“Recovery of Lifelines” following the 22nd February 2011 Christchurch Earthquake: successes and issues

Sonia Giovinazzi, Thomas Wilson.

University of Canterbury, Christchurch, New Zealand

2012 NZSEE Conference

ABSTRACT: The devastating magnitude M6.3 earthquake, that struck the city of Christchurch at 12:51pm on Tuesday 22 February 2011, caused widespread damage to the lifeline systems. Following the event, the Natural Hazard Research Platform (NHRP) of New Zealand funded a short-term project “Recovery of Lifelines” aiming to: 1) coordinate the provision of information to meet lifeline short-term needs; and to 2) facilitate the accessibility to lifelines of best practice engineering details, along with hazards and vulnerability information already available from the local and international scientific community. This paper aims to briefly summarise the management of the recovery process for the most affected lifelines systems, including the electric system, the road, gas, and the water and wastewater networks. Further than this, the paper intends to discuss successes and issues encountered by the “Recovery of Lifelines” NHRP project in supporting lifelines utilities.

1 INTRODUCTION

A magnitude 6.3 earthquake struck the city of Christchurch at 12:51pm on Tuesday 22 February 2011. The earthquake caused 182 fatalities, a large number of injuries, and resulted in widespread damage to the built environment. The Christchurch earthquake badly damaged over 6,000 residential and disrupted the main lifelines systems of the city (including the road, the water and wastewater networks and the electric systems) forcing thousands to leave their homes and communities. The February event compounded some of the effects of the 4 September 2010 earthquake, which did not directly result in any fatalities but did cause widespread property and infrastructure damage

Following the 4 September and 22 February earthquakes in Canterbury, New Zealand, the Natural Hazard Research Platform (NHRP) of New Zealand funded various projects to support and inform the decision making process during the recovery phase. The “Recovery of Lifelines” short-term project was established and funded by the NHRP to support the recovery of lifelines in the Canterbury Region. The project aimed to inform and help meet the short-term operational needs of lifeline utilities by: 1) facilitating the accessibility to lifelines of best practice engineering details, along with hazards and vulnerability information already available from the local and international scientific community; 2) informing the research community about the lifeline utility needs and information requirements. The project Principal Investigator, Dr Sonia Giovinazzi acted as a liaison person between the affected lifeline utilities, the National Engineering Lifeline Committee (NELC), the Canterbury Engineering Lifelines Group (CLUG) and the national and international research community to coordinate the provision of information and know-how. The project team included: Prof. Jarg Pettinga, Prof. Misko Cubrinovski, Dr Tom Wilson, Prof. Alan Nicholson, Ass. Prof. Neville Watson (University of Canterbury); Caroline Holden (GNS Science); Helen Grant (Environment Canterbury Regional Council); Mark Gordon (Canterbury Lifelines Utility Group).

The first section of this paper provides a brief overview on the impact of the Christchurch earthquake on lifelines by briefly summarising the physical damage to the networks, the system performance and the operational response during the emergency management and the recovery phase. A complete description of the impact on lifelines of the 4 September Darfield and 22nd February Canterbury earthquakes, is out of the scope of the paper and can be found in the reconnaissance report from the

Technical Council of Lifelines Engineering, TCLEE (Eidinger and Tang, 2011). Further accounts on the performance and emergency management of lifelines systems following the Darfield and Canterbury earthquakes can be found in Giovinazzi *et al.* (2011), Cubrinovski *et al.* (2011), Palermo *et al.* (2011), Massie and Watson (2011), Transpower (2011a, 2011b). The second section of the paper shortly summarises the operational short-term needs and the information requirements identified and discussed with the lifelines utilities as part of the Recovery of Lifelines project. The third section of the paper briefly outlines the way in which the researchers involved in the Recovery of Lifelines NHRP project engaged with lifelines utilities to provide know-how and information that could support their short-term operational needs. Issues encountered and lessons learned are discussed in the conclusion of the paper.

2 IMPACT AND POST-EARTHQUAKE RECOVERY OF LIFELINES IN CANTERBURY: A SHORT OVERVIEW

2.1 *Electric Power System*

The electric power system serving the Christchurch area is operated by two companies: Transpower and Orion. Transpower operates the high voltage nation-wide transmission system, with highest voltages in the Christchurch area of 220 kV, along with some 66 kV. Orion is the local power distribution company (the 3rd largest power distributor in New Zealand), which conveys power from Transpower to end user customers, via a low and medium voltage (66 kV, 33 kV, 11 kV and 400 V) underground and overhead distribution network.

The resilience of the high-voltage transmission grid in the Canterbury and northern South Island region, was challenged by the 4 September 2010 and 22 February 2011 earthquakes (Transpower 2011a; Transpower 2011b). However the impact from both earthquakes on the electrical stability and operation of both national grid and regional supply was negligible. In particular, following the 22 February earthquake the power to the national grid was unaffected, while power to the feeders into Christchurch City and regional substations was unavailable for up to 4.5 hours while safety checks and minor repairs were made. After that, the supply at the transmission grid exit points was restored to full capacity (Transpower 2011b).

The power distribution network was badly affected following the 22 February earthquake. The large ground deformation induced by the earthquake caused multiple faults in 66 kV and 11 kV underground distribution networks, inducing major power outages and loss of functionality to the power distribution system.

Of the 66 kV underground cable network, 50% of cables were damaged, 30 km out of a total of 60 km. All major 66 kV cables, supplying Dallington & Brighton zone substations were damaged beyond repair and had to be abandoned. These cables were pairs of radial 66 kV 3-core aluminium (300 mm2Al), oil filled, aluminium sheathed with an outer cover of semi-conducting plastic sheath over the aluminium (Orion AMP 2009). Multiple faults were also identified in the 66 kV underground cables located within and close by the Christchurch CBD, namely: cable from Transpower Addington GXP to Orion Armagh substation (oil filled cables); cable from Orion Lancaster to Orion Armagh district substation (and the copper cross-linked polyethylene cable, Cu XLPE,), installed in 2002 to provide additional system security to the Christchurch CBD (Figure 1a). As a matter of fact the vulnerability of oil filled cables to earthquake-induced differential ground settlements was previously identified by Orion as potential risks (Orion AMP, 2009). In particular the oil filled cable from Dallington to Bromley 66 kV (damaged beyond repair following the 22nd February earthquake, as mentioned above) was identified at higher risk, being located in the area on the south side of the Avon River (Orion AMP, 2009).

