LIFELINES PERFORMANCE AND MANAGEMENT FOLLOWING THE 22 FEBRUARY 2011 CHRISTCHURCH EARTHQUAKE, NEW ZEALAND: HIGHLIGHTS OF RESILIENCE

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SUMMARY

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, including significant disruption to the lifelines. The event created the largest lifeline disruption in a New Zealand city in 80 years, with much of the damage resulting from extensive and severe liquefaction in the Christchurch urban area. The Christchurch earthquake occurred when the Canterbury region and its lifelines systems were at the early stage of recovering from the 4 September 2010 Darfield (Canterbury) magnitude 7.1 earthquake. This paper describes 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. Special focus is given to the performance and management of the gas, electric and road networks and to the liquefaction ejecta clean-up operations that contributed to the rapid reinstatement of the functionality of many of the lifelines. The water and wastewater system performances are also summarized. Elements of resilience that contributed to good network performance or to efficient emergency and recovery management are highlighted in the paper.

INTRODUCTION

A devastating magnitude 6.3 earthquake struck the city of Christchurch at 12:51pm on Tuesday 22 February 2011. The earthquake killed 182 people, caused a large number of injuries and widespread damage to the built environment. The earthquake was very shallow and the epicentre very close (<10 km) to the city which created extremely high ground accelerations across the city. This event occurred when the Canterbury region and its engineering lifelines systems were at the early stage of recovering from the 4 September 2010 Darfield (Canterbury) magnitude 7.1 earthquake.

The impact of the 22nd February earthquake on the lifelines functionality was severe. The event created the largest lifeline disruption in a New Zealand city since the 1931 Hawke's Bay earthquake devastated Napier and Hastings. Much of the damage and disruption in Christchurch has been the result of wide spread and severe liquefaction in the Christchurch urban area.

However, it must be acknowledged that the strong "lifelines culture", promoted in New Zealand by Local Lifelines groups and a National Engineering Lifelines Committee, the Earthquake Commission and the Ministry of Civil Defence and Emergency Management, reduced the physical and functional impact of the earthquakes on lifelines systems.

The Civil Defence and Emergency Management Act 2002 (CDEM 2002) requires lifeline utilities "to be able to function to the fullest possible extent", even though this may be at a reduced level, during and after an emergency. The National Engineering Lifelines Committee, NELC, in New Zealand, defines Lifelines Engineering as "an informal, regionally-based process of lifeline utility representatives working with scientists, engineers and emergency managers to identify interdependencies and vulnerabilities to regional scale emergencies. This collaborative process provides a framework to enable integration of asset management, risk management and emergency management across utilities." (NELC, 2007). There are 16 Regional Lifelines groups across New Zealand, with national representation and coordination undertaken by the National Engineering Lifeline Committee (est. 1999).

There has been a strong focus on engineering lifelines in Christchurch. The Christchurch Engineering Lifelines Project

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was completed in 1994 for the Christchurch metropolitan area and published in "Risks and Realities" in 1997. This was followed by the formation of the Christchurch Engineering Lifelines Group (Canterbury CDEM Group, 2010). In 2004, a Canterbury Engineering Lifelines Group formed with a focus on further enhancing the resilience of critical infrastructure and is financially supported by the Canterbury Civil Defence and Emergency Management, CDEM Group. During an emergency, infrastructure response and recovery efforts fall within CDEM arrangements (see the National CDEM Strategy, MCDEM 2007, for more information). Lifelines Utility Recovery Task Teams are established at both territorial authority and CDEM Group levels, to assist in coordinating potential recovery efforts (Canterbury CDEM Group, 2010).

This paper presents the impact of the Christchurch earthquake on a few lifeline systems briefly summarising the physical damage to the networks, the system performances and the operational responses during the emergency management and the recovery phase. We present some background information on the earthquake and the severe geotechnical secondary hazards induced by the earthquake. Special focus is given to the performance and management of the gas, electric and road networks and to the liquefaction clean-up operations that highly contributed to the rapid reinstatement of many of the lifelines. A complete overview of the physical and functional performance for all the infrastructure and lifelines systems is out of the scope of the paper.

THE 22 FEBRUARY 2011 CHRISTCHURCH EARTHQUAKE

New Zealand is located at a plate boundary between the Pacific and Australian plates (Figure 1). It is also where the plate boundary changes from a subduction zone running down the east coast of the North Island which terminates off the northeast coast of the South Island (about 100 km north of Christchurch) to a transform boundary cutting through the continental crust of the South Island. Here the plate motions are accommodated by largely dextral strike-slip on the faults of the Marlborough Fault Zone and the Alpine Fault (Figure 2). However, all of the relative motions between the Australian and Pacific plates are not accommodated on one or two faults in a narrow zone, but on many faults across a much wider zone where large near-plate-boundary faults accommodate this complex distributed deformation. Significant to the recent Canterbury earthquakes, some of the plate boundary deformation in this transition zone is probably being transferred into Canterbury, where it is accommodated by dextral strike-slip faulting.

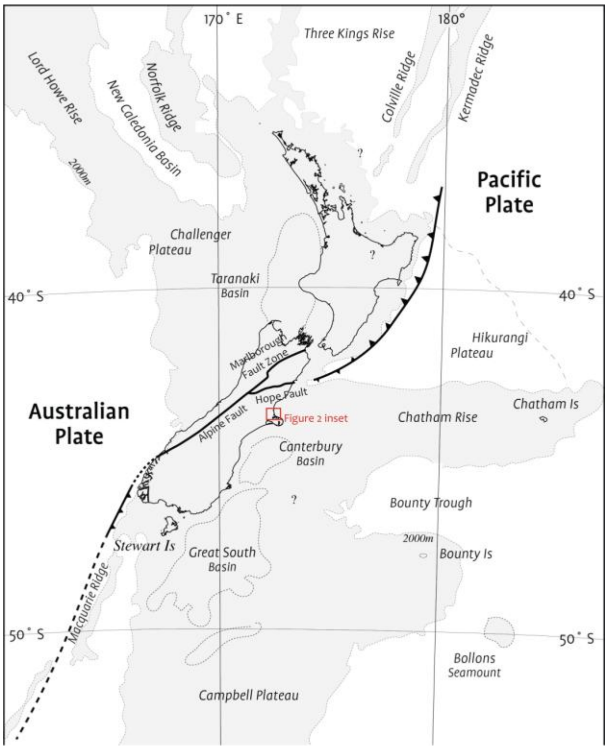

Figure 1: Pacific and Australian plate boundary crossing New Zealand.

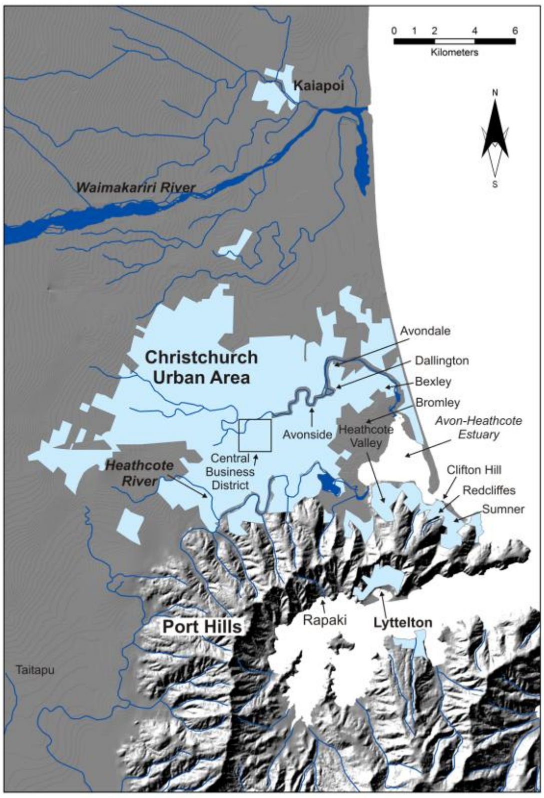

Figure 2: Location of Christchurch urban area.

