Seismic Performance of Buried Electricity Cables during the Canterbury Earthquake Sequence

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Abstract

The 2010-2011 Canterbury earthquake sequence, which generated significant ground shaking in Christchurch, New Zealand, caused building damage, human losses, and resulted in widespread damage to the city's infrastructure, including disruption to the buried electricity cables. This paper first describes the impact of the Canterbury earthquakes on the buried cables by briefly summarising their performance during the earthquakes, including the damage resulted from both ground shaking and land damage (i.e. liquefaction and lateral spreading). To increase the knowledge of the damage suffered by the buried electricity cables within the Greater Christchurch area, a GIS database of damage, geotechnical data, ground shaking and land damage information was created.

Next, preliminary lessons after carefully examining the GIS database are discussed. Special focus is given to quantitative assessment of the seismic performance of the buried cables. Fragility models, which present the relation between shaking intensity and the probability of reaching or exceeding a certain level of damage in the network, are derived using the available damage data along with the shaking and land damage information. The procedure to derive the fragility models is illustrated in detail followed by discussions in the light of the observed performance of the buried cables network in Christchurch. The results contribute to enhance the understanding of the seismic performance of buried electricity cables and therefore to minimise disruption and increase the resilience of communities after a seismic event.

Keywords: Canterbury earthquake sequence, buried electricity cables, liquefaction, damage index

1 INTRODUCTION

The Canterbury 2010-2011 Earthquake Sequence (CES) was very damaging to electricity network in Christchurch, causing widespread interruptions in service. Some outage even lasted until early March (Kwasinski et al., 2014), which led to huge economic loss to Orion, the local electricity distribution company (Orion, 2012).

In general, the above-ground electricity equipment performed well during the CES. Damage to high voltage equipment was relatively minor due to the well-installed equipment and low exposure number of substations to high ground shaking level (only one substation was exposed to peak ground acceleration (PGA) much over 0.5g) (Kwasinski et al., 2014). However, significant damage to underground buried cables was reported. For example, considerable faults of 66 kV buried cables in urban Christchurch were observed with most of the faults being in the area with intense liquefaction (Eidinger & Tang, 2012, Giovinazzi et al., 2011). Assessment of the 11 kV cables seismic performance during the September 2010 and February 2011 events also indicates that the main reason of the cable faults was liquefaction and lateral spreading, but some cable faults were also observed in areas without land damage. This suggests that cables are susceptible to damage caused by both ground shaking and ground deformation (Kongar et al., 2014).

This paper presents the results from studies on how the buried electricity cables in Christchurch performed during the CES, focusing on the most damaging aftershock of February 2011. The performance has been studied for the main voltage levels (i.e. 400 V, 11 kV and 66 kV) present in the Christchurch electricity networks, and is described through fragility models which are functions of both shaking intensity and ground conditions. Brief information on the events and the electricity networks affected are provided in the following sections, followed by a description of the data and methodologies used to derive the fragility models. Finally, the results are presented and discussed.

2 CANTERBURY EARTHQUAKE SEQUENCE

On 22nd February, 2011, Christchurch City experienced a direct hit from a destructive magnitude (M_w) 6.2 aftershock following the main event of magnitude 7.1 on the 4th September, 2010. The February event was followed by another destructive aftershock of magnitude 6.4 in June and later by a magnitude 6.0 aftershock in December. There were also numerous aftershocks of smaller magnitudes in between and after these main events. The February event caused severe shaking and widespread liquefaction in Christchurch, which caused significant damage to Christchurch's underground cables. Liquefaction caused failure of cables due to uneven settlement, uplift of cables, pull-outs of joints etc. The liquefaction was widespread but most severe in the suburb of Bexley and along the Avon River (Cubrinovski et al., 2013).

2.1 Shaking intensity

The shaking intensities in Modified Mercalli Intesity (MMI), for the February event were estimated using ShakeMapNZ, which is the modified version of the US ShakeMap for New Zealand. For estimating intensities, ShakeMapNZ uses the model of Allen et al. (2012) which includes macro-seismic intensity data from around the globe as well as from over 100 New Zealand events. For the February event, the inter-event uncertainty in the intensity prediction equation was removed by converting all

observed instrumental ground motions on 25 GeoNet (www.geonet.org.nz) strong motion recording stations around Christchurch, into macro-seismic intensity using the Ground Motion to Intensity Conversion Equation (GMICE) of Worden et al (2012). More details of the methods used in ShakeMapNZ can be found in Horspool et al. (2015).