Of the 11 kV underground network 14% of the cables were damaged, 330 km out of a total of 2,300 km. The affected 11 kV cables were either aluminium, or copper core cables of different length, diameters and types, including: paper lead; paper-insulated lead-covered, armoured, PILCA; PILCA HDPE cables, PILCA with a high density polyethylene HDPE outer jacket; cross-linked polyethylene, XLPE cables with PVC and HDPE protective outer jackets.

Damage to overhead lines (33 kV, 11 kV and 400 V) was relatively minor, including cracked insulators and poles affected by liquefaction.

Figure 1. 66 kV underground cable distribution network: a) damage to 1600Cu XLPE cables; b) repair activities (photo credit Orion).

Distribution building substations and zone substations (all strengthened as part of a $6 million seismic upgrade program that addressed all Orion substation buildings) performed well despite the ground motions exceeding the design codes of the seismic strengthening programme. One zone substation (out of 51) suffered from liquefaction. Of 314 distribution building substations located in Christchurch urban area only 4 experienced significant damage. The Orion Administrative buildings, located in the CBD, were badly affected and were evacuated soon after the 22 February earthquake. The control centre was re-established within 2 hours in an adjacent building that did not suffer major damage

Despite the severe physical impact of the earthquake on the Orion distribution and sub-transmission network, Orion was able to restore the power to about 50% of occupied households on the day of the event, 75% after 2 days, 90% within 10 days and 98% after 2 weeks. Temporary 66 kV overhead lines were installed on an emergency basis, within one-week, from Bromley to New Brighton (4 kilometre line) and from Bromley to the Orion Dallington substation (4.5 kilometre line) to ensure power supply to 20,000 customers in north-east Christchurch. More than 600 quake-related underground cable faults to both 11 kV and 66 kV cables were repaired within three months (Figure 1b). A total of more than 1000 faults in the 11 kV underground network were identified and repaired within six months (Orion Media release 31st August 2011).

Each of the cable faults took more than 12 hours to find and repair. The intensive post-earthquake work plan saw 700 electricity sector workers from around New Zealand and Australia contributing, under a mutual aid support agreement, more than 200,000 people-hours to earthquake recovery (Orion Media Release 22 June 2011).

2.2 *Road Network*

Road networks were extensively damaged by the significant liquefaction induced by the 22nd February earthquake that resulted in settlement, lateral spreading, sand boils and a large quantity of ejected silt, mud and water ponding on the road surface (Ciubrinovsky *et al.* 2011). Most of the State Highways remained open. Local roads in the eastern suburbs of the city were the most affected. Eighty-three sections of 57 roads were closed. Five of the 6 bridges crossing the lower Avon River were closed and many bridges required weight restrictions. Substantial temporary traffic management measures were put in place to manage the residual functionality of the road network: including temporary speed restrictions (30 kph); adjustments to traffic signals; and adjustments to bus routes. Despite the temporary traffic management measures and the effective programme to speed-up the liquefaction clean-up operations (Villemure *et al.* 2011) congestion remained problematic for months following the earthquake. Pre-earthquake seismic improvements to bridges on State Highways 73 and 74 proved successful in resisting substantial loads and keeping the highways in operation post-earthquake.

Rockfalls in the Port Hills led to several key road closures due to roads being blocked and were an on-going hazard from unstable rocks (Figure 2a). Closure included Evans Pass, which provides a vital link for oversized or explosive goods between Lyttelton Port and the city via Sumner, and Main Road which links the south-eastern suburbs of Redcliffs and Sumner to the city.

Figure 2: Earthquake-Induced Damage to the Highway System: a) RockFalls in Port Hills following 4th September 2011 (yellow) and 22nd February 2011 (Red), threatening Tunnel Road State Highway 74, (Image credit Max Letham); b) Liquefaction induced flooding on highways.

2.3 *Water and Wastewater Networks*

Christchurch water and waste networks suffered extensive damage as a result of the 22 February 2011 earthquake. 36,000 water and wastewater service requests were received and addressed by Christchurch City Council (CCC), which owns and manages the city's water and wastewater networks, in 5 months following the earthquake. Approximately, 50% of the city was without water for the first days following the earthquake; more than a third of households were without water for over a week. A month on from 22 February 2011, over 95% of occupied units (outside of the cordoned Christchurch CBD) had water, however a "boil order" was in-place for over six weeks for most of the city due to potential contamination caused by severe damage to the wastewater system. Chlorination, which was not used pre-earthquake, remained a requirement until 7 December 2011. Water conservation orders are in place as a result of damages to key water reservoirs and the loss of many groundwater pumping wells; all related to geotechnical problems. However, with few exceptions water reservoir structures and pump stations performed very well owing to pre-earthquake engineering and seismic upgrades (Charman and Billings, 2011).

The city continued to rely heavily on a temporary sewage service facilitated by chemical and portable toilets to supplement the fractured and fragile wastewater system for several month following the 22 February earthquake (Stevenson *et al.* 2011). Christchurch City Council set a target of returning sewer services to all homes by the end of August (6 months following the quake) and contractors have been working 24 hours a day, seven days a week since early March to achieve this goal. At 31 August work was completed on all public sewer pipes, but around 800 houses where out of service due to the damage to their private sewer pipes. Raw sewage continues to be disposed in the rivers and estuaries due to the inability to treat the waste as a result of significant liquefaction induced damage at the Bromley Waste Water Treatment Plant. The treatment plant has been unable to perform any more then partial primary treatment since the 22 February earthquake. Some sewage is bypassed directly to the sewerage ponds and some pumped directly into rivers. Concerns abound about the sewerage ponds becoming anaerobic and emitting a stench across the city. The treatment plant was also repeatedly damaged by sand and silt, which flowed into broken sewage pipes when the ground liquefied, continually washed into the basins. The plant was not designed for such heavy solids.

The water system restoration activities completed within six months time following the 22 February earthquake included: construction of 12 km of pressure main, reparation of 60 water supply wells, renewal of 150 km of water main and of 100 km of submain. It will take years to return the water and wastewater systems to pre-earthquake functions (Mark Christison, personal communication).

2.4 *Gas Distribution System*

Contact Energy (Rockgas) operates the Liquefied Petroleum Gas, (LPG) distribution system in Christchurch with a reticulated pipe network comprising of approximately 180 km of medium density polyethylene, (MDPE), pipes. The LPG network is supplied from one main feed plant, Woolston Terminal supplemented by a pressure peaker plant, and three backup plants. The distribution network is subdivided into 189 separately valved zones that can be manually shut off.

