. G. 2010)

This is a summary of a paper from the December 2010 Bulletin of the New Zealand Society for Earthquake Engineering, Vol 43, No. 4. It contains much information on the nature of the September 2010 earthquake and its impacts on the building stock. It also contains information on infrastructure, summarised below.

The main infrastructure-related points are:

Stopbanks

- Overall, the stopbanks along the Waimakariri River performed well during the earthquake, with only ~4 km out of ~17 km of stopbanks requiring repair. Longitudinal cracks were very quickly repaired.
- The stopbanks confining the Kaiapoi River suffered damage at various locations. These embankments, measuring about 2.5 m high and 2.7 m wide, have slopes of approximately 2H:1V on the riverside and 3H:1V on the landside at the point where the reconnaissance was undertaken. They remained serviceable despite incipient liquefaction in the abutments and settlement and cracking of the approach on the eastern side.
- The stopbank along the south bank of the Kaiapoi River also experienced extensive lateral cracking.

Bromley Sewage Treatment Plant

- The middle third of the Pond 1/2 A embankment sustained the most severe failure throughout the pond system over a length of around 45 cm. At this location there were multiple deep longitudinal cracks along the embankment.
- Each of the three pipelines became dislocated in the gap between a weir structure extending into an oxidation pond and the embankment, allowing water to flow directly into the pipelines at the gaps formed in the pipe separations. Furthermore, sink-holes were formed on the embankment berms and in the middle of Dyers Road indicating that the pipes had separated beneath the embankment fill.

- The distortion of the embankment is indicative of bearing failure of the embankment as it has settled and spread into the liquefied sub-soils, with large tension cracks forming through the fill used to form the embankments and pulling apart of concrete pipelines as the fill has spread.
- Because of the slumping of the pond banks, engineers decided to drop the pond water levels and reduce the hydraulic pressures on the embankments. Sheet piles were driven into the Pond 3/6 embankment to stabilize it and arrest further movement.

Bridges

- At road bridge locations where lateral spreading, or incipient lateral spreading, was observed in the abutments, the tendency for the abutments to converge (move inwards towards the centre of the span) appears to have been resisted by bridge decks, though there were typically signs of lateral spreading of the approach embankments perpendicular to the roadway.

- **South Brighton (Bridge Street) Bridge:** This bridge has an approximately 70 m span with a centre pier and seat type abutments and a slight skew. The bridge was damaged and closed due to differential settlement at the east abutment.

The abutment wall is supported by several rows of 14 inch octagonal precast, pre-stressed concrete piles including a row of batter piles. Incipient lateral spreading of the bridge abutment, lateral spreading along the banks of the river and closure of the gap at the bridge seat were observed at the west abutment. The west abutment also appeared to have back-rotated slightly, possibly due to the liquefaction induced settlement of the approach fill and tilting of the approach slab at the wing wall.

- **Avon River bridges** (Swanns Road, Gayhurst Road, Pedestrian Bridge): These are approximately 30m simple span bridges with integral abutments. Both road bridges had cracking in the roadway on the approaches, and at Swanns Road there was lateral spreading of the approach fill, incipient lateral spreading at the abutments and cracking at the abutment and retaining wall.
- **Kaipoi River bridges:** Damage was similar to the Avon River bridges. Buckling occurred of the lightweight deck of this pedestrian bridge as a result of lateral spreading.

- **Waimakariri River Bridges** (Chaney's Overpass, Highway 1 River Crossings): Chaney's is a three span bridge of 80m with what appeared to be seat-type abutments retrofitted with cable restrainers. Cracking and incipient lateral spreading was observed at the northern transition between the approach embankment and the abutment at Chaney's overpass. There was no apparent damage to the bridge structure or its foundation despite ample evidence of liquefaction beneath the bridge.
- **Kainga Road Bridge:** mixed girder-slab reinforced concrete bridge. Movement of the north-east abutment wing wall resulted in damage to an 18cm diameter sewage pipe that was rigidly connected along the bridge span. The ruptured pipe continued to discharge untreated sewage into the river for at least 12 days after the earthquake.

Directly below the bridge a pipe of similar diameter suffered no damage, and it was concluded that its support to the abutment wall was filled with a flexible foam.
- **Railroad bridges** are primarily of steel construction. One railroad bridge was damaged and service was impacted from bent rails at the fault trace and as a result of slumping ground in some locations.

Port

- Port facilities were operational within hours after the earthquake and no scheduled shipments were missed. The two main piers and a portion of the coal terminal were operational by 4 September.
- The port has three container cranes that were still performing following the earthquake. The crane rails are closely enough spaced that both rails fit on the wharf deck. Having both rails on the deck appears to have avoided differential movement of the rails and contributed to this good performance.
- As a result of liquefaction and lateral spreading, four tanks at the bitumen plant (at the oil berth) and some supporting piping suffered movement and damage. Tanks three and four were experienced movement that resulted in pullout of nearly all perimeter anchor bolts at their base. No structural damage was observed. Flexible connections survived the strong shaking with only minor leakage.

Water and Wastewater

- Damage to the CCC's system was predominantly to the water and wastewater mains, as a result of

ground movement and floating of manholes.

- A major problem with sewer lines was influx of liquefied sand and water through breaks in the line.
- All new pump stations are designed to have flexible joints and performed well. At older stations, one pipe with a rigid connection was sheared (at Halswell) and one water pump was lost.
- WDC officials wondered if they could have restored water service sooner by using more temporary above-ground flexible piping, as was done on the final days of restoration.

Landfill

- Christchurch City Council opened up a cell at the closed Burwood Landfill facility to accommodate the increased volume of waste generated by earthquake response and recovery.
- The Kate Valley landfill is located approximately 85 kilometres from the epicentre. The landfill is a valley fill with 2.5:1 slide slopes. The lining configuration consists of an encapsulated membrane back geosynthetic clay line / geomembrane system composed of a 0.4 mm high density polyethylene (HDPE) geomembrane with 6 mm of dry bentonite adhered to it, overlain by a 1 mm HDPE liner. No slipping of the waste body or damage to the lining system was reported by the operator. No damage was reported to other lined structures such as dairy milking barn wastewater ponds or lined reservoirs.

8.2 Geotechnical Aspects of the 22nd February 2011 Christchurch Earthquake

(Cubrinovski M. B. 2011)

This is a summary of a paper from the December 2011 Bulletin of the New Zealand Society for Earthquake Engineering, Vol 44, No. 4.

The main points are:

While much of this paper describes issues relating to the building stock, it also contains some material on infrastructure (summarised below).