2.2 Liquefaction

Extensive liquefaction is believed to be the main cause of substantial damage to Christchurch buried electricity cables (Eidinger & Tang, 2012, Kongar et al., 2014). The liquefaction severity maps used in this study were produced by Tonkin and Taylor Ltd (Van Ballegooy & Malan, 2013) using information collected from drive-by surveys, where evidence from liquefaction was mapped, taking into account visible lateral spreading, sand boil deposits, and land damage etc. Liquefaction was divided into 6 classes (Table 1) depending on the severity of the manifestation:

In this paper the extent of liquefaction, and its implications will be discussed along with its effects on the seismic performance of buried electrical cables in Christchurch aiming to understand what occurred in Christchurch and the lessons we can gain from studying the performance of the Christchurch underground buried cables during the CES. It is noted that due to the small area of some of the land deformation zones and the limited length of cables and number of faults in some of them, the original 6 liquefaction classes had to be consolidated into three broader categories, namely "No land damage", "Liquefaction damage", and "Lateral spreading", as shown in Table 1 to enable quantitative analysis of the performance

Table 1. Mapping between land damage categories used in this paper and those in Van Ballegoory & Malan (2013)

Land damage category (present study)	Land deformation class (Van Ballegooy & Malan, 2013)
No land damage	• No observed land damage • Minor land damage but no observed liquefaction
Liquefaction	• Moderate liquefaction but no lateral spreading • Severe liquefaction but no lateral spreading
Lateral spreading	• Moderate to major lateral spreading • Severe lateral spreading

3 OVERVIEW OF NETWORK

Transpower and Orion are the companies which service the electric power in central Christchurch. Transpower operates the high voltage (e.g. 220 kV and 66 kV) national transmission system, while Orion operates voltages of 66 kV, 11 kV within sub-transmission system and 400 V to final customers. Table 2 lists the length and material information of Orion's buried cables (Orion, 2009). Note that in the subsequent sections of this paper, EHV (extra high voltage), HV (high voltage) and LV (low voltage) are used to represent 66 kV, 11 kV and 400 V voltage levels, respectively.

Table 2. Length and materials of Orion's buried cables (Orion, 2009)

Cable Type & Code	Length (km)	Insulation Materials
66 kV (EHV)	64	• XLPE (7 km) • Oil-filled (57 km)
11 kV (HV)	2157	• XLPE (601 km) • PILCA (57 km) (remainder unknown)
400 V (LV)	2470	• XLPE (1353 km) • PVC (427 km) (remainder unknown)

Key: XLPE (cross linked polyethylene), PILCA (paper insulated lead cable armour), and PVC (Polyvinyl Chloride)

As mentioned previously, significant failure occurred to buried cables during the February earthquake, in particular for cables located in the liquefaction areas. A complete investigation of the buried cables' behaviour under both shaking and land deformation requires detailed information on the buried network in Geographic Information System (GIS) format, which was not available. However, approximate locations of faults on Orion's buried cables during the CES were available in GIS format and were used to derive the fragility models. Limited unverified location information was also available in GIS format on two buried cables networks namely underground buried cables (UG, including both 400 V and 11 kV) and EHV (66 kV cables). These network GIS layers were extracted from some old Orion's archives. The layers were checked against the Orion WebMap portal, which is Orion's current network map in high resolution PDF (Orion, 2014) and deemed to be adequate for the level of analysis intended in this paper. Unfortunately, the voltage level, material type and other cable attributes were not identified in the UG layer. Although these attributes were all available in WebMap, extracting the necessary attributes and assigning them back to the same cable in the GIS layer was quite time-consuming and could not be completed within the timeframe of this study.

Despite the above limitation of the data, in this paper the performance of UG and EHV cables is investigated to the extent possible, and is described through fragility models which are functions of both shaking intensity and ground conditions. Methodologies used to derive the fragility models are discussed below, followed by discussions on the results.