Following the 22 February main shock, the feed supplies into the system were shut off, as a precaution. The system was re-livened, starting 23 February, section by section following the positive outcome of a drop test (no leakages detected) after proof residual gas pressure was found within the section. No damage was observed both to the MDPE distribution pipes and to their welded joints, despite the gas pipes were located in zones that experienced severe liquefaction and ground deformations. The gas system performance in the 22 February earthquake (and in the 4th September 2010 Darfield earthquake and 13 June 2011 aftershock) was remarkably good compared to the performance of reticulated gas networks following large earthquakes in other parts of the world (Figure 3a), especially those where the use of cast iron and other older transmission and distribution pipe is still common (Schiff, 1995, 1998).

Lessons learnt following the Kobe earthquake and the participation in the emergency preparedness activities encouraged by the Canterbury Lifelines Utilities Group strongly influenced the design of a highly resilient system (Figure 3b) with robust and redundant hardware and suitable preparedness thanks to the availability of back-up resources (Smith and Yu, personal communication).

3 MEETING LIFELINES UTILITIES AND ASSESSING SHORT-TERM RECOVERY NEEDS

One of the primary objectives of the NHRP short-term project on Recovery of Lifelines was to establish and maintain communication with affected lifeline utilities to identify specific short-term needs and to discuss long-term modelling and analysis needs.

The Principal Investigator (PI) of the “Recovery of Lifelines” project, Dr Sonia Giovinazzi and the Canterbury Lifelines Utility Group, CLUG, representative, Mark Gordon, met with representatives of the main lifelines utilities to discuss with them their specific needs during the recovery phase. Meetings were held with affected lifeline utilities, in particular with representatives from power (Orion, Transpower); telecommunications (Chorus); water and wastewater (Waimakariri District Council) and transport utilities (New Zealand Transport Agency, CCC road and bridges staff). Further to the meetings, regular e-mail communication was instituted with the affected lifeline utilities to ensure a two-way liaison with the scientific community.

From the meetings held with each utility company, specific short-terms needs were identified and discussed (Table 1).

Table 1. Lifelines utilities short-term needs during post-earthquake recovery

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 comparing alternative solutions to built permanent capacity in the eastern suburbs of Christchurch
Assessing earthquake risk to underground lines versus wind and snow-storm risk to overhead lines

Assessing cable-bridge interactions and coordinating repair activities with road and bridge
Telecommunication
Assessing residual/future functionality of stretched copper cabling Existing standards/procedures to straighten the cellular network towers out of plumb due to liquefaction Seismic Scenario Analysis for assessing and comparing alternatives solutions to replace damaged exchanges
Highway and Urban Road
Assessing and accounting, within repair/rebuilding designing procedures, for the increased risk of flooding induced by the subsidence phenomena observed following the earthquakes (Figure 2b) Assessing and mitigating the rock-fall risk on roads induced by the earthquakes and following aftershocks
Water and wastewater
Documenting and analysing the seismic performance of different buried pipes typologies (material/age) to identify the less vulnerable solutions for repairing and rebuilding Identifying techniques and tools to support the prioritisation of repairing/reconstruction activities and to justify costs of earthquake resistant solutions Defining a method and a tool for automatically mapping and assessing earthquake-induced damage to sewage network, starting from CCTV (closed circuit television) footage
Gas
Existing standards/procedures to seismically design Liquefied Petroleum Gas feed plant

Longer-term modelling and analysis needs identified by lifelines utilities and discussed as part of the "Recovery Project" have been summarised in a document prepared for the National Engineering Lifelines Committee (NELC) and NHRP. The document has been used by NELC as a reference to identify infrastructure research priorities in New Zealand (Neo Leaf Global Ltd 2011).

4 INFORMATION AND KNOW-HOW PROVISION IN SUPPORT TO LIFELINES SHORT-TERM RECOVERY NEEDS

The information and know-how provided in response to the lifelines short-term needs are shortly presented below. Specific requests from the lifelines utilities are summarised into five main areas, namely:

1) standards, guidelines and best-practices for repair/retrofitting and designing earthquake-resistant lifelines systems;
2) best-practices for documenting and analysing the performance and damage of lifelines during the Canterbury earthquake sequence;
3) procedures for assessing the residual/future functionality of affected components;
4) best-practices for estimating the expected performance and risk of alternative repair and/or reconstruction strategies in case of further earthquakes;
5) procedures for reporting/documenting the lessons learned from the earthquakes before the knowledge is lost.

4.1 *Standards, guidelines and best practices for repairing damaged lifelines components, for retrofitting existing assets and for designing earthquake resistant and/or multi-hazard resistant lifelines systems*

A revision of existing standards for repairing, retrofitting and designing earthquake-resistant lifelines component is out of the scope of this paper and was out of the scope of the Recovery of Lifelines project. This section aims to briefly summarise what was discussed with the lifelines utilities in response to their request for existing standards and guidelines to be used as a reference for repairing, designing and retrofitting activities.

In 1996 a plan for developing and adopting seismic design guidelines and standards for lifelines was prepared in the United States by the Federal Emergency Management Agency (FEMA) with private sector input (FEMA 271). The American Lifelines Alliance (ALA) a public-private partnership between FEMA and the American Society of Civil Engineers (ASCE) was initiated with financial support from FEMA in 1998 with a primary goal of facilitating the development and improvement of the design of key utility (electric power, telecommunication, water, waste water, oil, natural gas, rail, and shipping ports) and transportation systems, to achieve the desired level of performance in natural hazards (Honegger et al. 2003).

Multi-hazard design of lifelines components and multi-hazard analysis of existing lifelines components - To assist in identifying gaps in existing knowledge or practice, ALA prepared matrices of existing guidelines and standards (ALA, 2004) for the design and/or analysis of existing components of lifeline systems accounting for the loads from natural hazards, (earthquake, wind, snow and ice) and man-induced hazards (cyber, radiological, chemical or blasts). Lifelines systems accounted for within the ALA guidelines and standards matrices include: oil products systems; natural gas systems; water system (potable and raw); wastewater systems; telecommunication systems; port and inland waterways; highways and roads; railroad (Figure 4).