Bridges

- Settlement and lateral spreading of bridge approaches occurred particularly relating to bridges on the Avon River downstream from the CBD.

- Land movement caused large stress on abutments of piled structures.

Stop Banks

- Damage to stopbanks was mainly due to liquefaction of underlying soils causing lateral spreading, slumping, and settlement.
- Longitudinal cracks were more common than transverse cracks. While not desirable, longitudinal cracks are less problematic than transverse cracks which can cause significant issues with respect to structural integrity of stopbanks.

Pipe Networks

- Large ground movements and deformation (in extension, compression, shear, and combined modes) including ground distortion, cracks, fissures and venting sink-holes, resulted from the severe liquefaction and lateral spreading. These caused severe damage to underground potable water, wastewater and stormwater systems.
- Potable water pipes are shallow and pressurized. 4.6% of the pipe segments were damaged, 80% of those in areas of moderate-severe, or low-moderate liquefaction.
- The sewerage network was harder hit. 8% of the system length was out of service and 31% was operating with limited service three weeks after the earthquake.
- Loss of grade, joint failures, cracks in pipes and failure of laterals were the most commonly observed types of failures.
- Loss of critical facilities such as pump stations also contributed to the overall poor performance of the system.
- Buoyancy of concrete vaults at potable water and wastewater pump stations, compounded by liquefaction-induced settlement, caused pipeline breaks at their connections with the vaults.
- Silt and sand from liquefaction washed into the Bromley sewage treatment plant from broken wastewater pipelines, causing damage in the primary settling tanks. Nearly all facilities at the sewage treatment plant were affected by liquefaction, which caused differential settlement of the clarifiers, thereby seriously impairing secondary treatment capabilities.
- Most severe water and wastewater damage was caused by lateral spreading.

Electricity

- Serious damage occurred to underground electrical cables due to liquefaction induced ground movements.

8.3 Learning from Earthquakes: The Mw 7.1 Darfield (Canterbury), New Zealand Earthquake of September 4 2010

(Earthquake Engineering Research Institute, 2010)

This is a summary of the Earthquake Engineering Research Institute's (EERI) Special Earthquake Report on the 2010 earthquake, November 2010.

The main points are:

- Because Christchurch was not considered a high-risk area it had a passive retrofit policy for its unreinforced masonry buildings. The damage to these non-retrofitted URM buildings from moderate shaking is an important lesson for other regions with large inventories of URM buildings.
- Overall, bridges suffered little damage. This was due to a complex set of circumstances. Most have small to moderate spans, which are recognized to exhibit a more sturdy seismic response because of their symmetry and limited reactive mass, and most were designed to resist forces substantially larger than the demands imparted by this particular earthquake. They also shared a number of common design features that gave them high seismic resistance, including a sturdy monolithic structure, wide wall piers and continuity of the superstructure from abutment to abutment.
- The biggest wastewater problems related to deep gravity mains, in many cases 3-4 m below the ground surface. With ground water only 2 m deep, trenching was difficult. When wastewater mains were located in the backyards of private residences, access and subsequent repairs were more difficult.
- Gas lines (including the few in liquefaction zones) were unaffected. The system has 170 km of 65 - 315 mm medium density polyethylene pipelines with thermal fusion welds.
- Damage to industrial storage racks was observed at many locations. Such damage, especially with respect to the food supply, illustrates the importance of non-structural mitigation for secondary building systems and contents.
- A curfew was useful in controlling the CBD which had large amounts of unreinforced masonry damage and debris in the street.

8.4 The Value of Lifeline Seismic Risk Mitigation in Christchurch

(Fenwick, T. 2012)

This is a summary of a 2012 report for the New Zealand Lifelines Committee on the value of lifelines seismic risk mitigation in Christchurch undertaken since publication of Risks and Realities¹ in the mid-1990s.

The main points are:

- Work following *Risks and Realities* served Christchurch well - losses were reduced and response / recovery facilitated
- Many of the elements that contributed to the benefits are not costly
- Inter-corporate and inter-personal relationships proved very valuable in aiding responses
- A range of other studies have found substantial benefits from seismic and other risk management
- The costs of seismic risk management in Christchurch have been repaid many times over.

The purpose of the report is to crystallize the experience and learnings from the recent earthquakes to foster further, well-targeted, seismic mitigation in New Zealand. Accordingly, the report:

- Comments on the value of pre-earthquake Christchurch lifeline engineering work to both the participating organisations and to the wider community.
- Suggests the elements that contributed most strongly to the benefits and that should therefore feature within the core activities of other lifeline utilities and groups in earthquake-prone areas.

The report notes that Orion's electricity distribution seismic strengthening programme, commenced in 1996 and progressed systematically each year, cost \$6 million and is estimated to have saved \$60 to \$65 million in direct asset replacement costs and repairs.

The elements that contributed most strongly to the general benefits, and that should therefore feature in work programmes, are:

- **Asset awareness and risk reduction: identifying points of particular vulnerability.** Issues likely to arise include:

- surveying for site-specific risks, for example buildings that do not meet AS/NZS1170 loading standards (including where assets are placed on top of existing structures), and where liquefaction is possible
- identifying likely fracture points (for example where cables and pipes enter structures such as buildings and bridges)
- identifying cases where restraints to restrict movement of sensitive equipment are needed.

- **Readiness: taking steps to improve organisational performance in emergencies,** such as:

- ensuring fit-for-purpose operating frameworks for business continuity
- working collaboratively with other lifelines and relevant agencies on common issues such as looking for key interdependencies, examining generator sufficiency and planning for petroleum outages, and establishing lifeline utility coordination arrangements to facilitate emergency response
- ensuring that engineers and contractors are available quickly to meet emergency needs
- managing spare parts to promote availability when unexpected pressures arise.

- **Perseverance: maintaining the effort over time while communicating realistic expectations.**

- Lifeline utilities that have retained a consistent focus on seismic mitigation have benefitted most significantly (asset management planning and similar annual-cycle processes provide an appropriate setting for much of the required work).
- Improving end-user knowledge of infrastructure reliability and encouraging users (particularly organisations with emergency response roles such as hospitals) to plan for a level of infrastructure outage in the more extreme events are also essential.

8.5 Recovery of Lifelines Following the 22nd February 2011 Christchurch Earthquake: Successes and Issues

(Giovianazzi, S., & Wilson, T. 2012)

This is a summary of a 2012 New Zealand Society for Earthquake Engineering conference paper on

¹ *Risks and Realities* was the major 1990s Christchurch infrastructure hazard vulnerability study.