At 12.51pm (NZ Standard Time) on February 22, 2011, a M 6.3 earthquake occurred 10 km south-east the centre of Christchurch Central Business District, CBD, at a shallow depth of 5 to 6 km. The earthquake resulted in destruction, injuries and deaths. The event is believed to involve a blind oblique-thrust rupture of an 8 x 8 km fault striking ~59° and dipping ~69° to the southeast. The peak slip of 2.5–3 m is a mixture of reverse and right-lateral slip and is located ~7 km east-southeast of Christchurch city centre at a depth of ~4 km. Slip of ~1 m reaches within ~1 km of the ground surface beneath the southern edge of the Avon-Heathcote Estuary (Beaven *et al.* 2011). The fault dips southwards at an angle of about 65 degrees from the horizontal beneath the Port Hills. There appears to have been no surface rupture, however satellite images indicate the net displacement of the land south of the fault was 500 mm westwards and upwards. It is a shallow fault with high fault friction and co-seismic stress drop, which produced highly directional seismic energy towards Christchurch city. The sedimentary basin of interbedded layers of gravels and sands underlying Christchurch amplified the source ground motion waves and lengthened the shaking duration, and thus damage (Guidotti *et al.* 2011; Quigley & Wilson, 2011). The peak ground acceleration (PGA) in Christchurch CBD was on average 0.5g in both the horizontal and vertical direction. The highest acceleration was recorded at Heathcote Valley Primary School, 1.7g in the horizontal direction and 2.2g in the vertical direction. The earthquake was characterised by a short duration, with the severe shaking only lasted 15s (GeoNet 2011).

Prior to the 22nd February earthquake, at 4:35am (NZ Standard Time) on September 4th, 2010 the rupture of the previously unrecognized Greendale strike-slip fault beneath the Canterbury Plains of New Zealand's South Island produced a Mw 7.1 earthquake that caused widespread damage throughout the region. The hypocentre was about 40 km west of Christchurch City, at a depth of 10 km. The epicentre was close to the town of Darfield. The event produced a ≥ 28 km long, dextral strikeslip surface rupture trace, aligned approximately west-east, with a component of reverse faulting at depth (Quigley *et al.* 2010). Close to the fault the strong ground shaking resulted in felt intensities as much as MM9 (New Zealand Modified Mercalli Intensity) and peak ground accelerations over 1.2g close to the fault. However, a maximum PGA of ~0.3g was experienced in Christchurch 30 km away (Cousin and McVerry 2010). During this event, extensive liquefaction, differential subsidence, and ground cracking associated with lateral spreading occurred in areas close to major streams and rivers throughout Christchurch, Kaiapoi, and Taitapu. Between September 4 to October 16 seismicity ($M \geq 3$) showed an eastward expanding pattern of aftershocks, suggesting an eastern transfer of stress through the crust.

On June 13, 2011 a significant M_w6.1 aftershock struck Christchurch in an extension to the continued expanding trend of aftershock just east of Christchurch. The faulting mechanism was primarily dextral strike-slip with some oblique thrust movements. This earthquake caused many areas to re-liquefy resulting in additional lifeline disruptions.

Liquefaction

Christchurch city is built at the coast of the Canterbury Plains on swamps, which have been mainly drained. In the western suburbs the deposits are mainly coarse gravels with the groundwater levels between 2-3 m below ground surface. In the eastern suburbs near the coast, swamp, beach dune sand, estuarine and lagoon deposits of silts and fine sands become more prevalent. Groundwater levels are between 0-2 m below ground surface, making these areas prone to liquefaction. The aquifer fed Avon and Heathcote rivers meander through the city and act as the main drainage system. Variable foundation conditions as a consequence of a high water table and lateral changes from river floodplain, swamp, and estuarine lagoonal environments, impose constraints on building design and construction (Brown *et al.,* 1995; Yamada *et al*. 2011). Most soils are generally classified as site subsoil class "D", i.e. deep or soft soil in terms of the New Zealand Standard used for determining earthquake loads (NZS1170.5, 2004). The subsoil generally comprises 15-45 m deep sediments overlying a 300 to 700 m thick inter-layered gravel formation.

The 22nd February 2011 earthquake caused significant liquefaction in areas throughout the Christchurch southern and eastern suburbs; notably Avondale, Avonside, Bexley, Bromley and Dallington (Yamada *et al.* 2011). Liquefaction induced ground damage was much more extensive and severe than in September 2010, mainly due to the much higher shaking intensities. In general, the most significant damage to lifelines and residential buildings was due to liquefaction. The liquefaction resulted in settlement, lateral spreading, sand boils, and a large quantity of ejected silt mud and water ponding onto the soil surface. This severely damaged foundations on thousands of residential homes in the eastern suburbs and CBD. The repeated liquefaction events led to cumulative damage, intensifying overall impacts. Lateral spreading close to the Avon and Heathcote rivers and the estuary lead to the significant impacts to foundations and buried services. Many bridges crossing the Avon River suffered tilting in their abutments due to lateral spreading and loss of bearing capacity due to liquefaction (Yamada *et al.* 2011). Fault and liquefaction induced subsidence, lateral spreading and heaving of the river-bed reducing channel volume, and settling of levees has significantly increased flood risk from the Avon river, requiring emergency levee construction and new storm water network construction.

Two liquefaction reconnaissance maps have been produced following the earthquake. One commissioned by the Earthquake Commission (EQC) assessed most of the land damage to residential areas (Tonkin and Taylor, 2011). A drive-through reconnaissance was conducted in the period from 23 February to 1 March to capture surface evidence of liquefaction as quickly as possible and quantifying its severity in a consistent and systematic manner (Cubrinovski and Taylor, 2011).

Rockfall and Rockslope Failure

The southern and south-eastern suburbs of Christchurch are constructed on the Port Hills, which were constructed 9.6-12 million years ago by the now extinct Lyttelton volcano. The Port Hills consist mainly of jointed basaltic lava flows, commonly interbedded with layers of clay-rich tuffaceous and epiclastic deposits. The crater rim is a series of lava flow outcrops and reaches up to 500 m above sea level on the northern flanks. On the eastern seaward side the lava flows have been eroded by coastal processes during the last glaciation (ending ~6,000 years ago), forming steep cliffs, a shore platform beneath and a series of small harbours. The most significant, Lyttelton, is used as the major port for Christchurch City and the Canterbury region. Most of the Port Hills are also covered in variable thicknesses of loess soils, which are vulnerable to mass movement failure. Prior to the 22 February 2011 earthquake rock falls, boulder roll and loess soil failure had been the only significant slope hazard considered for the Port Hills. Large scale rock slope collapse had not been seriously considered as an expected hazard.

The extremely high ground-shaking during the 22 February and 13 June earthquakes in the northern Port Hills lead to extensive rockfalls and rock slope failures. Rockfalls mostly occurred from the jointed lava flows, leading to tens of houses being impacted by falling rock in Redcliffs, Heathcote Valley, Lyttelton, Rapaki and Sumner. The time of day (mid-day) meant few were occupied which reduced the number of potential casualties. The mitigation measures in place (fences, benches and trees) were overwhelmed by the large number and volume of rocks, which came down off the hills (Bell, 2011). During the 22 February and 13 June earthquakes, large-scale cliff collapses occurred in Redcliffs and Sumner (south-east Christchurch suburbs). Up to 15 m of cliff failed along sub-vertical cooling fractures and through intact rock during each shaking event due to very high vertical and horizontal accelerations (>1.0g). This lead to hundreds of houses being severely damaged, requiring evacuation, and ~100 houses unlikely to be reoccupied both at the cliff top and base (Bell, 2011). Power, water and sewage services were also severely damaged in the hill suburbs. Clifton Hill collapses threatened the seaward road linking Red Cliffs and Sumner to Christchurch city, requiring the use of ballasted shipping containers to be used as a temporary catch fence (Figure 3).