ALA matrices include USA guidelines and standards only. The European Commission, the Japan Society of Civil Engineers, the Indian National Center for Earthquake Engineering, among others, have issued further guidelines and standards for the seismic design of lifelines components, e.g.: i) Eurocode-8: Design Provisions for Earthquake Resistance of Structures, Part-4: Silos, Tanks and Pipelines, (Eurocode, 2004); ii) Basic Principles of Seismic Design and Construction for Water Supply Facilities (JSCE, 2000a); iii) Recommended Practices for Earthquake Resistant Design of Gas Pipelines (JSCE 2000b); iv) IITK-GSDMA Guidelines for seismic design of buried pipelines (NICEE 2007).

Techniques and practices for seismic retrofitting lifelines components and systems - Seismic retrofitting techniques for components and systems are reviewed (including the benefits of retrofitting versus gradual replacement) and described in different hazard-specific and utility-specific documents and reports from ASCE, FEMA and ALA e.g.: i) Seismic Design and Retrofit of Piping Systems (ALA 2002); ii) Earthquake Resistant Construction of Electric Transmission and Telecommunication Facilities Serving the Federal Government (FEMA 202, 1990); iii) Earthquake Resistant Construction of Gas and Liquid Fuel Pipeline Systems Serving or Regulated by the Federal Government. (FEMA 233, 1992); iv) Guidelines for the Seismic Upgrade of Water Transmission Facilities (ASCE 1999).

Techniques and practices for repairing damaged lifelines components following earthquakes – A summary report and/or specific guidelines on techniques and practices for post-earthquake repairing of lifelines components could not be identified during the period of the project. The suggestion was made to look for specific examples in the many reconnaissance reports available from ASCE and ALA.

4.2 *Best-practice for documenting and analysing the performance of affected lifelines during the Canterbury earthquake sequence*

Lifeline utilities were advised on the need to document the damage sustained by the components of their networks, and on the need to analyse the relationships among the observed damage and the: ground motion, earthquake-induced permanent and transient ground deformation, groundwater, and surface and subsurface conditions at the location of the network components.

Detailed information on how to perform a post-earthquake vulnerability analysis can be derived from international literature. A detailed overview on how to analyse and represent the relationship between buried lifeline damage and various seismic parameters is provided in O'Rourke and Jeon (1999). ALA (2001) provides a complete guide on the formulation of seismic fragility curves for water system based on post-earthquake damage data processing.

As an easy and operative rule of thumb the following three steps were suggested to affected lifeline utilities:

Step 1. Collect, classify and represent within a Geographical Information System the damage and repair activities to the affected lifelines components following the 4 September 2010, 22 February 2011 and 13 June 2011 earthquakes;

Step 2. Overlay GIS layers of the damage sustained by their network, and vector or raster maps of the ground motion, ground deformation and soil conditions recorded/observed at the location of their networks and affected components;

Step 3. Estimate and represent the relationship between lifeline damage, the seismic input and liquefaction-induced ground deformations to get a first understanding of the seismic performance of the network components (and of different typologies of components, e.g. material/age, if applicable).

Figure 3 shows some preliminary maps and results of the damage to lifelines systems overlaid with the few maps and data on liquefaction induced ground-damage that were made available to the Recovery of Lifelines project (Table 2). In particular Figure 3a shows checks and repair activities to the wastewater network following 4 September 2011 earthquake. Figure 3b shows the percent of total length of different pipe materials within different ground deformation areas. Figure 3c shows the performance of pipes of different materials for the Kaiapoi water network following the 4 September earthquake. High Density Polyethylene (HDPE) pipes showed excellent performance.

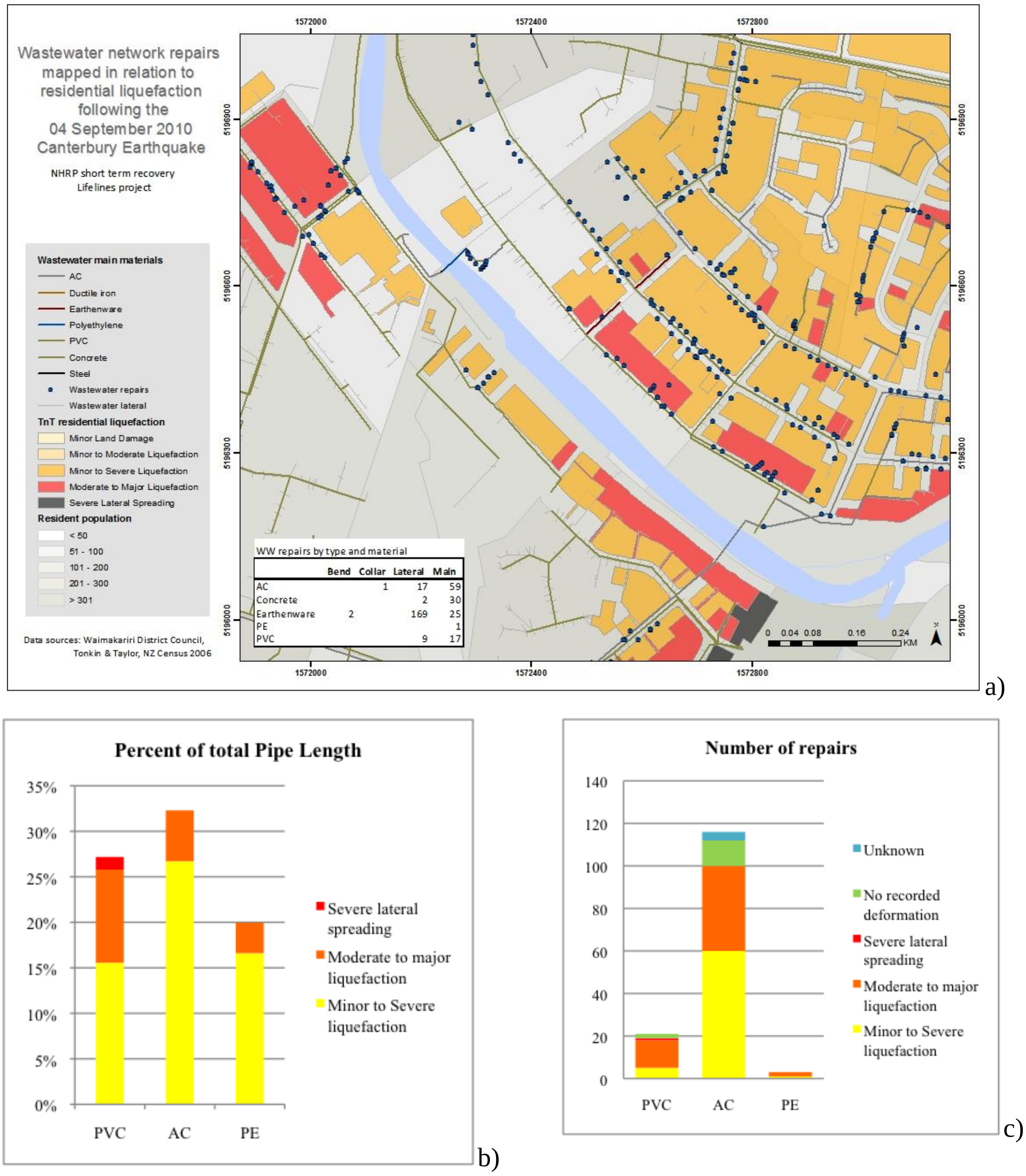
Table 2. Ground-motion and land damage data and maps requirements and availability at the time of the Recovery of Lifelines project

