Performance of Electric Power Systems in the 2010-2011 Christchurch New Zealand Earthquake Sequence

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From late 2010 to mid 2011, Christchurch suffered a series of earthquakes and aftershocks that affected the city's power supply. The most relevant of these events occurred on September 4, 2010, February 22, 2011, and June 13, 2011. In all these events transmission level power restoration occurred rapidly—within one day. Except for the second event, similar relatively minor damage led to rapid restoration of distribution-level power outages. However, extensive damage to underground cables during the February 2011 earthquake caused some outages that lasted until early March. This damage seems to be amongst the only extensively-documented such failures to date. Despite recorded strong ground shakings, damage to other power infrastructure facilities was moderate to minor. This satisfactory performance of power infrastructure is attributed to a program implemented during the decade prior to this earthquake sequence to seismically upgrade almost all unreinforced masonry substation buildings and reinforce other infrastructure elements.

INTRODUCTION

This paper describes the performance of Electric Power Transmission and Distribution systems in the 2010-2011 Christchurch, New Zealand earthquake sequence constituted by the initial M 7.0 Darfield event of 4 September 2010, as well as the later M 6.1 event of 22 February 2011 and M 6.0 earthquake of 13 June 2011 (magnitudes are based on USGS reports). While the epicenter of the first event happened about 50 km west of Christchurch, the epicenter of the other two earthquakes were localized much closer to the city's central business district (CBD), the February event at 6 km south-southeast and the other at 13 km

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south east of the CBD. All these earthquakes were relatively very shallow events at a depth of 5 km, 6 km, and 9 km in chronological order. These events caused significant liquefaction, primarily in the northeastern area of the city along the Avon River that includes the districts of Avonside, Avondale, Dallington, Bexley, and New Brighton. Such significant liquefaction is expected considering that the city was built on a mostly drained swamp. Although strong ground shacking was observed, initial effects on power grids and other infrastructures were not as significant as soil liquefaction. Likewise, although land slides and rock falls occurred, particularly during the February 22, 2011 earthquake, these land slides and rock falls happened mostly in the hilly south and south eastern areas of Lyttelton and Sumner where there is not a dense power infrastructure deployment. Hence, although damage to power infrastructure from strong shaking and rock falls did happen during these events, the damage was limited to a small number of sites.

This paper discusses the performance of electric systems operated by Transpower (high voltage transmission system serving the entire country of New Zealand), Orion and Mainpower (lower voltage distribution systems serving the area affected by the earthquake sequence). The differences between these transmission and distribution portions of New Zealand's South Island power grid go beyond power and voltage levels: while most of Transpower power lines are overhead, Orion's lines, including sub-transmission feeders, are mostly buried underground. This planning and design difference led to different performance during the earthquakes because buried infrastructure was more vulnerable to the effects of significant liquefaction found in some areas. Discussion about buried cables failure is an important contribution of this paper to existing literature on the subject of buried power infrastructure performance during earthquakes. Damage to infrastructure above ground was also limited thanks to mitigation measures, such as reinforcement of unreinforced masonry (URM) substation buildings, implemented by Orion in the decade prior to the beginning of this earthquake sequence. The discussion presented in this paper is the result of multiple field investigation trips conducted after these events. These trips were organized by the Technical Council of Lifeline Earthquake Engineering (TCLEE) of the American Society of Civil Engineers (ASCE). Due to lengths constraints this paper is intended as a relatively high-level overview on the discussed topic. Hence, numerical data reporting and analysis was limited to describing key observations from the damage assessment. However, a detailed description of the findings from these field damage assessments can be found in (Eidinger and Tang, 2012).