Figure 3: Cliff collapse at Clifton Hill following the 22 February and 13 June 2011 earthquakes - flown 14 June 2011. Note the partially collapsed house and use of ballasted shipping containers as temporary catch fences (Photo credit: Marlène Villenueve/David Bell).

ELECTRIC POWER SYSTEM

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

High voltage transmission grid

Transpower New Zealand owns and operates the high voltage electricity transmission grid in New Zealand. Some of the most important assets of the South Island grid are located in the Christchurch area (Figure 4), including 10 transmission grid exit points (GXP) to the distribution networks operated by Orion. In particular, the Islington substation (where power is transformed from 220 kV to 66 kV) is the main nodal substation in the South Island, which supplies a high percentage of the load to Christchurch, Nelson, Marlborough and the West Coast (McGhie and Tudo-Bornarel, 2011).

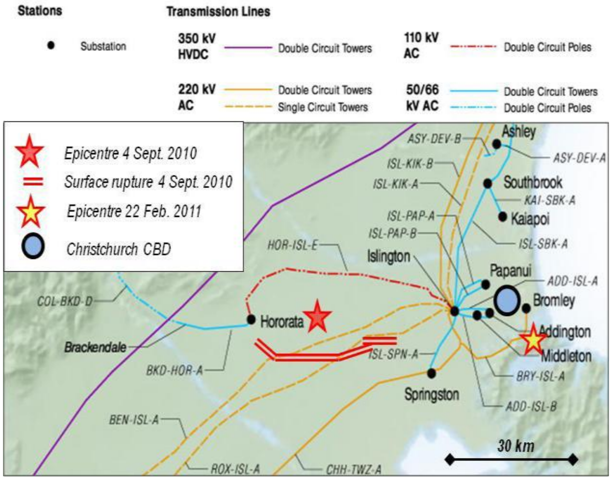

Figure 4: Transpower assets (substations and transmission lines) affected by the 4 September 2010 and 22 February 2011 earthquakes (Photo credit: Transpower).

The 4 September 2010 and 22 February 2011 earthquakes challenged the transmission grid resilience in the Canterbury and northern South Island region, but the impact from both earthquakes on the electrical stability and operation of both National Grid and regional supply was negligible. In particular, following the 22nd 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 the safety checks, the supply at the grid exit points was restored to full capacity and n-1 security, except at the Bromley substation where supply was restored with an n security level (Transpower 2011a; Transpower 2011b).

Load losses were experienced at different substations including: i) Bromley, loss of 90 MW and the load dropped to zero, twice after the earthquake; ii) Addington, loss of 80 MW; iii) Papanui, loss of about 80 MW; iv) Springston loss of 5 MW. The load took a maximum of 150 hours to recover to pre-quake levels (see Transpower 2011b for details).

Only minor structural damage of transmission assets was experienced (McGhie and Tudo-Bornarel, 2011). Most of the damage caused by the 22 February 2011 earthquake to Transpower assets occurred at Bromley, which experienced very high ground accelerations (Figure 5) and Papanui substations. Some minor damage occurred at Transpower's Addington warehouse, which consisted of local buckling of the pallet racking structures and collapse of one shelf.

A number of transmission towers were sited on ground, which experienced extreme liquefaction, but they were not adversely affected nor was the performance of the transmission lines.

Damage at the Bromley substation occurred in the 66 kV switchyards and 220 kV switchyards, where severe liquefaction occurred (Figure 5a), and within the adjacent control building from where the switchyard equipment is controlled and operated via switchboards (Figure 5c). Damage to the 220 kV switchyard included a broken 220 kV capacitor voltage transformer (CVT; Figure 5a). Damage to the 66 kV switchyards included two broken 66 kV transformer bushings (replaced by using bushings from a spare transformer available on site) and failure of a 66 kV cable circuit.

Figure 5: Bromley Substation: a) 220 kV failed current voltage transformer; b) Bromley bracing installed at the front and rear of the switchgear panels; c) dislodged ceiling tiles in the control and relay building, (Photo credit: Transpower).

Within the Bromley substation control building, short-term remedial work was undertaken soon after the earthquake to temporarily repair and enable the 11 kV switchboard equipment to return to service (Figure 5b). Action has been already taken to rebuild the Bromley substation and to install new 11 kV switchgear and switchboard. The new switchboard will be immediately available from an on-going substation construction project in Timaru.

The implementation of the lessons learned following the 1987 Edgecumbe earthquake, on the need to seismically restrain heavy equipment installed in the substations (e.g. transformer banks) and the subsequent seismic restraint retrofit programme, was demonstrably worthwhile and contributed to minimising seismic damage and disruption to the transmission grid following the 22nd February earthquake. Transpower will continue to reduce the seismic vulnerability of their assets by removing or strengthening existing buildings, items of plant not complying with Transpower's current Seismic Policy (TP.GG 61.02). As part of the lessons learnt following the 22nd February earthquake, all instruments with insulators held by “finger clamps” will be replaced as this type of clamping is known and has shown (Figure 5a) to perform poorly during earthquakes (McGhie and Tudo-Bornarel, 2011).

A summary of the Transpower Seismic Policy and further details on structural and system performance of the Transpower transmission grid can be found in the Transpower reports (Transpower 2011a, 2011b) for the 4th September Darfield and 22nd February earthquakes, respectively, and the TCLEE report (Eidinger and Tang, 2011) for both earthquakes.

Low and Medium voltage distribution network

Orion is the 3rd largest power distributor in New Zealand and owns and manages the distribution network across Christchurch City and the suburbs affected by the 22 February 2011 earthquake. Orion’s network in Christchurch consists of 66 kV, 33 kV and 11 kV and 400 V underground and overhead distribution systems. The 66 kV distribution system is supplied from Transpower’s grid exit points (GXPs) at Papanui, Addington, Bromley, Islington and Middleton, which feeds 15 district/zone substations (that allow for the voltage transformation of 66 kV or 33 kV to 11 kV) in and around Christchurch city (Figure 6). Network substations link the sub-transmission 11 kV system and the 11 kV distribution substations (Figures 6 and 7). Distribution substations (or local substations) take 11 kV supply, from either a district/zone, a network or another distribution substation and supply the consumer’s 400 V voltage distribution system (Figures 6 and 7).

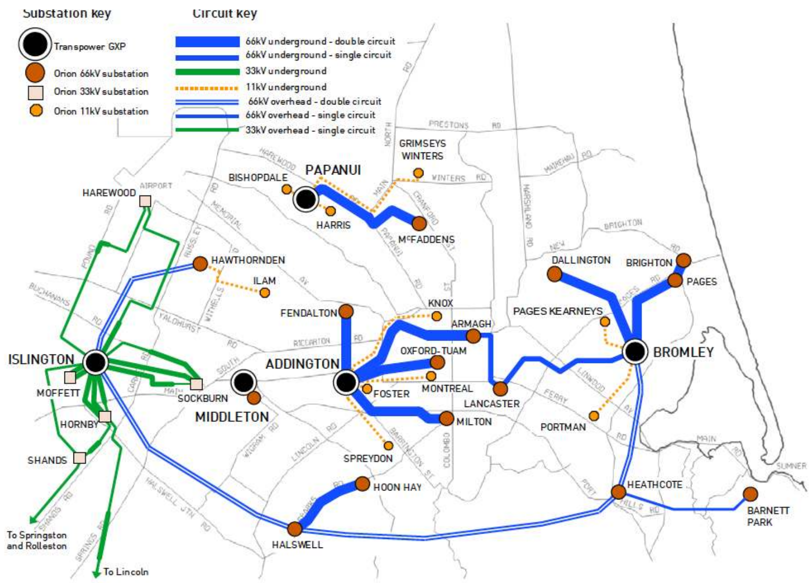

Figure 6: Orion sub-transmission overhead and underground distribution network (Orion AMP 2009).