	Maps and data description	**Availability**
Ground-motion	GeoNet Strong Motion Database - Strong motions records available at the location of the 132 GeoNet strong motion stations (GeoNet 2011)	Available at the location station point (derived interpolated maps)
Land damage: liquefaction induced soil failure, **surface fault rupture,** **rock fall.**	Liquefaction drive-through reconnaissance map mapping surface evidence of liquefaction on roads and adiaject areas (Cubrinovski and Taylor, 2011).	Available (raster format).
	Land damage to residential areas (Tonkin and Taylor, 2011), commissioned by the Earthquake Commission (EQC)	Available to the project team only. Not available to lifelines utilities due to confidentiality issues*
	LIDAR data	Not available to the project
	Damage to underground water waste-water and sewage network to be used for microzoning purposes (O’Rourke and Jeon, 1999)	Not available to the project
Surface and shallow soil conditions **Groundwater data**	Geology map of the Christchurch Urban Area 1: 50,000 (Brown and Weeber, 1992);	Available (raster format)
	Ground-water table	Available
	“Swamp to City” Christchurch Drainage Board (Wilson, 1989)	Available (raster format)
	In-situ tests commissioned by EQC*	Not available to the project*

* These data and maps were made available by the Earthquake Commission, by publishing on the EQC website, http://canterbury.eqc.govt.nz/news/reports from late November 2011/middle December 2010 (The Recovery of Lifelines project was already concluded at that time). Maps representing EQC in-situ tests and further maps can be found on https://CanterburyRecovery.ProjectOrbit.com/ web site.

4.3 *Procedures for assessing the residual/future functionality of affected components*

Lifelines utilities were advised that laboratory tests were necessary to support the assessment of the residual and future functionality of affected components. As an example in case of damaged underground cables it would have been necesssary to assess: 1) possible increasingly damaging effects with higher levels of ground deformation, starting with deformation leading to impaired electrical conductivity, to increased loss of electric flow, to full electric power disruption; 2) states of deformation leading to loss of electric stability over time; 3) levels of deformation that break down insulation from groundwater effects (Prof. O’Rourke personal communication).



WW repairs by type and material

	Bend	Collar	Lateral	Main
AC		1	17	59
Concrete			2	30
Earthenware	2		169	25
PE				1
PVC			9	17

Figure 3. Kaiapoi waste-water and water networks following the 4 September Darfield Earthquake: a) map representing checks and repair activities to the wastewater network; b) Percent of total length of different pipe materials of the water network within different ground deformation areas (courtesy of Anna Mason); c) Number of repairs made on mains and rider mains in different levels of ground deformation areas. (Knight, 2011).

4.4 *Best-practices for estimating the expected performance and risk of alternative repair and/or reconstruction strategies in the event of further earthquakes*

Lifeline utilities were advised that running scenarios analysis would have been the ideal approach for comparing different alternatives envisaged by lifeline utilities during the recovery phase, to replace damaged component and/or to rebuild permanent capacity where temporary solutions were adopted (Figure 3).

As part the Recovery of Lifelines project, the attempt was made to collect and provide the following necessary information for running scenario analysis: 1) subsurface structure and earthquake likelihood for the specification of hazard scenarios (epicentre location, moment magnitude, directivity parameters); 2) ground motion predictive models on rock and models for representing soil - amplifications (New Zealand-specific and calibrated on Canterbury earthquake data); 3) ground deformation and land damage predictive models (New Zealand-specific and calibrated on Canterbury earthquake data).

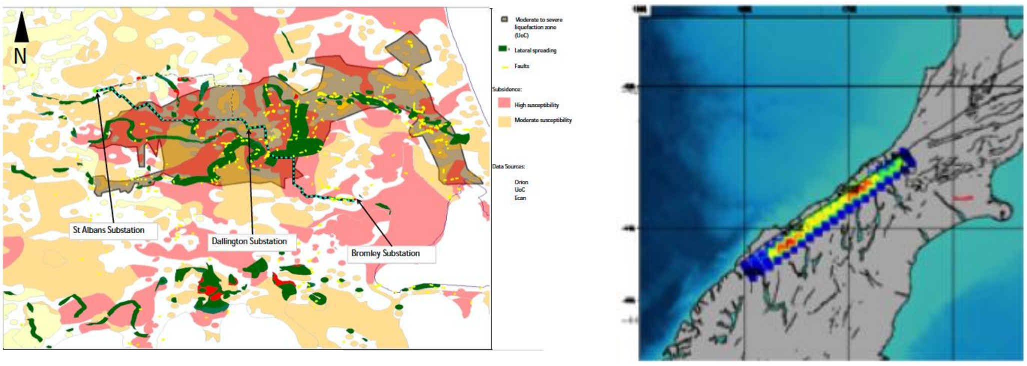


Figure 4: Estimating the expected performance and risk of alternative repair and/or reconstruction strategies: a) planning for permanent electric distribution network in north-east Christchurch; b) preliminary hazard scenario modelling for the Alpine Fault (Holden and Zhao, 2011), picture courtesy of Caroline Holden.

A preliminary hazard scenario modelling for the Alpine Fault (Holden and Zhao, 2011) was made available to the lifeline utilities on request. Synthetic seismograms in Christchurch (computed broadband 0.5-20hz), and derived ground-motion measures, for a large potential Alpine Fault earthquake were made available for the study from Holden and Zhao (2011). At first seismograms were computed for rock site condition. In order to account for soft soil conditions, site effects equivalent to a site class D (e.g. Botanic Garden in Christchurch) were added to the "rock-site" seismograms (work by John Zhao). Synthetic seismograms, including various site effects, could have been computed for specific locations of particular interest for the lifelines utilities (e.g. location of main components of the lifeline networks) provided the availability of soil profile data for the specific site location of interest.