POWER INFRASTRUCTURE PERFORMANCE DURING THE SEPTEMBER 4, 2010 EARTHQUAKE

As Fig. 1 shows, Christchurch is primarily served by two substations that step down the voltage from transmission-level 220 kV into sub-transmission level of 66 kV. The main one of these substations, called Islington, is located west of Christchurch and serves most of the city except for the eastern districts served by the other main substation, called Bromley, which is located east of Christchurch. Electric power is generated south of Christchurch and outside of the area affected by the earthquake sequence. Hence, none of the earthquakes in the discussed sequence affected electric power generation. Power from the generation plants is transmitted through three 220 kV lines with steel lattice towers. Two of these lines, the Benmore –Islington (BEN-ISL-A) and the Roxburgh-Islington (ROX-ISL-A) were affected during the September 4, 2010 event due to the resulting fault offset of about 4 meters. As Fig. 2 (a) shows, the fault offset passed close to one of the towers of the ROX-ISL-A line and although this tower was not damaged, the fault offset caused the conductor suspension insulators to be displaced at their base causing tension to appear in the insulators anchoring point to the tower. Still, although these insulators ended up at an angle of about 45 degrees from the normal vertical position (Fig. 2 (b)), the tension at their anchoring point was not sufficient to cause any permanent damage. Short circuits due to the fault offset did not occur because the displacement occurred primarily along the direction of the conductors. A similar action affected the BEN-ISL-A line, but in this case, the notable effect was observed on one of the guard conductor—a grounded conductor that runs on top of transmission tower intended to absorb lightning strikes—which had its supporting steel brace bent as a result of tensions caused by the fault offset (Fig. 3). The 220 kV Bromley-Islington A line also presented issues when differential settlement of steel lattice tower footings caused tilting of four towers. One of these towers required the use of temporary guy ropes attached to concrete blocks to prevent further tilting until permanent repairs could be made.

Some little to moderate damage also happened at Transpower’s substations. In the substation of Papanui, the 66 kV line from the Islington substation broke at the terminal tower, but even with considerable signs of soil liquefaction at this, no damage occurred except, possibly, for two damaged transformers spill prevention containment walls. In Springston’s substation, the main issue was having two transformers tripping offline due to vibration. The same problem happened in Hororata substation located at approximately 18 km west of the epicenter where shaking with peak ground acceleration of about 0.45g horizontal and about 0.80g vertical caused two transformers to trip offline. In Bromley substation one lattice tower of the line to Islington was found leaning. However, grid operators could not confirm if this issue was caused by significant soil liquefaction observed in this substation or if it was leaning before the earthquake. Transformers tripping due to vibration also happened at the Islington substation where the three transformer banks tripped offline. These spurious transformer trips at Springston, Hororata and Islington were due to the malfunction of the mercury safety switches used in some of the on-load tap-changer oil relays, main Buchholz relays and temperature relays. This issue was identified by Transpower some years ago and a program to replace these old relays with modern seismically rated models commenced prior the 4 September earthquake. In Islington one 220 kV transformer mounted surge arrester failed at its base. Other minor damage observed in this and other substations included cracks in the control room and damage in a warehouse. Transpower service restoration was completed by about 8:30 am, i.e., approximately 4 hours after the earthquake.

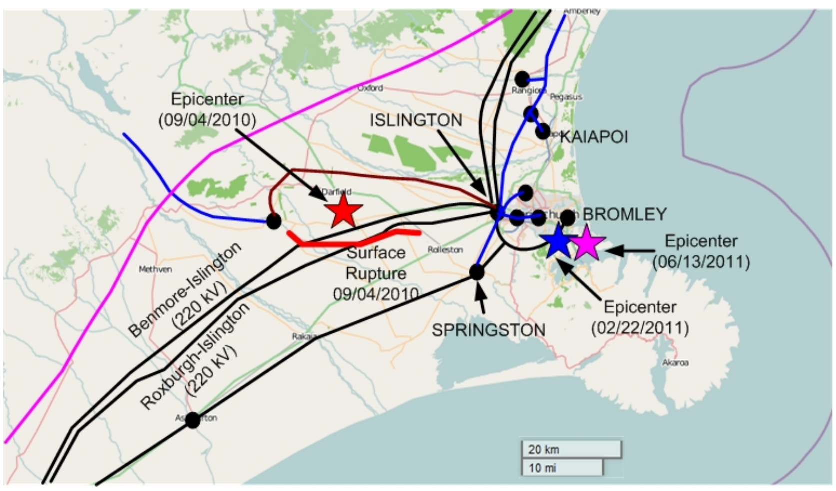

Figure 1. Map of Transpower transmission infrastructure around Christchurch. The approximate location of the epicenters for the three events discussed here are also indicated. The surface rupture in the September 4, 2010 event is also indicated.