Lifelines' immediate research needs following the February 2011 earthquake. The work was funded under the Natural Hazards Research Platform.

The following are the main points:

Power

- Analysis of seismic performance of underground cables and identification of the multiple causes of the damage to the underground network.
- Assessment of the residual/future functionality of affected power underground cables seismic scenario analysis for assessing and comprising alternative solutions to build permanent capacity in the eastern suburbs of Christchurch.
- Assessment of earthquake risk to underground lines versus wind and snow–storm risk to overhead lines.
- Assessment of cable bridge interactions and coordinating repair activities with road and bridge.

Telecommunications

- Assessment of residual/future functionality of stretched copper cabling.
- Improvements to standard procedures to straighten the cellular network towers out of plumb due to liquefaction.
- Scenario analysis for assessing and comparing alternative solutions for replacement of damaged exchanges.

Highways and Urban Roads

- Assessment and accounting, within repair/rebuilding designing procedures, for the increased risk of flooding induced by the subsidence phenomena observed following the earthquakes.
- Assessment and mitigation of the rock-fall risk on roads induced by the earthquakes and following aftershocks.

Water and Wastewater

- Documentation and analysis of the seismic performance of different buried pipes typologies (material/age) to identify the less vulnerable solutions for repairing and rebuilding.
- Identification of techniques and tools to support repairing/reconstruction activities and to justify costs of earthquake-resistant solutions.
- Definition of a method and tool for automatically mapping and assessing earthquake induced damage to sewage networks, starting from CCTV footage.

Gas

- Improvements to standards/procedures for seismic design of liquefied petroleum gas feed plant.

8.6 Lifelines Performance and Management Following the 22 February 2011 Christchurch Earthquake, New Zealand - Highlights of Resilience

(Giovinazzi, S., Wilson, T., Davis, C., Bristow, D., Gallagher, M., Schofield, A., et al. 2011)

This is a summary of a paper from the December 2011 Bulletin of the New Zealand Society for Earthquake Engineering, Vol 44, No. 4.

The main points are:

- The strong lifeline culture in New Zealand promoted by local lifelines groups, National Engineering Lifelines Committee. Earthquake Commission and Civil Defence and Emergency Management reduced the physical and functional impact of the earthquakes on lifelines systems.
- In urban locations further analysis is needed on hills that support resident communities, including investigations into rock falls, boulder rolls and loess soil failure due to earthquake movement. Previously these risks had not been seriously considered as an expected hazard in Christchurch.

Power

- The national grid was unaffected due to resilience measures used implemented by Transpower. Local power in Christchurch was affected for around 4.5 hours while safety checks were performed.
- Transmission towers situated in extreme liquefaction zones remained operational.
- The Christchurch earthquake highlighted the need to implement previously learnt lessons. For example Transpower learnt in the 1987 Edgecumbe earthquake the need to seismically restrain heavy equipment in substations, and as a result of undertaking this before February 22nd in all of their substations there was very little damage to the national transmission grid.
- Following the 22nd February earthquake all

instruments with insulators held by “finger clamps” will be replaced as this type of clamping performed poorly during the earthquakes.

- There is a very strong correlation between line cable failure and liquefaction / lateral spreading. As part of the maintenance plan there needs to be a priority to install liquefaction-resilient cables in areas where extreme liquefaction are expected. Long cables, such as the one between the Lancaster and Armagh substations are also extremely vulnerable to damage and should be monitored more closely than others.
- Orion’s resilient maintenance programme significantly improved the performance of their substations, in some cases surviving better than neighbouring buildings. It may be unnecessary to upgrade a substation to a performance level for an extreme earthquake where demand for electricity reduces because surrounding buildings do not survive. Substations should be upgraded to the point where they are only slightly stronger than the neighbouring properties.
- Temporary overhead lines can be used to quickly re-establish service while proper design and consultation procedures are undertaken to build a permanent supply.
- While most major emergency repairs to the local power supply network were completed in 6 months, it is expected to take years before the network will be back to pre-earthquake resilient levels. This demonstrates that while a network may be fully operational quickly, it takes a long time to restore the network to the same functionality levels.
- The local power network is needed to work closely with demolition and restoration crews to ensure that buildings are safely disconnected from the power network before demolition or repair activities start.
- Without the earthquake strengthening work completed by Orion after ‘*Risks and Realities*’ it is expected that the repair bill would have been double and the loss of power would have been much worse, lasting several more weeks, if not several months for many customers throughout the network. “Even so, the power cuts that did result have been very disruptive.”

Roading

- Congestion remained a problem for months following the earthquakes despite traffic management measures and programmes to speed-up the removal of liquefaction.

LPG

- The availability of back-up resources was crucial to relieve lifelines interdependency issues and to maintain the LPG system functionality despite the reduced functionality of the electric and water networks. Diesel engine back-up generators guaranteed the supply of electric power to the feeder plants. Buried storage tanks (500 t) provided several weeks supply for the network in case of any on-going disruption to the business-as-usual LPG supply through the Lyttelton port. Road haulage options for LPG were placed on standby.

Wastewater

- Christchurch relied heavily on temporary sewage treatment services which were facilitated by portable chemical toilets to supplement the wastewater system.
- HDPE pipes are now being used extensively for pressure mains as they were found to perform well following all three earthquakes.
- Health issues were used during hot and windy conditions, as silt was mobilised by the wind because of fears that raw sewage had contaminated much of the liquefaction ejecta which would create respiratory health issues and provide a long-term health risk to the community.

Other

- “The value of resilient design, interdependency planning, mutual assistance agreements, extensive insurance cover and highly trained and adaptable human resources are the success stories that this paper aims to highlight.”
- Mutual aid agreements and contingency measures by lifeline utilities helped them ensure prompt availability of resources, materials and technical expertise during operational repairs.
- There are significant challenges in managing aging infrastructure, as highlighted by the events. These components are known to be vulnerable, but often too expensive to upgrade / replace in the short-term. These components such as weak buried pipes / cables played a significant role in the lifelines performance during the earthquakes.
- The management of the cordon caused frustration, as strict access protocols made it difficult for lifelines utilities and their contractors to service key sites. A police escort for utilities was provided sporadically upon request.
- Extended closure of the Christchurch CBD exposed difficulties in re-optimising infrastructure use.

8.7 Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifeline Performance – Lifeline Interdependence

(Eidinger, J. & Tang, A.K. Eds. 2012)

This is a summary of chapter 15 of the Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph 40, February 2012 Revision O. Chapter 15 is on debris management.