Similar hazard scenario modelling for the Greendale Fault causing the 4 September 2010 earthquake and for the other Christchurch local faults causing the many aftershocks were not made available at the time of the project.

A predictive model for assessing liquefaction susceptibility and liquefaction induced ground deformation at territorial authority scale and at different detailed levels was proposed by Giovinazzi and Cubrinovsky (2007). However, due to the lack of the necessary data (e.g. in-situ tests, Table 2) the model could not be implemented to assess the liquefaction susceptibility for the purposes of the "Recovery of Lifelines" project. Reference was therefore made to the "Liquefaction hazard map" and "Liquefaction ground damage map" (Beca, 2005).

Simplified analysis and discussions to support urgent recovery decision making processes of lifeline utilities were performed as part of the Recovery of Lifelines project based on these maps and on the data and information available (Table 2).

It is worth highlighting that a liquefaction susceptibility review study is currently underway at Environment Canterbury (Environment Canterbury media-release 25/11/2011). The project is jointly funded by Environment Canterbury and the Natural Hazards Research Platform (NHRP) with inputs from Christchurch City Council, Selwyn District Council and Waimakariri District Council. The project aims to analyse geological and geotechnical data derived both from the recent earthquakes and pre-earthquake information, held by research institutes, local authorities and private companies. The data will be processed according to a consistent methodology to produce updated liquefaction hazard information. Maps will be made available to city and district councils and lifelines utilities to guide future development (including the required level of geotechnical investigation for future development). Liquefaction Resistance Index Map for Christchurch City, based on expert-opinion and observed liquefaction-induced land damage following the Canterbury Earthquakes has been recently defined (Cubrinovski and Hughe, personal communication).

4.5 *Standardised procedures for reporting/documenting the lessons learned from the earthquakes before the knowledge is lost.*

Following a workshop sponsored by the Earthquake Engineering Research Institute (Pasadena, CA 2002) many issues and criticalities for the collection and management of earthquake data were identified and discussed (EERI, 2003). Table 3 summarises, from the EERI report, some of the criticalities and issues that affected the collection and management of earthquake data in the aftermath of 22 February earthquake.

4.6 *Standardised procedures for reporting/documenting the lessons learned from the earthquakes before the knowledge is lost.*

Following a workshop sponsored by the Earthquake Engineering Research Institute (Pasadena, CA 2002) many issues and criticalities for the collection and management of earthquake data were identified and discussed (EERI 2003). Table 3 summaries, from the EERI report, some of the criticalities and issues that affected the collection and management of earthquake data in the aftermath of 22 February earthquake.

Table 3. Common criticalities and issues for the collection and management of post-earthquake hazard and damage data

Lack of coordination: After earthquakes, multiple teams are in the field, performing reconnaissance and/or research. These teams may not be well coordinated, collecting the same data, and overlooking other critical and perishable data.
Lack of repositories: Data that are collected are often stored by individual researchers and field investigators, making access by others difficult.
Data maintenance and access: Difficulties in addressing and responding to issues of data access and data maintenance.
Perishable data: Some of the data are extremely perishable. With little coordination and/or access, these data sometimes disappear before they can be collected.
Different time frames for data collection: Different types of data need to be collected at different time periods before and after an earthquake. Some data are impossible to collect in the first few days after an earthquake, including accurate direct and indirect costs of the earthquake, complete damage surveys, extent of lifelines disruption, and rebuilding and reconstruction policies. Inventory data are, by definition, collected prior to an event. These different time frames mean that different tools are necessary for accessing and storing data.

It is worth highlighting that ALA is working toward the development and implementing of a Post-earthquake Information Management System (PIMS), an end-to-end system for post-hazard event data collection, archiving of data, and distribution of post-earthquake data for use to improve hazard mitigation. ALA is working to define: 1) the breadth of data that needs to be accommodated by PIMS; 2) key issues not currently addressed through existing post-earthquake investigations; 3) necessary tools for storing, presenting, analyzing, and disseminating that information; 4) types of data searching and collating features that users would like to have (database searching, output format, GIS compatibility, etc.).

The breadth of data to be collected for documenting the performance of lifelines systems and the societal and economic impact of their disruption was suggested as part of the Recovery of Lifelines project and is presented in Table 4.

Table 4. Data collection and data processing for consolidating the knowledge on the seismic response and impact of lifelines following Christchurch earthquakes

Objective 1 – Consolidate the knowledge on the seismic response and impact of lifelines following Christchurch earthquakes;

Task 1 - Data Collection – data related to the behaviour and impact of Christchurch and Waimakarir lifeline systems, following the 4 September, 22 February and 13 June earthquakes, will be collected according to the following categories:

1.1 Network characteristics: systems structure, system components and sub-components;

1.2 Component characteristics: design (e.g. construction year, seismic design), properties (e.g. material), geometry, geospatial representation;

1.3 Seismic hazard and induced geotechnical hazard: ground shaking (recorded PGA), land damage (including liquefaction, lateral spreading, landslides and rock falls) at the location of the system components;

1.4 Physical impact on the network component: (e.g. damage, disruption, deformation, etc.);

1.5 Functional impact: loss/reduction of the system functionality (e.g. loss of connectivity; reduced serviceability);

1.6 Social impacts of lifeline disruptions:

1.7 Impact of lifeline disruptions on organisations:

1.8 Direct and indirect economic losses:

1.9 Interdependencies: Physical, Social, Economic Interdependencies

1.10 Repair/restoration practices, strategies, times

Task 2 – Data Processing

2.1 *Definition of taxonomies*: physical damage classification scheme (to network component), system performance metrics, socio-economic performance indicators;

2.2 *Data elaboration* according the above-defined taxonomies;

2.3 *Geospatial representation of data* (according to a common agreed Geographical Information System)

Task 3 – Data Dissemination (conditional to the agreement of the lifeline utilities)

3.1 Data aggregation: to overcome confidentiality issues and allow for data disclosure;

3.2 Develop an information sharing web centre (with restricted access) to allow the use of the aggregated_data for national and international researchers

5 CONCLUSIONS

The 22 February 2011 Christchurch earthquake created very strong ground motions and widespread liquefaction throughout the Christchurch urban area and surroundings, leading to significant damage and disruption of lifeline systems. It was well established that large areas of eastern Christchurch were built on ground highly susceptible to liquefaction, however seismic hazard assessments, prior to the 4 September 2010 Darfield earthquake, never anticipated the possibility of a large earthquake occurring directly under the city. The 22 February 2011 earthquake exceeded hazard assessment estimates and design codes, yet many systems continued to function, albeit in a reduce state, mitigating the impact of the event on the Christchurch and New Zealand economies and communities.