4 METHODOLOGY

In this study, the segment centroid is used to represent the cable location. Each segment is then assigned a shaking intensity in MMI by geospatially joining the cable centroid locations with the event MMI map. Observed liquefaction severity categories were also assigned in a similar way by spatially joining the centroid locations with the observed liquefaction severity maps from Tonkin and Taylor.
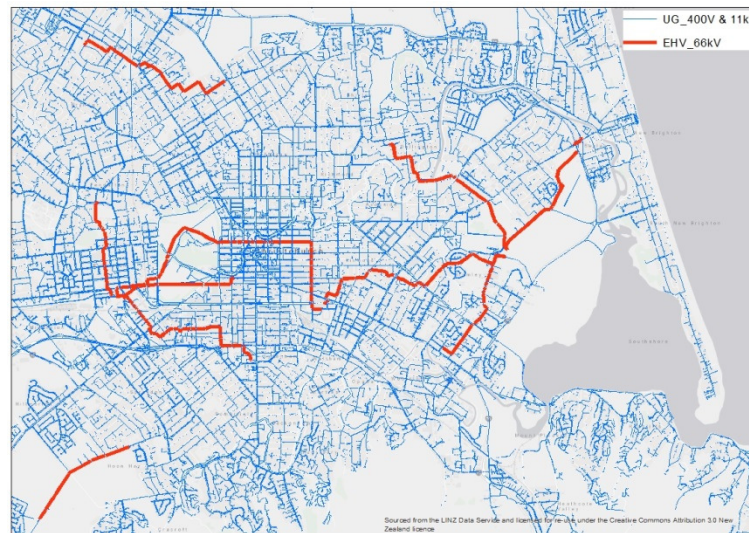
Figure 1. Orion buried cables network

4.1 Damage data

A map of a total of 1204 observed faults of HV (i.e. 11 kV) cables were supplied by Orion (Orion 2013) (Fig. 2). It is noted that the supplied map only contained fault locations, no descriptions or records of which event caused the faults. It is also noted that Orion had implemented a variety of seismic mitigation measures, in combination with the relatively modest levels of ground shaking, resulted in relatively excellent performance (Eidinger &Tang, 2012). For example, the rapid restoration in the September event suggests that damage was relatively minor and that almost all buried cables and power distribution substations were unaffected (Kwasinski et al., 2014). It was estimated that the September event damage affected about 4% of the 11 kV buried cables, causing about 30 faults (Kwasinski et al., 2014; Kestrel Group, 2011). In other words, the faults caused by the September event counted for only 2.5% of the total faults in the dataset (30 out of 1204). Therefore in the present study, it was assumed that all of the cable faults were caused by the February event.
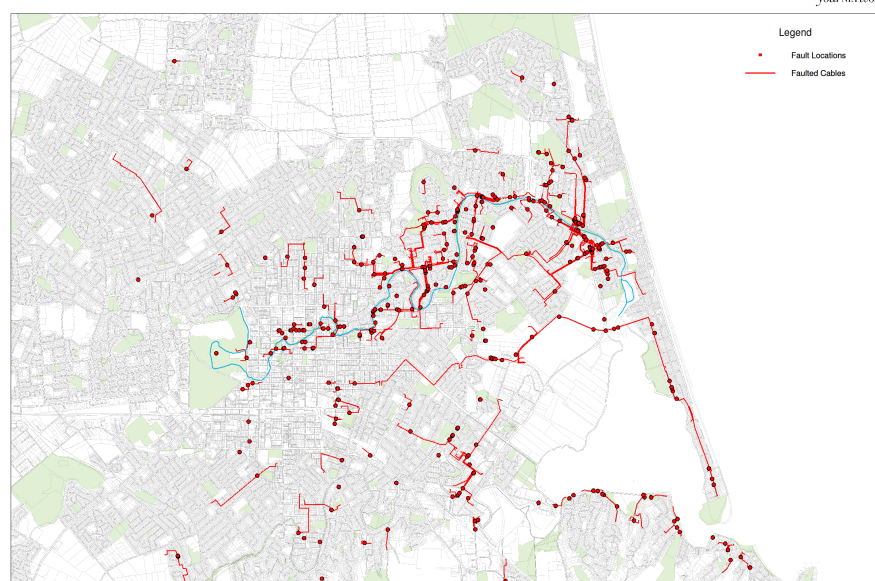

Figure 2. fault locations of HV (i.e.11 kV) cables during the February earthquake

In terms of damage to EHV (i.e. 66 kV) cables network during the February earthquake, it was reported that 50% (30 km out of the total of 64 km) of cables were affected (Eidinger, 2012, Giovinazzi et al., 2009). For example, the cables in the major liquefaction areas (e.g. Dallington and Brighton) were abandoned due to its uneconomic repair. In addition, six faults were identified and repaired in the moderate liquefaction areas (e.g. Armagh and Lancaster).