The main points are:

- 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 cell phone providers had implemented seismic anchoring or battery racks and equipment and used portable generators, neither could mobilize a sufficient number of generators fast enough to prevent phone outages. Cell phone sites were fully functional once mains power was restored.

- Much of the water system was de-pressurized in the first day after the September 2010 earthquake, due to water pipe damage and broken wells in several cases. The loss of mains power to the wells likely had limited impact on the overall performance of the water system.
- Because road, telecommunications and electricity were largely functional quite quickly, the main hindrance to restoration of water and other services was the time needed to make inspections and repairs.

9 RESPONSE COORDINATION

9.1 Review of the Civil Defence Emergency Management Response to the 22 February Christchurch Earthquake

(McLean, I., Oughton, D., Ellis, S., Wakelin, B., & Rubin, C. B. 2012)

This is a summary of chapter 4 of the report on the review of the Civil Defence Emergency Management response to the February 2011 earthquake (chapter 4 deals with Lifelines).

The main points are:

- Many organizations showed significant improvement in responses to the February 2011 earthquake compared with September 2010.
- Restoration of lifelines is more difficult where organizations use contractors vis-à-vis own staff. The management and tasking of contractors and own staff on emergency response must be embedded and practices.

Water and Wastewater

- It was learnt in the September earthquake that it was beneficial to zone the city in terms of water supply so that responses could be targeted to probable areas of need.
- Having established relationships with contractors and industry bodies meant that there was a network of support that could be relied on following the February earthquake. These relationships developed prior to the event, although often informal (and not through CDEM channels), helped to establish water and wastewater services.
- It was learnt that there were disadvantages to using portaloo waste disposal systems due to possible health risks, lack of security and reluctance to use them at night. Chemical toilets were preferred.
- There is a need to develop shut-down and containment procedures for sites containing dangerous chemicals as part of CDEM planning.
- Chlorination of potable water was required. This task was undertaken by a team from a local authority from another part of New Zealand.
- In order to maximise effective use of the repair

gangs the delivery of equipment and materials was reversed in that suppliers delivered these directly to the requirements of the gangs on site. This was possible due to the pre-developed relationships between the City Council and contractors.

- The ability to generate damage maps (amongst others) is important for communication to the EOC and the public and needs to be an embedded capability for EOCs.

The Review notes the following issues that could have been done better:

- More business continuity planning could have been done in advance.
- Communications with households where supplies were disrupted were inadequate.
- Better damage maps could have been prepared.
- Aspects of the provision of alternative sanitation could have been improved. This includes providing adequate advice on alternative sanitation while portaloos or chemical toilets are being obtained.
- Better communication with the CRC through the Lifelines Utility Coordinator was needed.
- Consideration should be given to establishing reconnaissance teams with their own communications to gather data for multiple lifelines in the same visit, for example, road, water and waste water.

Solid Waste

- There must be pre-planning undertaken for the disposal of non-toxic solid waste, putrescent waste from rotting food, liquefaction silt, demolition material and solid waste from toilet arrangements. This should be done as part of Lifeline plans.

Electricity

- Orion is a commercial company that has integrated risk management in its normal operations.
- Orion had carried out analysis of weak points on the network prior to the 4 September 2010 earthquake and again before the 22 February 2011 event. Mitigation measures costing \$6 million are expected to have saved them around \$60 million.

- Flexible supply design with extensive interconnections assisted restoration by providing routing options.
- Orion had the internal organisation and emergency procedures as well as the in-house capability to respond effectively.
- Orion had the relationships with outside organisations and suppliers to be able to obtain additional staff and resources quickly, including through mutual aid agreements.
- Organisational culture and leadership are important. Ascertaining staff status after the earthquake, feeding staff and contractors, seeing to medical care needs, management of the staff workload and ensuring timely relief were important factors.
- The main Orion Operation centre was inside the cordon. Cordon management was inconsistent and inflexible for staff who had to work within the cordon with frequent changes to access arrangements.
- Contact with the relevant decision makers within Orion and the CRC was confusing with difficulty in contacting the correct person to address issues.
- Overall demolition management could be improved. Protocols need to recognize electricity safety and supply issues.
- The key to the resilience of Orion's services was that it understood its assets and their vulnerabilities.

Telecommunications

- Telecom had a recovery and priority plan that helped them respond to the February earthquake. This included establishing an alternative operating centre in Linwood to provide an alternative to the main exchange that was inside the cordon.
- There was no pre-plan for access through the cordon, providing difficulty to Telecom since ongoing access to their main building was required. This emphasises the need for pre-planning for cordon access in emergencies.
- There is a need for a well thought out and controlled demolition plan and a willingness to share information on buildings to be demolished, since they often had sensitive equipment and/or cables on or under them.

Roads

- Principal roading routes were cleared quickly due to the relationships that were in place between CCC and two major contractors; Fulton Hogan

and City Care. Maintenance contracts also included a clause requiring assistance in the event of an emergency and a schedule of payment rates for the work. This enabled work to commence promptly following the event.

Air

- Systems need to be carefully managed after an emergency. Personnel may be shocked or have personal / family issues and may not be operating with the same level of productivity, alertness and judgment.
- A need arose to contact other control centres around the country. The cellphone network was overloaded / inoperable during the critical phase. To mitigate this satellite phones have since been purchased.
- A mistake from September was to resume BAU too early with consequent staff overload. In February the crisis management team was kept in place until a formal planned handover was appropriate.
- The airport had a well developed and fully practiced emergency management plan which worked well.
- The National CDEM plan should include provision for priority transport of ATC staff from Christchurch to Auckland to service the alternative airways traffic control centre. (New Zealand's main centre is located in Christchurch.)
- In airport emergency planning consideration could be given to rapid evaluation of runway status to enable early emergency operation of military aircraft.

Rail

- KiwiRail had in place a well defined crisis management response for emergencies that allowed BAU and worked due to well-established communication channels.
- An additional rail control centre is needed outside of Wellington as there is almost no local control in the remainder of the country. This would reduce the vulnerability to loss of this centre if a disaster were to occur in Wellington.
- KiwiRail should be urged to take part in local CDEM exercises as well as those at a national level and through lifeline links.
- The relationship between KiwiRail and Fonterra proved beneficial in September 2010, when rail milk tankers were utilized to take water to Christchurch.
- There was a lack of communication between

KiwiRail and the Lifeline Utility Coordinator in the CRC (Christchurch Response Centre) following the February 2011 earthquake.