Orion is the electric power distribution utility company serving approximately 193,000 customers in Christchurch. During the September 4, 2010 earthquake as much as 166,845 of Orion's customers experienced loss of service. Due to South Island's grid relatively low inertia, this sudden load loss led to a rapid increase in New Zealand's South Island grid frequency which briefly exceeded the required upper limit of 50.75 Hz until power generation actuators were able to compensate this load loss (Fig. 4). By late September 4, only 15,523 customers remained without power. That is, about 90 % of the customers that lost service during the earthquake were restored within the same day. This rapid restoration speed suggests that damage was relatively minor and that almost all buried cables and power distribution substations were unaffected. The relatively minor damage can be attributed to moderate observed PGAs in the range of 0.18g to 0.25g horizontal and about 0.3g vertical in Christchurch and a $NZ 6 million program implemented in the decade prior to this earthquake to reinforce about 200 small unreinforced masonry (URM) distribution substation buildings (some of these substations are shown later in this paper as part of the description of the effects of the September 22, 2011 event) and to upgrade three bridges across the Avon River each supporting two 66 kV pipe-type oil-filled circuits.

Figure 2. a) Left: Surface fault near a steel lattice tower of the ROX-ISL-A line. b) Right: Displaced insulators on a steel lattice tower as a result of the surface fault offset (photos: Transpower).

Figure 3. Bended steel brace supporting a guard conductor in a lattice tower (photo: Transpower).

Eighty percent of Orion’s power outages were caused by distribution substation transformer tripping offline due to vibration affecting mercury-filled safety switches. Most of the substations were not damaged by this earthquake except in Greendale, Pages and Brighton zonal substations, which still could maintain normal operations. At least one small

URM substation building that was abandoned by Orion suffered cracks in its walls. None of the 66 kV buried power lines suffered service interruption damage. However, two 66 kV oil-filled low pressure cables were partially crushed at the point where these cables transitioned from a buried condition into the pile-supported bridge across the Avon river at Dallington. After this September earthquake, Orion temporarily braced this bridge. Damage affected about 4 % of the 11 kV buried cables causing about 30 faults. Overhead lines experienced little damage. None of towers and poles supporting 66 kV overhead lines suffered damage and only a few of the insulators and binders in 33 kV and rural 11 kV overhead lines were damaged due to liquefaction. As Fig. 5 exemplifies, soil liquefaction also caused some of the poles supporting 400 V power distribution circuits to tilt. These poles are buried about 2 meters into the ground and none of them toppled. As Fig. 5 also shows, Orion added concrete blocks next to many of these tilted poles to support them in hope that they would not topple particularly during aftershocks.

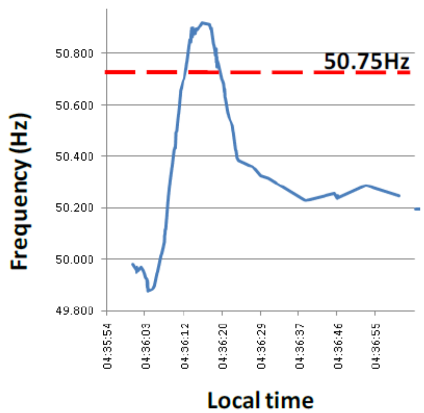

Figure 4. New Zealand's South Island operating frequency response in the September 4, 2010 earthquake (Transpower)

Figure 5. Tilted pole for 400 V power distribution being supported by a concrete block. Poles are shared with communications service providers.