4.2 Fragility model for buried electrical cable

Following the approach presented in Park et al. (2006) to evaluate the seismic performance of underground cables, Damage Index, DI, as defined in Equation 1, was used to describe the Christchurch underground cables seismic performance in the present study.

$$\text{Damage Index } i = \text{DI}_i = \frac{\text{affected network length in shaking contour i}}{\text{total network length in shaking contour i}} \tag{1}$$

Given the buried cables network overlaid with the MMI contours and the liquefaction map, the lengths of the damaged cables and total cables in each MMI contour and liquefaction class were tabulated and used to calculate DIs.

With the above calculated DIs, Logistic regression model (Hosmer and Lemeshow, 2000) was used to determine the fragility models of buried cables. The form of the logistic regression model and its logit transformation are shown in Equations (2) and (3).

$$\pi(MMI) = \frac{e^{\beta_0 + \beta_1 MMI}}{1 + e^{\beta_0 + \beta_1 MMI}} \tag{2}$$

$$g(MMI) = \ln\left[\frac{\pi(MMI)}{1 - \pi(MMI)}\right] = \beta_0 + \beta_1 MMI \tag{3}$$

5 RESULTS AND DISCUSSION

5.1 Results

The logit model parameters for the UG cables damage indices are listed in Table 3 for different liquefaction severities. The same models are also shown as curves in Figure 3a. As Table 3 and Figure 3a show, overall, the cables in no observed land damage areas showed more robust seismic behaviour, followed by cables in liquefied areas. As expected, cables in lateral spreading areas were most affected. When comparing fragility model of cables with various voltage levels, UG cables performed better than EHV cables, as shown in Figure 3b.

Table 3. Derived damage index model parameters for 400V and 11kV underground cables in different land deformation zones

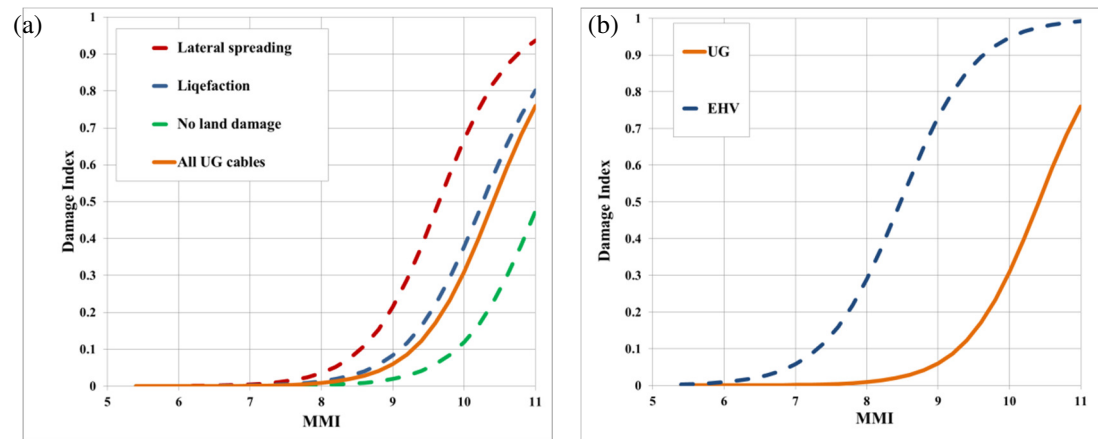| Christchurch Feb 2011 EQ parameters	β_0	β_1
All cables	-19.75	1.95
Cables w/o land damage	-20.5	1.9
Cables w. Liquefaction damage	-19	1.9
Cables w. Lateral spreading	-18.5	2

Figure 3. The derived damage index curves for (a) UG cables in different ground deformation categories, and (b) UG and EHV cables given MMI values for February earthquake