Port

- The Lyttleton Port Company (LPC) undertook extensive pre-planning and modelling of their infrastructure. The actual behaviour of the wharves in the earthquake was close to predicted giving confidence in the structures and the planning.
- There is a need for closer cooperation and better communications between LPC and CRC in emergency planning.
- There is also a need for open, pre-planning and practiced emergency management communications and knowledge of responsibilities, particularly between the LPC and NZTA.
- LPC should join in local CDEM planning.

Fuel Supplies

- A water supply was needed at the tank farm as a fire-fighting precaution (oil is supplied via pipeline) and the existing supply arrangements failed. Now there is a stand-by fire water supply and pumps in case of further event.
- The ongoing investment in the management of risk and emergencies by the oil industry and their emergency response teams helped in the response to the earthquake.
- There is a need at fuel stations to have standby electricity.
- The issue of fuel distribution and management and the procedures to be used during any restrictions should be addressed at a national level.
- The integrity of tanks and piping at service stations has to be checked prior to fuel delivery. This means there is a need in lifelines response planning to identify the location of priority stations.

Lifelines Coordination

- The LUC team in Christchurch was formed mainly by personnel from one consulting engineering company, who lost access to their offices. This formation has its advantages in terms of cohesion, but also risks such as the loss of the LUC team in the event of a building collapse.
- Pre-established sector coordination responses worked well such as the relationship between the Telecommunications Emergency Forum and the Transport Response team.

- The Lifelines companies that performed the best were those that already had embedded operational and maintenance relationships that were transferred smoothly into emergency mode.
- The contribution by LUC's from other regions in both the CRC and NCMC was of significant benefit. Established personal relationships also assisted.
- The lack of initial documentation (such as the availability of contact lists) impeded the initial setup and it took some time to establish the necessary document and information management and recording systems.
- The principles and practices surrounding lifeline relationships with EOCs should be reviewed and publicised with a view to clarifying the roles of LUC and individual lifelines. This should include relationships between individual lifeline companies and EOCs, TLA-owned lifelines and EOCs, national lifeline companies and the NCMC.
- Nationally based (nationally consistent) training of LUCs should be undertaken.
- National policies should be developed and promulgated in respect of fuel allocation and distribution in an emergency.
- The resilience of infrastructure providers in the main centres in New Zealand should be evaluated to provide a national picture of vulnerabilities and a basis for improvement.

9.2 Capturing the Learning Points from the Christchurch Earthquakes 2010-2011 – Accomplishments, Suggested Improvements and Transferable Knowledge

(Wright, S. 2011)

This document describes Christchurch City Council activities arising from the earthquakes, focussing on the Emergency Operations Centre immediately following the February 2011 earthquake. The issues raised relate to all sectors, but the summary below describes the many issues that had a bearing on infrastructure.

The main infrastructure-related points are:

Coordination

- The need for quick but coordinated response in the Emergency Operation Centre (EOC) and between agencies is the most important learning.
- Further training for Civil Defence Emergency Management (CDEM) staff is warranted.
- Effective shift handover information and briefing information is critical to effective coordination within and between functional areas.
- A standardised handover template was developed by some units and worked well. It identified personnel welfare / availability, key messages, handover tasks to be completed and anticipated issues of the next shift.
- During shift handover it is advantageous for teams to be brought together for a quick debrief session. This avoids duplication of tasks, ensures the strategy is set for the next shift and provides emotional and motivational support for those going off-duty and those about to start.
- Staff known to need EOC access prior to an emergency should have a pictured civil defence identification card that is unequivocally recognised by all agencies involved.
- All agencies involved should meet immediately after the event to coordinate efforts.
- Planning, Intelligence and operations should be in close physical proximity and have regular information sharing debriefs at a management level.

EOC Structure and Delegations

- Align EOC roles more closely with business-as-usual roles to minimise confusion amongst Council staff and maintain normal reporting lines and delegations during an emergency.
- Floor plan locating functional areas and key liaison personnel needs to be accessible.

Relationships

- Sharing of information (between agencies) is critically important and is one of the key learning points from the earthquakes.
- Agencies involved in emergency management need to proactively collaborate in order to document arrangements as to how to work together during an emergency.
- The importance of an up to date contact list is noted.
- Pre-planning was helpful as staff had pre-assigned emergency roles and responsibilities.

- When a national state of emergency is declared, but the emergency is localised, the National Controller should consider using the Council's own delegations systems.
- Local council legal services should be brought into the pre-planning stage of emergency operations so that documentation, templates, protocols and processes can adhere to both council protocols and CDEM legislation. This reduced the need to "break and bend" the rules and minimises legal risk to the council.

Utilising Human Resourcing and Rostering

- Memoranda of understanding need to be established with other metropolitan cities to ensure the local council is supported in a major emergency (e.g. water services, building inspectors).
- Environmental Health Officers offer critical intelligence during an emergency situation and should be embedded into EOCs to assist with water and waste management and subsequent public health issues.
- There should be just one report per functional area and this should be electronically filed in a consistent location.

Standard Operating Procedures

- SOP documents should be developed. These should outline basic operational information, methods and systems, standardised naming conventions for electronic documents and contact information for each function.

Procurement / Finance

- Robust processes and procedures should be put in place for procurement of resources.
- Document all expenditure e.g. asset registers and tracking for Christchurch City Council (CCC) resources and unsolicited donations, delegation limits, authorisations.
- Establish an asset register template that can be used in an emergency so that resources and donated goods can be inventoried, tracked and recalled as necessary.

Information Communication Technology

- Cell-phones should be allocated to roles not people and should stay in the EOC to ensure "on-duty" personnel can be contacted.
- The SIM cards used by these phones should guarantee mobile network access.
- Any future EOC site should be equipped with

wireless technology, fibre distribution and additional networking.

- The call center needs to be located with the EOC; its facility and experienced personnel need to be incorporated into emergency pre-planning.
- It is important to have an up-to-date accessible Geographic Information System (GIS) to provide infrastructure maps on the first day of an emergency operation.

Civil Defence Training & Planning

- Key staff who will be involved in civil defence responses should have role-specific civil defence training.
- Need for an up to date disaster plan for all units across the Council.

Physical Layout of EOC

- Having a centralised map/floor plan of the EOC locating functional areas (e.g. Planning and Intelligence, Operations etc) and key liaison personnel is important.
- Evacuation procedures should be clearly identified.
- A list on the wall should explain each functional area identifying tasks.
- Security guards must be on-site early on and need to secure the EOC 24 hours a day.