Weak buried pipes and cables, played a major role in the seismic response of the water, wastewater, telecommunication and power systems. The event highlighted the challenge of managing aging infrastructure, of which components are known to be vulnerable, but are too expensive to be replaced/upgraded in the short-term as part of risk mitigation programmes.
The total lack of investment in the past in seismically-designed buried utilities in Christchurch and in New Zealand in general, cannot be overlooked. Wellington buried utilities are probably as seismically vulnerable as Christchurch ones. There are diverse private and public sector responsibilities for the

performance of lifeline systems. A call for action is needed

On a positive note it is worth highlighting that the value of resilient design of non-buried lifeline components, interdependency planning, mutual assistance agreements, extensive insurance cover and highly trained and adaptable human resources were all success stories that contributed to mitigate lifelines disruption. The gas system showed an excellent level of robustness, remaining undamaged despite the high level of ground shaking and liquefaction-induced ground damage. The implementation of lessons learnt from previous damaging earthquakes contributed to the design of such a robust and redundant network. Limited interdependency issues were experienced between lifeline systems, with generally a good level of coordination and communication experienced among the lifeline utilities and with the Christchurch Response Centre. All the lifeline utilities had mutual aid agreements and contingency measures in place that helped them to guarantee the prompt availability of materials and technical experts required for the repair operations. Many of the lifeline utilities had the availability of back-up resources that helped them to cope with the reduced functionality of other networks.

The 22 February earthquake also demonstrated that some emergency management and response issues have still to be addressed to improve future pre-event planning. The temporary traffic management of the highway and local road network faced severe challenges to adapt to the damaged network and to the reorganisation of the city, as businesses and residents relocated following the closure, demolition and rebuild of the CBD. The management of the CBD 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. The 22 February event has also exposed the difficulties in re-optimising a city's infrastructure following closure of its CBD for an extended period.

The Christchurch earthquake has also shown that societal, economic and political expectations for a lifeline system’s functionality in a post-disaster environment continue to rise. The widespread disruption to services caused significant social impacts, leading to major economic disruption, political involvement and social trauma - which contributed in part to the migration of thousands of Christchurch residents out of affected areas. However, it has to be acknowledged that community members showed incredible levels of resilience, coping and adapting to the, sometime, long lifeline restoration times and repeated outages during aftershocks.

The event has provided a wealth of lessons for increasing the resilience of engineering lifelines in New Zealand and beyond. This event will no doubt be regarded as a reference example of the impact of severe liquefaction-induced ground damage on lifeline systems and overall on an urban environment.

ACKNOWLEDGEMENTS

We gratefully acknowledge Helen Grant, Environment Canterbury Regional Council, and Peter Wood, Ministry of Civil Defence and Emergency Management for the constructive and thorough review and comments on the paper. Thanks to Dave Brundson, and Tony Fenwick, National Engineering Lifelines Committee and to Mark Gordon and Joanne Golden, Canterbury Engineering Lifelines Group, for their ongoing assistance. We are grateful to the utility and lifeline engineers and staff who described their systems and provided map and data. The financial support of the Natural Hazard Research Platform to the “Recovery of Lifelines” short-term project is gratefully acknowledged. We gratefully acknowledge the New Zealand GeoNet project and its sponsors EQC, GNS Science and LINZ, for providing data/images used in this study. Finally, special thanks to: the 2011 HAZM 403 class at the University of Canterbury, Mark Letham, Laura Mills, Sally Mitchell, Victoria Rowe, Joanne Wallace and Sonali Weerasekara; and to Stuart Knight, student at the CNRE Department, University of Canterbury. The assistance of Matthew Hughes, Research Fellow at University of Canterbury and Anna Mason, EngD student at the University College London is gratefully acknowledged.

REFERENCES:

ALA (2001), Guidelines for Design of Buried Steel Pipes, A report by public-private partnership between American Society of Civil Engineers (ASCE) & Federal Emergency Management Agency (FEMA), American Lifelines Alliance (ALA), July 2001.

ALA (2002). Seismic Design and Retrofit of Piping Systems, A report by public-private partnership between American Society of Civil Engineers (ASCE) & Federal Emergency Management Agency (FEMA), American Lifelines Alliance (ALA), July 2002.

ALA (2004). Matrix of Standards and Guidelines for Natural Hazards. A report by public-private partnership between Federal Emergency Management Agency (FEMA) and National Institute of Building Sciences (NIBS), American Lifelines Alliance (ALA), 2004

ALA (2005), Seismic Guidelines for Water Pipelines, A report by public-private partnership between Federal Emergency Management Agency (FEMA) and National Institute of Building Sciences (NIBS), American Lifelines Alliance (ALA), March 2005.

ASCE (1984), Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, Committee on Gas and Liquid Fuel Lifelines, American Society of Civil Engineers (ASCE), US, Nyman, D. J. (Principal Investigator).

ASCE (1997), Guide to Post Earthquake Investigation of Lifelines, Technical Council on Lifeline Earthquake Engineering (TCLEE), Monograph No.11, American Society of Civil Engineering (ASCE), Schiff, A. J. (editor), July 1997.

ASCE (1999), Guidelines for the Seismic Upgrade of Water Transmission Facilities, J. Eidinger, E. Avila (Editors), ASCE, TCLEE Monograph No. 15, January 1999.

Beca Carter Hollings and Ferner Ltd (2005) Christchurch Liquefaction Study – Stage IV (Addendum Report). Environment Canterbury report number U04/25/2, Christchurch.

Charman, N. and Billings, I. (2011). Christchurch City Council Lifelines- Performance of concrete potable water reservoirs in the February 2011 Christchurch earthquake. NZSEE Bulletin, Vol. 44, No. 4, December.

Cubrinovski and Taylor (2011).Liquefaction Map – Drive-through Reconnaissance Retrieved 27th August 2011 from http://db.nzsee.org.nz:8080/web/chch_2011/home

Cubrinovski, et al. (2011). Geotechnical Aspects of the 22 February 2011 Christchurch Earthquake, NZSEE Bulletin, Vol. 44, No. 4, December.