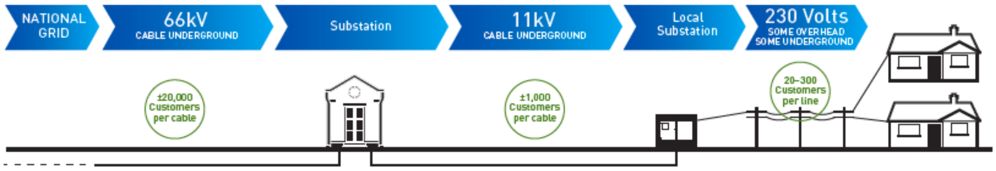

Figure 7: Orion simplified network structure (Orion media release, 22 June 2011).

The impact of the 22nd February earthquake vastly exceeded previous disruptions to Orion's network. With an estimate of 629 million customer-minutes lost, it resulted in 20 times more outages than were experienced during the 1992 snowstorm, the most significant natural hazard event affecting Orion network, before the 4th September earthquake.

The cost of the 22nd February event for Orion was ten times greater than the 4 September 2010 event (Table 1).

Table 1. Some data on the impact of 4th September 2010 earthquake, 22nd February 2011 earthquake and 13th June 2011 aftershock on the Orion network.

	Restoration of 90% of the service	Estimated Cost	Customer minutes lost
4th Sept 2010	Day 1	$4M	~90M
22nd Feb 2011	Day 10	$40-50M	~ 629M
13th June 2011	Day 1	$3M	

Physical impact on the overhead and underground distribution network

The large ground deformation induced by the 22nd February earthquake badly affected and caused multiple faults in 66 kV and 11 kV underground cable 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 (north-east area of Christchurch, Figure 6) were damaged beyond repair and had to be abandoned. These cables were pairs of radial 66 kV 3-core aluminium (300 mm^{2}Al), oil filled, aluminium sheathed with an outer cover of semi-conducting plastic sheath over the aluminium. The two cables were laid in a common weak mix concrete trench (750 mm depth) spaced 300 mm apart and capped by a 50 mm layer of stronger concrete (Orion AMP 2009).

Multiple faults were, also, identified in the 66 kV underground cables located within and close by the Christchurch CBD, namely: the 66 kV cable from Transpower Addington GXP to Orion Armagh substation; and the 66 kV cable from Orion Lancaster to Orion Armagh district substations. It is worth highlighting that the 66 kV cable from Orion Lancaster to Orion Armagh zone substations is a 1,600 mm^2 3x1 single core copper cross-linked polyethylene, cable Cu XLPE, recently installed 2002 (Figure 8a). This cable is installed in a weak mix of thermally stabilised concrete and capped with a 50 mm layer of stronger concrete that has been dyed red. The 66 kV cable from Transpower Addington GXP to Orion Armagh substation are 300 mm^{2}Al cables with similar features to the ones serving Christchurch north-east areas, described above. Figure 9 presents Orion 66 kV faulted cables and (following the 22nd February Earthquake overlaid with Tonkin and Taylor liquefaction map (Tonkin and Taylor 2011)

Regarding the 11 kV underground cable network, 14% cables were damaged, 330 km out of a total of 2,300 km (Figure 8b). A total of more than 1000 faults were identified and repaired at 31st August (Orion Media release 31st August 2011). 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.

(a)

(b)

Figure 8: a) 66 kV XLPE cable fault; b) Typical 11 kV internal cable damage (Photo credit: Orion).

Figure 10 presents Orion 11 kV faulted cables following 22nd February earthquake overlaid with Tonkin and Taylor liquefaction map (Tonkin and Taylor 2011) and the "Drive-Through" Reconnaissance map (Cubrinovski and Taylor, 2011). It is worth noting that the two land damage maps show a general agreement with each other. Table 2 summaries the percentage of 11 kV cables faults falling within the differently affected ground damages areas identified by the "driving through" liquefaction survey (Cubrinovski and Taylor, 2011).

Table 2. Percentage of 11 kV cables faults in different land damage category ranges following the 22nd February Christchurch Earthquake.

Land Damage Category (Cubrinovski and Taylor, 2011)	% 11 kV cable faults
Moderate to Severe Liquefaction	86%
Minor to Moderate Liquefaction	8%
Minor Land Damage	6%

An analysis of the 11 kV cable faults following the 4th September 2010 earthquake, 22nd February 2010 earthquake and 13th June 2011 aftershock is in progress to ascertain the possible influence of certain cable characteristics (including cable material, diameter) or external factors (e.g ground topography, liquefaction extent, transient ground deformation), on the cable damage rate.

Regarding the low-voltage 400 V underground cable network, 0.6% of cables suffered multiple damages.

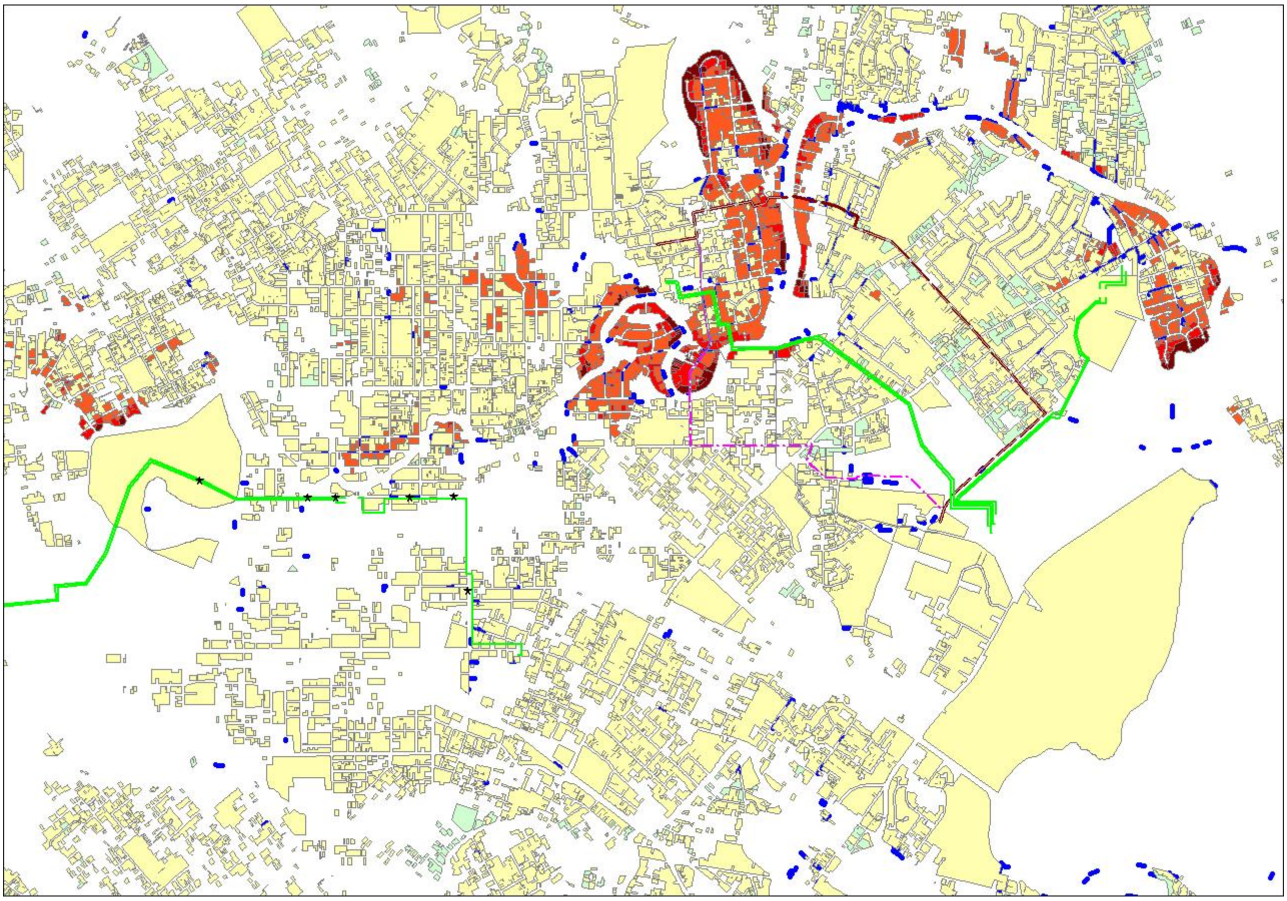

Figure 9: Orion 66 kV faulted cables following 22nd February Earthquake.