Media

- It is important to identify an experienced individual who can actively front the media, has media training and standing within the local community.
- Do not let media into EOC as they can potentially misuse sensitive information.

9.3 Observations, Lessons and Experiences from the Inside

(JasonSmith, G. 2011)

This summary is from a presentation to the 2011 National Lifelines Forum. It describes on-the-ground experience of the lead Lifeline Utility Controller (LUC) in the Christchurch Response Centre following the February 2011 earthquake.

The main points are:

- It is apparent that a large scale event requires more than one person to perform LUC roles

because of the volume of calls being received, the time taken to resolve issues and time taken attending briefings etc.

- Telcos provided additional local cell capacity at ECC. This made a huge difference including ability to use mobile internet.
- Unconventional shift times worked for us, they allowed LUCs to meet the workload and provide time at home for people to attend their families.
- Organisation within the ECC was dynamic and difficult to comprehend. New functions were being added continuously, and others removed or relocated. More strategic direction was necessary.
- Night shifts within the ECC were problematic. Directions, goals and systems often seemed to change overnight. This resulted in lost hours the following morning attending to system needs.
- Some of the ad-hoc parts of the ECC were difficult work with - this may have been because the lack of planning for new functions.
- There is a need for a Demolitions and Site Clearance Coordinator in each ECC, with documented roles and role limitations, and training.
- It was important to keep track of requests that staff were considering "too hard" to ensure they didn't fall through the cracks.
- The CCC IT system was used as the base. It seemed not to be a very good solution.
- A more reliable central email system is necessary. The normal fixed Lifelines ECC email addresses could not be used during the response, instead multiple email addresses were utilised.
- It was often very difficult to contact people in other sections. There was too much reliance on "who you know" and having their personal cell phone number. It was often difficult for the phone owners to get a break when off shift.
- We did not develop a good hand-over system within the LUC section. Too much reliance was put on staff continuity, there was insufficient time to prepare detailed written hand-over notes..
- At the end of the response phase there was no formal hand-over to the recovery organisation.
- LUC-prepared status reports and updates were duplicating those received in SITREPS so they were discontinued. However, LUCs maintained an overview of the situation.
- LUCs expected involvement in the "what about

next week” part of the process but this was virtually zero. Lifelines rapidly became embroiled in detail especially building demolition.

- The only way to reliably contact people to resolve issues was to “visit” them frequently, but first it was necessary to find out who they were and where to find them.
- The procedures around cordon management were never satisfactorily resolved once the army took over from the police.
- Much of the detailed information in SITREPS could be transmitted via standard GIS layers rather than transcribed from text to map at each level. SITREPS could then become a true summary of the situation.
- Contact numbers should relate to the position, not the name. This makes contacting the person on shift much easier.
- The responsibilities and duties of ECC quiet time / night shift staff need to be determined in advance and be clearly understood.

9.4 Lifeline Utility Coordinator Experiences and Learnings

(Roberts, L. 2011)

This summary is from a presentation to the 2011 National Lifelines Forum.

The main points are:

- Established relationships with national utilities enabled the provision of good information which was collated in the NCMC. CRC LUCs were primarily involved in problem solving for local utilities.
- National utility arrangements generally worked well. The local (Christchurch) to national (Wellington) Lifeline Utility Coordination relationship also worked well.
- There was a great amount of general goodwill between utilities which was very helpful.
- Because planned communication links and roles were not always followed, the LUC role becomes reactive rather than strategic. A need arises to clarify LUC’s role with the overall EOC response machinery. Improved training for GECC staff in lifeline utility coordination and expected interactions with LUC is required.
- Improved / standardised process improvements are needed. Specific points noted include:

- Lack of standardised forms and procedures (for handovers, monitoring of actions/requests, priority utility sites, critical fuel customers etc).
- Difficulties in handling and processing information (there was large amount of information churn).
- Improved spatial reporting from utilities (and an improved ability to handle such information when received) would help.
- Plans and procedures for cordon management and building assessment need preparation, and sector coordination arrangements and response plans (e.g. fuel / power/ transport) need development.
- Need to take a more coordinated approach within EOCs to assessing / responding to infrastructure damage.
- There could be an improved use of electronic information management and provisions on status key elements, e.g. building status.

9.5 Canterbury Earthquake – Lifeline Utility Coordination Review

(Fenwick T. & Brunsdon D. 2012)

This is a summary of a brief report to the Ministry of Civil Defence & Emergency Management on lifeline coordination in the days following the February 2011 earthquake.

The main points in the report are:

- More trained Lifeline Utility Coordinators (LUCs) are needed to staff the function in EOCs and ECCs, and to support inexperienced personnel called in to help.
- Existing relationships developed pre-event considerably helped LUC work in the response.
- Sector coordination worked well (e.g. in telecommunications and transport). Existing “business as usual” coordination arrangements in the petroleum sector also worked well.
- EOC coordination and LUC role clarity needs to be improved. Promotion and awareness of the LUC role needs to be fostered.
- TLAs communicated on issues relating to lifelines that they own (roads, water) direct to Christchurch Response Centre (CRC) using

existing intra-corporate communication lines, bypassing the LUC who therefore had an incomplete view of lifeline response issues.

- A lot of time was spent compiling Sitreps including understanding technical information. Local geographic-specific information challenged LUCs who came from other parts of New Zealand to assist.
- LUC systems (e.g. email management) and handovers need to be improved.

The following recommendations are included:

- Work on expanding the number of LUCs nationally, and training, needs to be resumed urgently. The training needs to be nationally-based, or at least nationally consistent. Useful modules exist in several regions and are proliferating. A basis for engagement of LUCs at regional level is also needed (pre-event / on-going).
- The principles and practices surrounding lifeline relationships with EOCs should be reviewed and

publicised with a view to clarifying LUC, SCE and individual lifelines' roles. This to include relationships between:

- Individual lifeline companies and EOCs
- TLA-owned lifelines and EOCs, and
- National lifeline companies' and the NCMC.
- Consideration needs to be given to reporting arrangements from and to lifeline companies with simplification, standardisation and accuracy of summaries in mind. Consideration also needs to be given to tailoring the new Emergency Management Information System to meet utility-specific needs.
- Management and administrative practices in EOCs should be reconsidered. Issues include confirming and promulgating the LUC role at the commencement of EOC activities, optimising LUC periods of duty (especially for the more experienced LUCs), and setting up effective LUC desk operating systems.