Eidinger, J. and Tang, A. (Eds) (2011). Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifelines Performance. Technical Council

Eidinger, J. (2001). Replacing seismically weak and aging water pipes. Proceeding of The 2nd Japan and U.S. Workshop on Seismic Measures for Water Supply

Eidinger, J. and Tang, A. (Eds) (2011). Earthquake Sequence of Mw 7.1 September 04, 2010, Mw 6.3 February 22, 2011, Mw 6.0 June 13, 2011: Lifelines Performance. Technical Council on Lifeline Earthquake Engineering. Monograph No. 40. December 2011. ASCE

GeoNet (2011). Canterbury Earthquakes. Available from <http://www.geonet.org.nz/canterbury-quakes/>. Accessed 18 October 2011.

Eurocode (2004), Eurocode-8: Design Provisions for Earthquake Resistant Of Structure, Part-4: Silos, Tanks and Pipelines, European Committee for Standard, Stage 34 Draft, December 2004.

FEMA 202 (1990). Earthquake Resistant Construction of Electric Transmission and Telecommunication Facilities Serving the Federal Government. National Institute of Standards and Technology. Gaithersburg, MD.

FEMA 221 (1991). Collocation Impacts on the Vulnerability of Lifelines during Earthquakes with Applications to the Cajon Pass, California: Study Overview. Federal Emergency Management Agency. Washington, D.C..

FEMA 224 (1991). Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States. Applied Technology Council. Redwood City, CA.

FEMA 233 (1992). Earthquake Resistant Construction of Gas and Liquid Fuel Pipeline Systems Serving or Regulated by the Federal Government, Federal Emergency Management Agency (FEMA), Earthquake Hazard Reduction Series 67, July 1992.

FEMA 271 (1996). Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines. National Institute of Standards and Technology. Washington, D.C., 1996.

Giovinazzi, S. and Cubrinovski, M. (2007). "Liquefaction Hazards for Seismic Risk Analysis". Proc. of 2007 NZSEE, Conference of the New Zealand National Society for Earthquake Engineering.

Giovinazzi, S. Wilson, T. Davis, G. Bristow, D. Gallagher, M., Schofield, A. Villemure, M. Eidinger J., Tang A. (2011). Lifelines Performance and management following the 22 February 2011 Christchurch Earthquake, New Zealand: Highlights of Resilience. NZSEE Bulletin, Vol. 44 (4), December, pp.402-417.

Holden, C. and Zhao, J. (2011). Preliminary broadband modelling of an Alpine fault earthquake in Christchurch, GNS Science Consultancy Report 2011/28. 19p.

JSCE (2000a), Basic Principles of Seismic Design and Construction for Water Supply Facilities, Earthquake Resistant Codes in Japan, Japan Society of Civil Engineers (JSCE), Japan Water Works Association, January 2000.

JSCE (2000b), Recommended Practices for Earthquake Resistant Design of Gas Pipelines, Earthquake Resistant Codes in Japan, Japan Society of Civil Engineering (JSCE), Japan Gas Association, January 2000.

Knight, S. (2011). Impact and Recovery of the Kaiapoi Water Supply Network following the September 4th 2010 Darfield Earthquake. Dept. of Civil and Natural Resources Engineering. University of Canterbury. Final Year Projects, 2011.

Massie, A. and Watson, N. R. (2011). Impact of the Christchurch earthquakes on the electrical power system infrastructure. NZSEE Bulletin, Vol. 44, No. 4, December.

Neo Leaf Global (2011). Infrastructure Research Related to Canterbury Earthquakes. Informative Report Prepared for NELC.

O’Rourke T. and Jeon S. S. (1999). Seismic Zonation for Lifelines and Utilities

ORION AMP (2009). Asset Management Plan: a 10-year management plan for Orion‟s electricity network. from 1 April 2009 to 31 March 2019. http://www.oriongroup.co.nz/publications-and-disclosures/asset-management-plan.aspx

Orion Annual Report (2011) retrieved from: http://www.oriongroup.co.nz/downloads/OrionAR11_WEB.pdf

Orion Media releases (2010 and 2011) retrieved from http://www.oriongroup.co.nz/news-and-media/EQ-news-Feb2011.aspx.

Palermo, A. et al (2011). Lessons Learnt from 2011 Christchurch Earthquakes: Analysis and Assessment of Bridges, NZSEE Bulletin, Vol. 44, No. 4, December.

Schiff, Anshel J. (Ed.), (1995). Northridge Earthquake: Lifeline Performance and Post- Earthquake Response. Technical Council on Lifeline Earthquake Engineering, Monograph No. 8, ASCE.

Schiff, Anshel J. (Ed.), 1998. Hyogo-Ken Nambu Earthquake of January 17, 1995-Lifeline. Technical Council on Lifeline Earthquake Engineering, Monograph No. 14, ASCE.

Stevenson, J. R., Kachali, H., Whitman, Z., Seville, E., Vargo, J., Wilson, T. (2011). Preliminary observation of the impacts of the 22 February Christchurch earthquake on organisations and the economy: a report from the field, (22 February – 22 March 2011). NZSEE Bulletin, Vol. 44, No. 2, June 2011, pp65-76.

Transpower (2011a). “4 September 2010 Darfield earthquake. Lessons learned”. TRANSPOWER NEW ZEALAND LIMITED Internal Report, 30 March 2011.

Transpower (2011b). “22 February 2011 Christchurch earthquake Key findings and lessons learned” TRANSPOWER NEW ZEALAND LIMITED Internal Report, 30 June 2011.

Tonkin and Taylor (2011). Christchurch Earthquake 22 February 2011, Geotechnical Land Damage Assessment, Tonkin & Taylor Ltd, 2011.

Villemure, M. Wilson, T.M. Bristow D., Gallagher M., Giovinazzi S., Brown C. (2012). Liquefaction ejecta clean up in Christchurch during the 2010-2011 earthquake sequence, NZ, NZSEE 2012.

Watson, N.R. (2010). Impact of the Darfield earthquake on the electrical power system infrastructure”, NZSEE Bulletin, Vol. 43, No.4, December 2010, pp421- 424.

Wilson, J. (1989). Swamp to City: A Short History of the Christchurch Drainage Board 1875-1989. Lincoln, New Zealand: Te Waihora Press.

Yamada, S., Orense, R., Cubrinovski, M., (2011). Geotechnical Damage due to the 2011 Christchurch, New Zealand. ISSMGE Bulletin 5 (2): pp27-45.