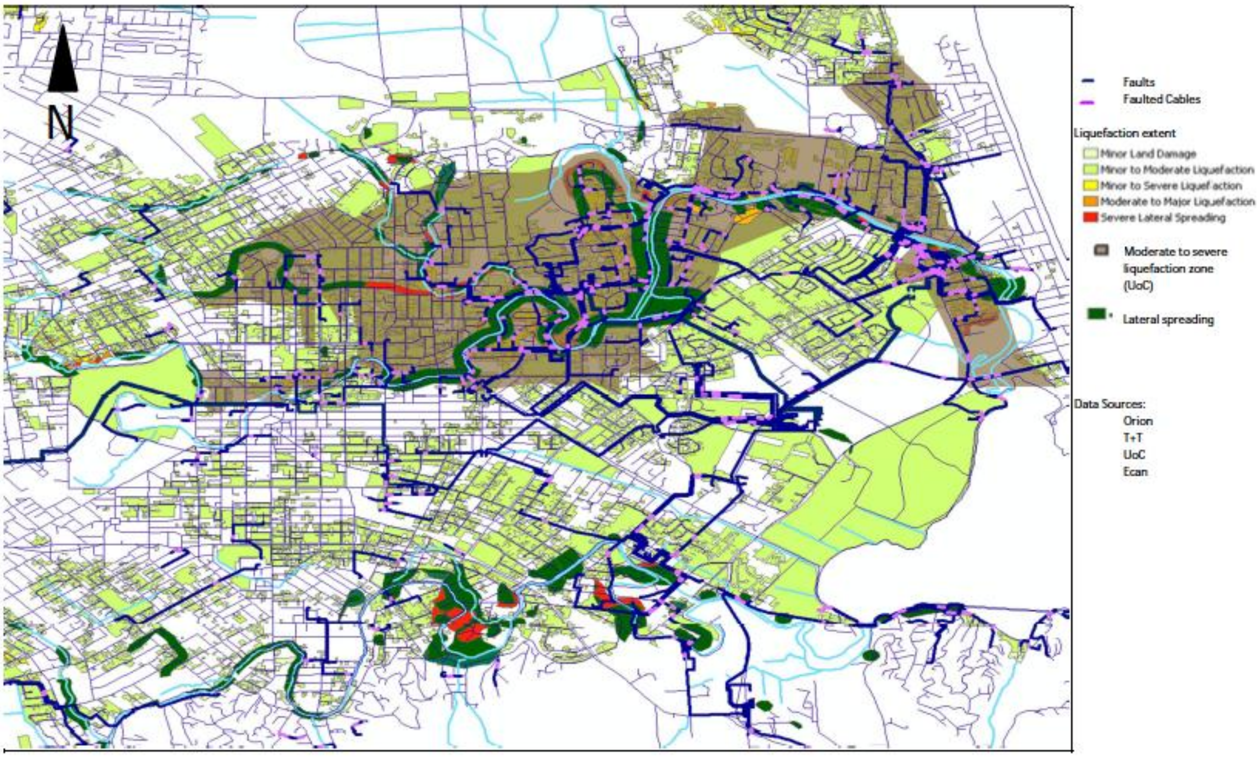

Figure 10: Orion 11 kV faulted cables following 22nd February Earthquake liquefaction maps from Tonkin and Taylor (2011) and Cubrinovski and Taylor (2011).

The 33 kV, 11 kV and 400 V overhead lines experienced some relatively minor damage including cracked insulators and poles affected by liquefaction (Figure 11).

Physical impact on zone and distribution substations and administrative buildings

One zone substation (out of 51) suffered from liquefaction. The Brighton substation (Bexley Road) in New Brighton sank two metres into the ground due to ground settlement (Figure 12a).

Of approximately 300 distribution building substations located in Christchurch urban area only 4 experienced significant damage. The Sumner substation was hit by a rockfall (Figure 12b).

The Orion Administrative buildings, located in the CBD, were badly affected and evacuated following the 22nd February earthquake. However, the control centre was re-established within 2 hours as a hot site established in an adjacent building that did not suffer major damage.

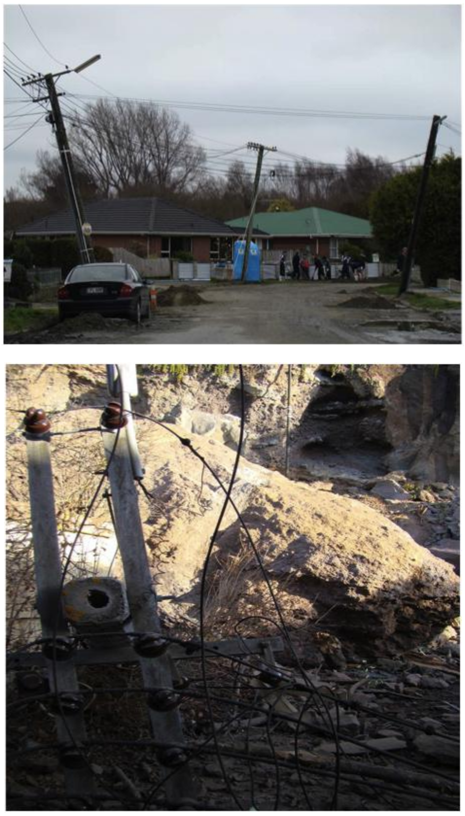

Figure 11: Damage to the distribution over-head lines: a). (Top) Leaning poles due to a combination of shaking and liquefaction in Kingsley street; b). Poles and insulators along the Sumner road affected by rockfall and landslides. (Photo credit: Andrew Massie CPIT).

Figure 12: ***Damage to Orion substation: a) (Left) New Brighton substation . (Photo credit: Orion.; b) Sumner substation hit by a boulder falling form the Sumner Cliffs (Photo credit: Andrew Massie CPIT).***

Emergency management and restoration activities

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 (Figure 6). This project would normally take at least six months depending on consenting issues (Shane Watson, personal communication). These temporary 66 kV overhead lines will represent a long-term temporary solution, for the three years that it will take to design and build a permanent supply. Options for permanent high voltage supply from Bromley to New Brighton and Dallington are currently being investigated (October, 2011).

The construction of a new substation in the Rawhiti Domain was commissioned, as well, as part of the immediate recovery plan to replace the severely damaged New Brighton substation.

More than 600 quake-related underground cable faults to both 11 kV and 66 kV cables were repaired within three months – more faults than Orion is used to experiencing in a decade. The approach followed to restore the functionality of the 66 kV underground cable traversing and serving the Christchurch CBD and the faulted 11 kV underground networks has been to locate the cable faults by cutting out of the damaged section and inserting a new piece of cable with two repair joints, whose resistance to further movement induced by potential aftershocks can not be, unfortunately, guaranteed. Each of the cable faults took more than 12 hours to find and repair. Cable crews were assembled from around New Zealand and Australia under a mutual aid support agreement. Following a massive work programme fault detection and repair was completed by the end of April 2011.