10 MISCELLANEOUS

10.1 Infrastructure Recovery Following the Canterbury Earthquakes

(Cleary, G. 2012)

This brief 2012 paper contains observations from Waimakariri District Council on infrastructure recovery.

The main points are:

- “It’s about the community, not the Council’s assets”. Public were most interested in the provision of services to their properties; when their water would be working, and whether or not they could flush their toilets.
- The primary focus of the public in the recovery phase was on rebuilding their houses. They were not concerned with the reestablishment of roading or pipe networks, but wanted to know how to deal with insurers and commencing work on their houses.
- Having a good understanding of the current capacity of the existing assets and the future capacity that would be expected due to growth allowed the council to make more informed decisions.
- The Council had developed, in collaboration with business owners and the community. Rangiora and Kaiapoi Town Centre strategies. This gave the Council a base plan to work on, facilitating progress toward normality faster than would usually be anticipated.
- Modern materials such as plastic piping stood up well during the earthquakes, even in areas where the pipes were used as trunk mains in liquefaction affected areas. It can be concluded here that the more modern technology has been effective in achieving a more robust infrastructure in the Waimakariri District.

10.2 The Canterbury Earthquake – The Impact on Farming Organisations

(Whitman, Z., Seville, E., Wilson, T., & Vargo, J. 2012)

This paper describes the impact of the earthquakes on the farming sector.

The main points are:

- The most disruptive impact on farmers (particularly dairy farmers), following the Darfield earthquake, was the loss of power (e.g. can’t milk dairy cows, which has a potential health impact on the cows).
- Other disruptions (particularly to mixed and arable farmers) arose from interrupted water supply (e.g. damage to wells or breaks in water lines). Economic impact of this disruption is time dependent (i.e. whether or not the water loss occurs during times of high irrigation or not).
- Turbidity of water in wells affected irrigation.
- Some of the lifelines impacts were mitigated by good neighbour relationships (ability to share resources and help each other get resources needed).

10.3 Observed Performance of Industrial Pallet Rack Storage Systems in the Canterbury Earthquakes

(Uma, S. R., & Beattie, G. 2011)

This is a summary of a paper from the December 2011 Bulletin of the New Zealand Society for Earthquake Engineering, Vol 44, No. 4.

The main points are:

- Investigations by the authors draw attention to an apparent lack of consistent national control over the design and construction of racking systems.
- The collapse of pallet and racking systems lead to significant loss of shop stock and other goods.
- The failure of pallet and racking systems can be attributed to various reasons including inadequate design, inappropriate operational condi-

tions, improper installation and lack of maintenance.

- National control over design and construction of racking systems would be beneficial, as would clarity over what systems require a building consent.
- The revised seismicity factor in Christchurch will have an effect on the suitability of racking systems. Racking owners need to check their systems and either strengthen or reduce loadings if required.
- Second-hand racking systems should be considered scrap metal due to the uncertainty of the residual capacity of the system.
- Regular detailed inspection of racking systems is highly recommended to reduce life and economic losses in the event of an earthquake.
- Professional training programmes are recommended for users and installers of racking systems.
- Progress towards the publication of a revised and extended design guide is also described in the paper.

10.4 Bank of New Zealand: Response in Christchurch

(Beaumont, C. 2011)

This summary is taken from a BNZ report prepared for the Continuity Forum.

The main points are:

Key Learnings

- Staff welfare: staff contacted through a variety of media, cash grants given and EAP services offered
- Returning to business as usual has helped psychological healing of staff.
- Customers welcomed contact about their well-being and financial assistance packages
- Some disruption occurred to services due to building damage and ATM inaccessibility.
- Critical functions were moved to Auckland and Wellington temporarily.
- No long term key supplier issues arose.

Keys to a Successful Recovery

- Business Continuity Planning: contingency planning is important but equally, flexibility to

adapt leads to quick and innovative solutions.

- Test Plans: testing increases the skills and proficiency of staff to cope during a business interruption event.

10.5 The Recovery of Canterbury's Organisations: A Comparative Analysis of the 4 September 2010, 22 February and 13 June 2011 Earthquakes

(Stevenson, J., Vargo, J., Seville, E., Kachali, H., McNaughton, A., & Powell, F. 2011)

This document describes a range of learnings arising from the earthquakes. The summary below focuses on infrastructure-related issues.

The main points are:

- Organisations should improve the resilience of their supply chain to disruption through measures such as identifying alternate suppliers or suppliers that are outside of the region and therefore unlikely to be affected in a regional disaster.
- Organisations should consider setting up mutual agreements or collaborations with other organisation to ensure critical supplies can be accessed if disruptions occur.
- Supplier issues were more problematic following the February 2011 earthquake compared to the September 2010 earthquake. This suggests that many organisations may not have adequate contingency plans in place.
- Very few business indicated having alternatives or backups to electricity prior to September 2010. Twenty-nine per cent of organisations surveyed indicated that they felt they had not done enough planning for electricity supply disruption.
- Organisations did not feel they had done sufficient planning for sewerage and road network disruptions, and some of these indicated they were unsure of how to plan for these kinds of disruptions.

The report includes the following note:

Following the 22 February and 13 June earthquakes, road network problems were found to be the most disruptive critical service issue for organisations. As reconstruction continues, road

networks are likely to continue to be disrupted. Also long-term changes in road networks, such as the decision to delay repairing the Sumner Road, are likely to have major impacts on some organisations. Organisations will need accurate and up-to-date information on road network disruptions and planned road works.

10.6 Lessons from Liquefaction in the Canterbury Earthquakes for Enhancing the Resilience of the Built Environment

(Brabhakaran, P. 2012)

This summary is from a paper delivered to the INGENIUM Conference in June 2012.

The main points in this paper are:

- Liquefaction and consequential ejection of sand, ground subsidence, flooding and lateral spreading caused widespread damage to infrastructure, commercial and residential properties. Those most damaged were located close to rivers or on reclaimed low-lying land and this was due to lateral spreading.
- Some of the liquefaction effects could have been avoided if there had been adequate consideration of liquefaction as a hazard in more recent times. More knowledge has come to light since the days when Christchurch was built.
- The importance of hazard assessments is noted; e.g. publication of maps that identify ground damage (lateral spreading from liquefaction for example), the active promotion of these maps, and community education.
- Attention to land use planning is needed to avoid zoning areas for urban development where land is prone to extensive natural hazards.
- Leaving land use planning to developers has proven ineffective in Christchurch and it would be more effective to have town planners with interaction from geotechnical engineers decide on land use and hazard mitigation in order to promote consistency.
- Liquefaction caused significant damage to a number of bridges in the liquefied areas, although as a whole, bridge structures performed very well outside these areas. The resilience of bridges and other transport infrastructure can be enhanced through appropriate design.
- Lifeline networks including underground utilities are vulnerable to liquefaction and ground damage. The resilience of these networks can be assessed, and enhanced through long term planning, consideration of resilience in the development of lifeline network upgrades, and through selection of appropriate forms.
- It is important to foster early co-operation between professionals who are involved in the development of the built environment, such as planners, architects, structural engineers and geotechnical engineers.
- Early integrated focus on resilience by building professionals in the development of projects will help conceive concepts and forms that are more resilient to earthquakes, and achieve resilience without significant additional cost.