During this earthquake, almost 10,000 of Mainpower's approximately 32,000 customers lost service. Peak power outages reported by Mainpower includes 7,964 in Kaiapoi, 1,050 in Hawarden, and 892 in Woodend. Most of these outages were caused by 18 reported faults in 11 kV underground cables and in two severely damaged substations that required to be rebuilt. Overhead lines also had damage with some poles leaning (some of them severely) and a few more sinking into the ground a few feet due to soil liquefaction. In some cases power was restored temporarily with the use of up to six 11 kV portable diesel generators, which operated up to 12 days. In addition, 3.5 km of new 11 kV cables were laid during the restoration phase and the two substations were rebuilt.

POWER INFRASTRUCTURE PERFORMANCE DURING THE FEBRUARY 22, 2011 EARTHQUAKE

Of the 3 discussed events in the earthquake sequence that affected Christchurch from September 2010 to June 2011, the event on February 22, 2011 was the one that caused most extensive damage in power infrastructure. Still, this damage primarily affected Orion's distribution network. Transpower suffered only a little damage to its infrastructure and, the little damage was centered at and around Bromley substation. This small amount of damage allowed restoring service by 5:30 pm (four and a half hours after the earthquake).

Figure 6 shows the horizontal response spectra (5 % damping) recorded near Bromley substation. As this figure indicates, the spectral acceleration exceeded the design limits indicated by the lines corresponding New Zealand's standard NZS 1170.5 for various types of buildings. Still, the two-story reinforced concrete control building at Bromley experienced no damage except for a few tiles from a suspended ceiling that fell without causing any effects to people or equipment. Thanks to adequate restraining measures, no damage was observed on equipment located on desks and tables. The main damage observed at this building was a 11 kV switchgear that partially toppled when its trolley became dislodged from its rails. This item was located in a rack, within the control building. At the time of the earthquake, it appears that this position had been rolled out from its housing, for maintenance purposes; during the earthquake, it rocked, breaking its cast supports, resulting in the component being nearly toppled. Since this switchgear was placed out of service before the earthquake struck no service was affected by this damage. There was also evidence of anchorage damage at many other positions in this rack, but the other equipment remained functional. After the earthquake, all positions in this rack were braced as a temporary measure. The long term solution was to replace this older equipment, entirely. Due to space limitations details and photos of this failed equipment could not be included in this paper. However, interested readers can obtain such additional details, including photos of the failed equipment in (Eidinger and Tang, 2012).