Six months following the 22nd February earthquake, Orion completed the major emergency repairs needed to deliver power supply across the city. 95% of all known faults (more than 1,000) faults to the 11 kV have been repaired. Each one of the 4,500 local substations has been individually assessed and some of them have been moved. All significant damage to the 400 kV overhead lines have been addressed and repaired. However, it will be a number of years before the network is restored to pre-event levels of functionality.

In areas where land is to be abandoned, Orion is working with demolition and restoration crews to ensure that buildings are safely disconnected from the power network before demolition or repair activities start.

The intensive post-quake work plan saw 700 electricity sector workers from around New Zealand and Australia contribute more than 200,000 people-hours to earthquake recovery (Orion Media Release 22 June 2011). Their work and the great resilience and the patience of Christchurch people has been acknowledged by Orion (Orion Annual Report 2011): "Faced with an electricity network decimated in some areas by massive earth movement, our people went to work and got the power back on. Again and again. Thank you to them, and to the people of Canterbury for your support and patience". However all urgent substation repairs were completed within four months time following the February event. Significant difficulty was also experienced by crews moving about congested, damaged and liquefaction affected transportation networks in the hours to weeks after the 22 February event. This was particularly difficult within the CBD area.

Further information and photos documenting the restoration of the Orion infrastructure can be found in Massie and Watson (2011).

Orion seismic risk mitigation programme

During the mid 1990s Orion was part of a study investigating how natural disasters would affect Christchurch. As a result, Orion spent over $6m on seismic protection work and a further $35m building resilience into their network.

Without this earthquake strengthening work, it is likely Orion's projected $70m earthquake repair bill would have more than doubled. In terms of hours without power, the impact would have been much worse with weeks and even months of continuous power cuts across most of Christchurch. Even so, power cuts have been very disruptive.

The excellent performance, with a few exceptions, of the network substations can be attributed to a $6 million seismic upgrade program that addressed all Orion substation buildings (Orion AMP 2009). Despite the ground motions exceeding the design codes of the seismic strengthening programme (in some instances this was dramatically exceeded), only 1 of the 314 upgraded buildings failed. The seismic upgrade programme was undoubtedly cost-effective. It is estimated that the upgrades saved up to $30-50 million (John O'Donnell, personal communication). By comparison, one non-upgraded building not required by Orion, was heavily damaged following the earthquake.

Furthermore, the vulnerability of oil filled cables to differential ground settlements induced by an earthquake had been previously analysed and identified by Orion as potential risks (Orion AMP, 2009). In particular the Dallington to Bromley 66 kV cable was identified as high risk, being located in the area on the south side of the Avon River. As part of risk mitigation actions undertaken by Orion, the Armagh Street bridges and the Dallington footbridge traversed by the cable were reinforced (Mackenzie, 2011); and a 1,600 mm^2 3x1 core copper Cross-linked Polyethylene, Cu XLPE, cable was installed from the Bromley GXP to Lancaster and Armagh district/zone substations (Figure 6) aiming to provide additional system security to the Christchurch CBD. This cable suffered multiple faults following 22^{nd} February earthquake (Figure 10). The faults have been identified and repaired (October 2011).

GAS DISTRIBUTION SYSTEM

Contact Energy (Rockgas) operates the Liquefied Petroleum Gas, LPG distribution system in Christchurch. The LPG is typically a mixture of 60% propane and 40% butane and it is distributed through a reticulated network at a pressure of about 90 kPa. The Contact Energy reticulated pipe network (Figure 13) comprises approximately 180 km of medium density polyethylene, MDPE, pipes. Diameters of the pipes range from ∅= 63 mm to ∅= 315 mm. The pipe wall thicknesses is 6 mm for ∅= 63 mm pipe and 9 mm for ∅=160 mm pipe (SDR 17.6 & SDR11). The depth to cover of the pipes is typically between 600-800 mm. The pipes are welded using electrofusion fittings (Figure 14) and polyethylene PE butt-welding, where a MDPE pipe is melted to another MDPE pipe with a time measured electrical current.

The LPG network is supplied from one main feed plant, Woolston Terminal (Figure 13) 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. Beyond the main distribution network, several standalone networks are fed from gas cylinders or tanks.

One hour and half after the 22 February main shock, Contact Energy National Operations Manager – LPG received a request from Civil Defence to isolate the CBD. The company further decided to shut off the feed supplies into the system, as a precaution. The CBD isolation and the four feeders of the system were shut off as a first step. Key network valves were subsequently manually shut off, to aid re-livening. Approximately eight technicians were dispatched to isolate the system. Damage to the road network and chaotic traffic occasionally delayed the aforementioned operations, which was partly overcome by using bicycles. Communication issues were experienced with the back-up radio system that will be now replaced, but the cell system functioned sufficiently by 23 February to adequately meet the communication needs.

Re-living operations started the evening of 23 February, beginning from the Harewood Feeder (Figure 13). Up to 30 technicians (22 from Rockgas' emergency contractors around the South Island and eight from overseas parent company were deployed to reliven the system. The system was re-livened 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 or to their welded joints, despite the gas company's pipes traversing zones of severe liquefaction and ground deformation. A few valve pits had moved relative to the road surface where the road surface sustained permanent ground deformations. None resulted in damage to the valve and connected pipe. One service lateral was sheared due to the customer casting concrete around the pipe and subsequent differential movement during the earthquake.

The gas mains outside the CBD cordon were re-livened within 9 days after the earthquake. Reconnection of customers continued during and after the re-livening operations of the mains and were completed within 10 days after the earthquake. Figure 15 presents the Contact Energy gas reticulation system and service restoration curves following the 22 February 2011 earthquake. As shown in Figure 15, 15% of the piping falls within the CBD cordon and could not be restored immediately after the earthquake. All services that could be restored were restored within 2 weeks. There were many customers who did not restore their gas services due to lost buildings, isolation from the CBD, or they left the area. As a result, in April 2011 Rockgas had lost 40% of their customer services and was providing only about 1/2 of the volumes they were supplying prior to the 22 February 2011 earthquake. Some additional service recovery will occur over time as some people return to Christchurch and as portions of the CBD are reopened. As at Nov 11, 6% of mains remains within the cordon and is not yet live. Customer re-livening has grown to around 80% of pre-earthquake customer numbers.

The availability of back-up resources was crucial to relieve lifelines interdependency issues and to maintain the 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 ongoing disruption to the business-as-usual LPG supply through the Lyttelton port. Road haulage options were placed on standby.

The Contact Energy gas system also performed well, without damage, in both the 4^{th} September 2010 Darfield earthquake and 13 June 2011 aftershock. The gas system performances in these three earthquakes was remarkably good compared to the performance of reticulated gas networks following large earthquakes in other parts of the world, 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 organised by the Canterbury Lifelines Group strongly influenced the design of a highly resilient system with robust and redundant hardware and suitable preparedness thanks to the availability of back-up resources (Smith and Yu, personal communication).

As part of the post-earthquake recovery activities, Contact Energy is continuing to work with Civil Defence and Emergency Management to ensure the safety of the gas system and with demolition crews as damaged buildings are demolished.

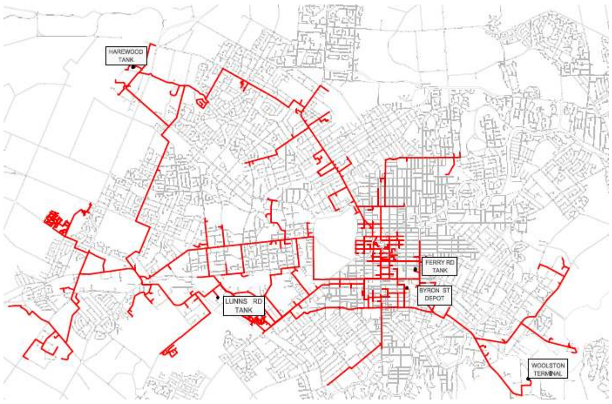

Figure 13: Contact Energy Service Areas and Pipeline Network (Courtesy of Rowan Smith, Contact Energy LPG).