5.2 Comparison with global damage data

To evaluate the derived fragility models, the derived curves were compared with those presented in Park et al. (2006) from 2001 Nisqually (Washington, US) and 1995 Kobe (Japan) earthquakes, as shown in Figure 4.
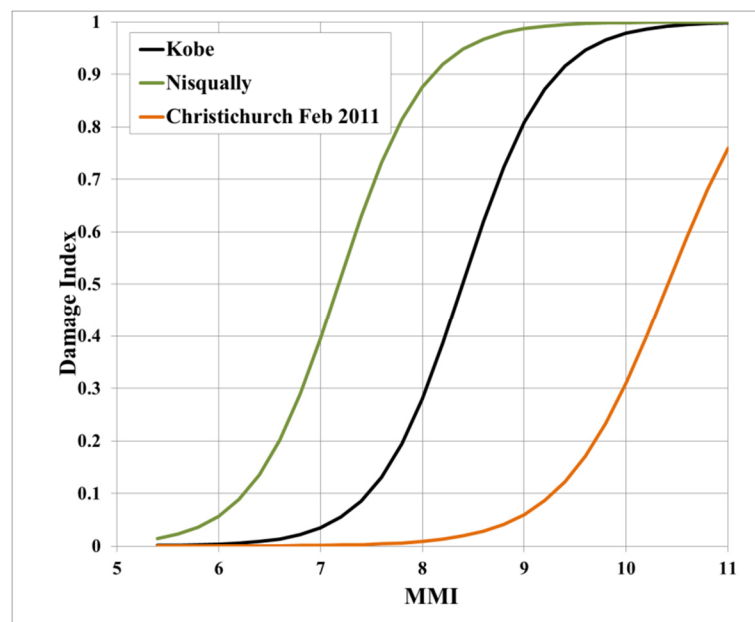

Figure 4. Comparison of derived damage index curves for underground cables with damage data in Nisqually and Kobe earthquakes

5.3 Discussion

The effect of liquefaction in Christchurch was both horizontally and vertically non uniform, with large changes in severity even inside the same liquefaction severity class (Cubrinovski et al., 2013). Not only did the buried electrical cables experienced high changes in liquefaction observable at the surface, it experienced additional subsurface liquefaction at higher severities and variability, than the liquefaction map suggests (Cubrinovski et al., 2013). This sporadic nature of liquefaction might have a large influence on the overall damage index curves derived and should be taken into account when the results are used.

The discrepancy when comparing with other global damage data might result from various reasons, some of which are discussed here.

- ***Different definitions of affected network length (affected feeder length vs. cable faults)***

In Park et al. study, the feeder network included all systems operating at 26 kV originating from distribution substations to the customer meter. The above system included poles, overhead lines and underground cables, transformers, etc. While only 11 kV and 400 V underground cables were considered in the comparison. Since the electricity network in Christchurch comprises both overhead lines and underground cables including high voltage buried cables, which are all also vulnerable to ground shaking and deformation, the total damage index might be higher. Therefore, the derived fragility models will need to be investigated further when more data become available either from the CES or future events.

- ***Differences in MMIs (Instrumental MMI vs. ShakeMap NZ MMI)***

The instrumental MMI values which were used in Park et al. study were based on the relationship between peak ground acceleration (PGA), peak ground velocity (PGV) and Modified Mercalli intensity, details of which can be found in Wald et al. (1999). It is noted that the above calculation was also used to generate USGS ShakeMap. Although ShakeMapNZ is an implementation of ShakeMap for New Zealand, it incorporated New Zealand specific ground motion prediction equations (GMPEs), a New Zealand Vs30 model, and is optimised for the GeoNet instrumentation records. Therefore, the MMI values from ShakeMap NZ might be different from those from ShakeMap, although its influence might not be significant.

6 CONCLUSIONS

This paper combined the invaluable damage data from the Canterbury Earthquake Sequence on the Christchurch buried electricity cables with the shaking and ground deformation information to propose Modified Mercalli Intensity (MMI)-based network damage index models for buried electricity cables networks when subjected to earthquake shaking, including the influence of liquefaction. The fragility models proposed are based on damage data that were analysed systematically to ensure the true performance of cables is captured. As with most empirical fragility models, the proposed models are not well-supported by data, and since they are based on the Modified Mercalli Intensity, inherit the subjective-ness of the macro-seismic scale. Work is currently underway to develop fragility models which are based on engineering demand parameters to address this issue.

7 ACKNOWLEDGEMENTS

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