10.7 Building Issues for Lifeline Utilities Following Major Earthquakes

(Brunsdon, D. 2011b)

This November 2011 presentation to the Auckland Engineering Lifelines Group summarises some key issues relating to seismic performance of buildings.

The main points are:

- Many key facilities were behind the CBD cordon.
- Questions that utilities should ask themselves include:
 - What is the likely seismic performance of your premises?
 - Has an engineering assessment been undertaken?
 - Have the premises been designed to meet the appropriate Importance Level, e.g. Level 3 or 4 (in terms of Table 3.2 AS/NZS 1170 Part O:2002)?
 - Do you have good access to structural engineers for immediate safety assessments?

10.8 Impacts and Emergency Response to 12th June 2006 South Island Snowstorm

(Wilson, T. M., Johnston, D. M., Paton, D., & Houghton, R. 2009)

This is a summary of a GNS Science report (April 2009) on a survey relating to the emergency response to the June 2006 snowstorm.

The main points are:

- The June 2006 Canterbury snowstorm caused widespread impacts, resulting in a major regional emergency response. This report presents the results of a survey covering the issues arising, together with limited interpretation and analysis.
- There was particularly widespread and severe damage to electrical distribution networks due to the heavy weight of the dense, wet snowfall. Telecommunication services failed as batteries in exchanges were unable to sustain services once mains power was lost. Disruption of transportation networks for periods of a few hours to several days hindered the emergency response.
- The rural sector in particular was heavily impacted by loss of power and telecommunications for an extended period of time (up to 3 weeks in some areas). Livestock losses were minimal on most farms although the loss of condition resulted in a considerable reduction in many farms' productivity. Widespread damage occurred to fences, trees and some buildings.
- A survey was sent to 92 individuals or organisations involved in the emergency response. The survey aimed to record damage, impacts on urban and rural communities, effectiveness of organisations' response plans and lessons for dealing with future snowstorms.

Key lessons taken from survey responses include:

- There is a strong desire for a more detailed and accurate meteorological warning of what impacts snowstorms will cause spatially and temporally, and the characteristics of the snow itself.
- The value of effective and efficient impact assessment was highlighted during and following this event.
- Widespread electrical power failure is largely inevitable in a large snowstorm. Organisations and communities need to adequately prepare.
- The failure of communications systems caused

significant problems. Organisations should diversify their communications systems to mitigate this problem.

- Disrupted transport networks made it important for emergency responders and repair crews to be equipped with 4WD vehicles / chains.
- Experienced staff, staff training and continuously updated emergency response plans are highly effective.
- Coordination of information and communications at intra-organisational and inter-organisational levels appeared to be lacking in some cases. Future planning should focus on effective (co-ordinated) dissemination of hazard, impact and resource availability information) and on inter-organisational issues.
- Rural communities will generally be without essential services for much greater periods than urban areas and may suffer isolation for extended periods. They should plan to adequately deal with this reality.

10.9 Analysis of the 2008 Flooding in the Hurunui District

(Alexander, D., Crawford, G., Dixon, B., England, K., Falcon, D., Farrell, D., et al. 2009)

This summarises a draft paper prepared by University of Canterbury students in October 2009.

The main points are:

- Strengths of the flooding response were the effective CDEM group-led evacuation and strong informal rural networks.
- Weaknesses were the warnings and warning systems, community awareness of media warning outlets, CDEM log records and the hindrance to response caused by RMA (1991) constraints.
- The key recommendations to improve CDEM processes, warning systems, infrastructural resilience, and insurance policy development are:
 - Continue to develop and work with the community in improving the flood warning system (including weather prediction, rain/river gauges, modelling) and awareness of how the system operates, including developing informal communication networks (i.e. gathering observation data from locals). In

particular, limited information / modelling exists for flood prediction on rural properties.

- Streamline legislation that focuses on sustainability within a hazard management paradigm, specifically in relation to updating the RMA to include consequence-based decision making processes (e.g. taking aggregate from river without consent for road repair).
- Improve the flood modelling capability in the Hurunui District. This requires upgrading and expanding the existing river flow and level gauge stations, as well as modelling inundation in the lowland and coastal areas.
- Submit an updated application to the NZ Transport Agency (NZTA) to request the Inland route (Route 70) from Waiau to Kaikoura to be designated a State Highway.
- Create a simple pro-forma template that could be distributed to those taking calls, with prompts to write down date, time, contact details and the body of the notification which would create a more robust master record.
- CDEM outpost communication could have been improved. Posts were sometimes unmanned due to volunteers tending their own properties.
- Previous lifelines studies concentrated on vulnerability of road networks.
- Flood damage to water supply networks, mostly where pipes located under stream beds that were scoured out.
- Flood had little or no impact on telecoms and electricity. Partly due to location of poles (i.e. no scour around poles and no damage to culverts carrying services).
- Damage to transportation network had biggest impact on community.
- Overall flooding had limited infrastructure impact compared with the 2006 Canterbury snow storm, where the electricity and telecommunications networks were non-operational for extended periods (up to three weeks in some cases).
- Economic impacts arose from loss of transportation routes and costs to repair damaged roads and water supply networks.
- Further hazard modelling and analysis of flooding impact on critical infrastructure in Hurunui is recommended.
- Limited funding availability for critical infrastructure maintenance and emergency works due to a low population density across a large geographic area. A major concern for the District is that the economic impacts sustained were from a relatively low magnitude event that did not result in widespread disruption to critical infrastructure and yet, the impacts have left the District very vulnerable to future events.
- Social impacts during the flooding events were primarily a result of damage to the transportation network, with 64 per cent respondents reporting their day-to-day activities were affected by road access. These social impacts could have been more extreme if the telecommunication and electricity supply networks were also impacted, as would be likely during an earthquake.

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