Figure 14: ***Example of MDPE electrofusion joint for the Contact Energy pipes***

Despite the excellent performance in multiple earthquakes, as indicated in Figure 15, from a broader community perspective the gas system could not return to its pre-earthquake service levels due to the reduced number of customers as a result of the earthquake and related impacts.

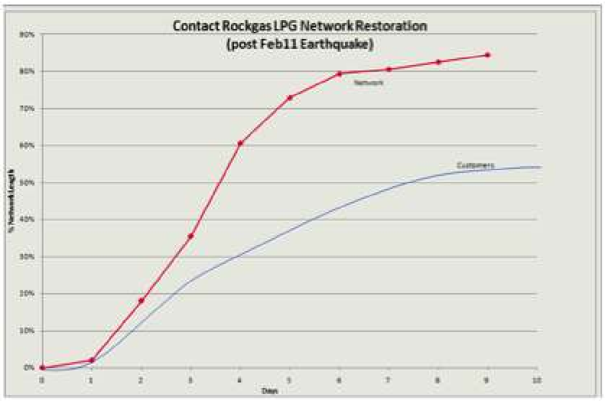

Figure 15: ***Rockgas serviceability following the 22nd February2011 earthquake.***

ROAD AND TRANSPORT NETWORK

Major transport nodes performed well. Christchurch International Airport was operational for emergency flight the same evening of the earthquake the re-opened at 7.00am on 23 February, the day after the earthquake. Lyttelton Port was located nearly directly at the earthquake's epicentre and was further affected by liquefaction ground damage and strong shaking, but was able to continue functioning almost immediately with services re-established to meet demand after 10 days. Despite this, it is expected damages and business interruption costs will extend to $300 million. Nearly all rail lines opened for freight on 24 February with some speed restrictions. The Lyttelton to Christchurch line and West Coast to Lyttelton line re-opened on 5 March 2011. The functionality of the airport, port and rail lines guaranteed large freight movements that were vital to support the emergency management operations.

Road networks were extensively damaged by the significant liquefaction that resulted in settlement, lateral spreading, sand boils and a large quantity of ejected silt, mud and water ponding on the road surface. Most of the State Highways remained open. Only-one tunnel of the state highway network had extended impacts, Lyttelton Tunnel, which reopened on 26 February, initially for restricted use.

Local roads in the eastern suburbs of the city were the most affected. 83 sections of 57 roads were closed. Five of the 6 bridges crossing the Lower Avon 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 significant programme to speed-up the liquefaction clean-up operations, congestion remained problematic for months following the earthquake.

Pre-earthquake seismic improvements to bridges on Highways 73 and 74 proved successful in resisting substantial loads and keep the highways in operation post-earthquake (Figure 16).

Figure 16: ***Pre-earthquake seismic improvements to bridges on Highways 73. (Photo credit: Craig Davis).***

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. Closure included Evans Pass, which provides a vital link for oversized or explosive goods between Lyttelton Port and the city, and Main Road which links the south-eastern suburbs of Redcliffs and Sumner to the city.

Further details on the structural and system performance of the road and transport can be found in the TCLEE report (Eidinger and Tang, 2011). A detailed account of the bridge response to the 22^{nd} February earthquake can be see in Palermo *et al.* (2011).

WATER AND WASTEWATER NETWORKS

Christchurch water and waste networks suffered extensive damage as a result of the 22 February 2011 earthquake. A review and discussion of the physical impact of the 22 Feb earthquake on the water and wastewater networks can be found in Eidinger and Tang (2011) and Cubrinovski *et al.* (2011). The TCLEE report (Eidinger and Tang, 2011) also includes impacts of the 4^{th} September 2010 and 13 June 2011 earthquakes.

The Christchurch City Council, CCC, owns and manages the city's water and wastewater networks. Following Christchurch earthquake, the CCC has been committed to restore the service and to keep the community informed on the restoration activities progresses. Maps providing an overview of some of the key issues and repair work facing the city have been published and regularly updated on the CCC website.

36,000 water and wastewater service requests were received and addressed by Christchurch City Council 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, remains a requirement to ensure water is disinfected. 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 water system restoration activities completed within six months time following the February event 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 (Mark Christison, personal communication).

HDPE pipe is being extensively used for all new pressure mains as it was found to perform well in the 4th September and 22nd February earthquakes and 13th June aftershock. Figure 17 show preliminary results on the performance of different pipe material for the Kaiapoi water network following the 4th September earthquake.

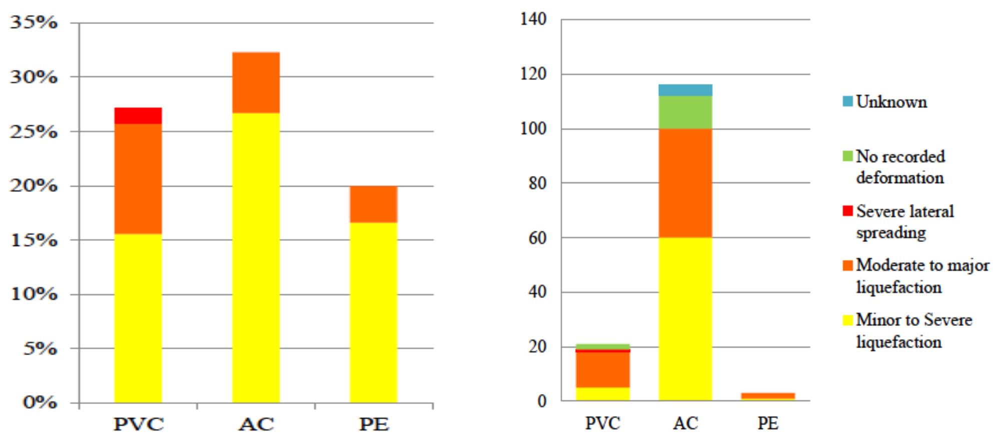

Figure 17: Kaiapoi water network following the 4th Sept, Darfield Earthquake: a) (Left) Percent of total length of different pipe materials within different ground deformation areas; b) (Right) Number of repairs made on mains and rider mains in different levels of ground deformation areas. (Knight, 2011).

The city continues to rely heavily on a temporary sewage service facilitated by chemical and portable toilets to supplement the fractured and fragile wastewater system (Stevenson *et al.* 2011). Christchurch City Council set a target of returning sewer services to all homes by the end of August and contractors have been working 24 hours a day, seven days a week since early March to achieve this goal. Work has been completed on all public sewer pipes, however as at 31 August there are still around 800 houses with damage to their private sewer pipes which needs to be addressed before full service is returned. Contractors have completed 500 such repairs to date and are working with EQC to get these completed as soon as possible. Portable toilets will remain on city streets where they are still needed.

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 February 22 earthquake. Some sewage is bypassed directly to the lagoons and other pumped directly into rivers. Concerns abound about the lagoons going 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.

Water and wastewater services continue to be impacted by significant aftershocks that liquefy the soils, including significant damages caused by the June 13 aftershock. It will take years to return the water and wastewater systems to pre-earthquake functions. Further studies are warranted to assess the water and sewer system's seismic resilience and means to improve future system performances

LIQUEFACTION CLEAN UP

The 22nd February 2011 earthquake induced widespread liquefaction phenomena across the Christchurch urban area that resulted in widespread ejection of silt and fine sand (Figure 18). This created unique impacts to many lifelines. Road networks with significant liquefaction ejecta deposits were difficult to transit or impassable for two-wheel drive traffic and contributed to traffic congestion. Liquefaction ejecta, continually erodeding over time, had the potential to infiltrate and contaminate the damaged storm water system and the urban waterways. Due to the extensive damage to the sewage disposal networks, there was the risk that much of the liquefaction ejecta had been contaminated with raw sewage creating a long-term health risk to the population (P. McDonald & J. Rutherford pers. comm., 2011; Weerasekara, 2011). During hot and windy conditions the dry, finer portions of silt was mobilised by the wind creating a respiratory health hazard.

With thousands of residential properties inundated with liquefaction ejecta, residents were eager to remove it from their properties to restore household functionality, remove the depressing grey deposits and retain a sense of control and normality. Wet or moist silt was also much easier to handle compared to when it had dried, as it became denser, hardened and was more difficult to remove (P. McDonald, pers. comm., 2011). However, with hundreds of thousands of tonnes of sediment to clear, many residents lacked the capacity (time or resources) to clean up their properties without external assistance.

Figure 18: ***Piles of liquefaction ejecta cleaned from residential properties and roads, ready for removal by heavy earth moving machinery at Bracken Street in the suburb of Avonside. (Photo credit: Jarg Pettinga).***

Cleanup Coordination

The liquefaction silt clean up response was co-coordinated by the Christchurch City Council (CCC) and executed by a network of contractors (including Fulton-Hogan Ltd and City Care Ltd) and volunteer groups, including the 'Farmy Army' – a group organized by rural organizations and made up mainly of farmers and rural workers – and the 'Student Army' – a group organized by the University of Canterbury Students Association and made up mainly of tertiary students. The rapid and very generous response to any request from local and international businesses and individuals encouraged everyone involved.

The liquefaction cleanup process included the following four subsequent steps: 1) initially cleanup operated by contractors using heavy machinery; 2) difficult to reach areas, e.g. residential properties and the area around vehicles cleared by teams of volunteers; 3) removal of the silt piled up in the street by the volunteers operated by contractors; 4) final cleaning via water-carts (truck mounted water tank and sprinkler system) to suppress windblown silt from the roads and to clean the silt possibly left into the storm water system (P. McDonald 2011, pers. comm., 2011).

The liquefaction cleanup operation required significant coordination of resources. During the peak cleanup after the 22 February 2011 earthquake it was estimated in excess of 1,500 people working on the cleanup, along with approximately 1,000 student and Farming volunteers (Fulton 2011). At the peak, the Burwood landfill was accepting 1 truck every 20 seconds into the waste disposal area (D. Harris, pers comm., 2011).

The use of a coordinated incident management system (CIMS) and staff trained in its use was essential for managing the clean up (Peter McDonald, pers. comm., 2011). Furthermore, all the parties involved acknowledged that the lessons from the first clean up in September-October 2010 contributed to a more efficient and effective clean up following February and June events. Also, a job dispatch and mobile workforce management system, GEOOP, donated to the Student-Army was successfully experimented and used for coordinating the works of volunteers around the city.

The majority of liquefaction ejecta was disposed at the Burwood Landfill, identified as part of disaster planning, as a storage area for disaster waste (D. Harris pers. comm., 2011). The Burwood landfill in Bottle Lake Forest (map) had been operational from 1984-2005 serving Christchurch's waste disposal needs and at the time of the earthquake was undergoing a final stages of restoration and remediation work (started in 2010).

Because of the severity of the road damage following the 22 February 2011 earthquake and the huge volumes of silt, further strategic locations were identified to temporarily stockpile silt (Figure 19; D. Harris, personal communication, 2011).

Figure 19: ***Estimated > 400,000 tonnes of liquefaction silt removed from the Christchurch urban area after the February 22 earthquake at the Burwood landfill disposal site.***

Duration and estimated Cleanup Cost

The duration of the clean up time of residential properties and the road network was approximately 2 months following the 4th September and 22nd February 2011 earthquakes and 13th June aftershock (Table 3).

Table 3: Estimated mass of silt removed by Fulton Hogan in Christchurch between September 2010 and August 2011 (Fulton 2011).

4 September 2010 – early November 2011	31,000 tonnes
22 February - April 2011 (mostly completed by late March)	315,655 tonnes
13 June – early August 2011	87,364 tonnes
Total	**434,019 tonnes**

During the period of data collection the final financial cost of the cleanup effort to contractors was not available. However, from available sources the estimated cost of cleanup at September 2011) is summarised in Table 4.

Table 4: Estimated costs of liquefaction clean up following the 4 Sept 2010, 22 Feb and 13 June 2011 earthquakes in Christchurch (P. McDonald; D. Harris; J. Rutherford pers comm., 2011).

Item	Estimated Cost	
	Subtotal	*Total*
Disposal Site Running Costs	$1,200,000 *(1 month post 22 Feb 2011)* $500,000 *(est. post 4 Sept 2010)* $500,000 *(est. post 13 June 2011)*	$2,200,000
Disposal Site Infrastructure		$800,000
Transport and disposal of 500,000 tonnes of silt		$2,500,000
Contractor Staff Time		$2,000,000
Estimated volunteers labour contribution	$1,000,000 (Student Army) $1,000,000 (Farmy Army)	$2,000,000
Donations to the Student Army	$20,000 (MSD) $10,000 (Mitre 10/ANZ wheelbarrows) $30,000 (other donations)	$60,000
Total Estimated Costs		**$9,560,000**

The liquefaction clean-up experience in Christchurch following the 2010-2011 earthquake sequence has emerged as a valuable case study to support further analysis and research on the management, logistics and costs not only for liquefaction related phenomena, but also any kind of hazard which might cause the deposit of large volumes of fine grained sediment in urban areas, (e.g. volcanic ash or flooding; see Johnston *et al.* 2001).

8. 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.

The value of resilient design, interdependency planning, mutual assistance agreements, extensive insurance cover and highly trained and adaptable human resources are the successful stories that this paper aims to highlight. 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 lesson learnt from previous damaging earthquakes, contributed to the design of such a robust and redundant network. Limited interdependency issues were experienced between lifelines systems, with generally a good level of coordination and communication experienced among the lifelines utilities and with the National and Local emergency operations and coordination centres. All the lifelines utility 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.

However the event has also 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. Weak buried pipes and cables, played a major role in the seismic response of the water, wastewater and power systems.

The 22nd 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 city and highway 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 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 22nd 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 a urban environment.

As a last word of this paper, we would like to acknowledge the significant contribution made by members of the original Christchurch Engineering Lifelines Project team in the mid 1990s to increasing Christchurch's lifeline infrastructure resilience to hazards. This ground-breaking work, lead by John Lamb, has been continued by former and current members of the Canterbury Engineering Lifelines Group. Their contribution has greatly reduced service disruption, repair costs and ultimately societal disruption for this generation of Cantabrians, and the legacy will continue to benefit future generations.

ACKNOWLEDGEMENTS

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: Christophe Tudo-Bornarel (Transpower); John O'Donnell, Shane Watson, Peter Elliot (Orion); Rowan Smith, Wai Yu (Contact Energy/RockGas); Pete Connors (NZ Transport Agency): Murray Sinclair (Christchurch City Council, Road); Mark Christison (Christchurch City Council, Water, Wastewater); Gerard Cleary, Gary Boot, Ric Barber (Waimakariri District Council). Our sincere thanks to interviewees: Dave Harris, (General Manager Burwood Landfill, Christchurch City Council); Peter McDonald (Pavement Liaison Engineer/Operations Manager, CCC); Lee Hautler (Maintenance Divisional Manager, Fulton Hogan Ltd); Lisa Chapman (Volunteer co-coordinator, Farmy Army/Federated Farmers); Sara Russell (New Zealand Young Farmer Manager); Jade Rutherford (club secretary/internal communications, Student Army/USCA, University of Canterbury). We gratefully acknowledge the support of Terry Howes, Richard McCracken, and James Feary of the CCC water and wastewater unit. We gratefully acknowledge the New Zealand GeoNet project and its sponsors EQC, GNS Science and LINZ, for providing data/images used in this study. The financial support of the Natural Hazard Research Platform to the "Recovery of Lifelines" short-term project is gratefully acknowledged. 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.

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