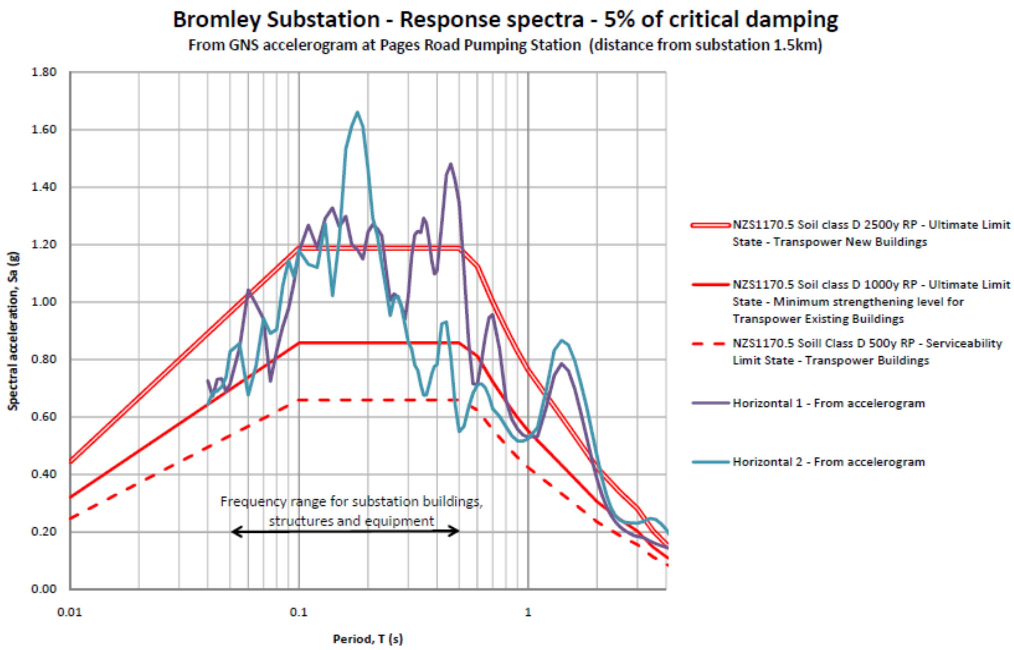

Figure 6. Response spectra from the February 22, 2011 earthquake and design limits at Bromley substation (Transpower).

Damage to the 220 kV switchyard included a broken 220 kV capacitor voltage transformer (CVT) (Fig. 7). A very short straight connection between the CVT and rigid bus was identified as a possible cause of the failure. However, it is noted that the CVT insulator is held by finger clamps which create localized stresses on the porcelain material that may increase their failure rate during earthquakes as a result of fatigue induced weakening of the porcelain, as the cracks in the porcelain near the corner of the finger clamps seem to suggest (see Fig. 7). In this event, this failed CVT was one of three in existence. Other (newer) 220 kV equipment including circuit breakers, current transformers and disconnectors were undamaged. The rigid bus was also undamaged despite significant liquefaction in the vicinity of the foundations (Fig. 8 (a)). As Fig. 8 (b) shows, some disconnect switches had some offset in their contacts but their contacts did not disconnect. Damage was observed in a 66 kV transformer bushing that failed probably due to insufficient slack in the connecting conductor. A voltage transformer also failed possibly due to a combination of differential settlement and shaking that affected its vertical tie to a rigid bus. Liquefaction was also observed in nearby steel lattice transmission towers of the 220 kV line to Islington (Fig. 9).

Still, even when a tower had some minor buckling in a few secondary braces, no tower had any significant structural issue that compromised their operation. Other observed damage to steel lattice towers was caused by a rock that fell between the legs of a steel lattice tower in the Port Hills area. However, operation of this line (likely owned by Orion) was not affected because the rock only damaged some auxiliary braces between legs.

Figure 7 Broken 220 kV CVT insulator mounting showing finger clamps. The arrows in the photo on the right indicates fatigue induced cracks initiated in the porcelain edges in contact with the corner of the finger clamps. (photos: Transpower)

Figure 8 a) Left: Significant soil liquefaction at Bromley substation. One of the authors is standing inside a sand "volcano." b) Right: 1 cm offset at a disconnect switch in Bromley substation

Figure 9. Examples of soil liquefaction at the base of steel lattice towers.

During this February 2011 event and like in the September 2010 earthquake over 80 % of the Christchurch area lost power, with only the suburb areas of Hornby and Riccarton avoiding power outages. However, power outages during the February 2011 earthquake lasted significantly longer than in the September 2010 event, totaling about 629 million customer-minute outages in the latter which was approximately 7 times worse than in the earlier event. In the February 2011 earthquake, 90% of the outages were restored by March 4th, when a new 2.5 km temporary 66 kV line running from Bromley to Brighton substations and bypassing Pages substation was placed into service in order to power the most severely affected areas of Brighton and Dallington. This new line, shown in Fig. 10, was necessary because both 66 kV cables serving this area and indicated in the map in Fig. 11, failed. As the maps in Fig. 12 show this area where most of the damage occurred roughly coincide where significant liquefaction happened. In total, Orion reported that 140 cables had damage with as many as 600 faults in these cables (more faults were detected in the following months which increased the number of faults to close to 1,000). In the Brighton-Dallington area all 80 underground 11 kV cables had faults. As recognized by Mr. Sutton, Orion's CEO, "much of the damage is to underground cables which take longer to locate and repair than overhead lines." In practice, each fault in an underground cable took a minimum of 12 hours to locate the fault point and repair it. In total, 50 % of 66 kV cables, 5.5 % of 11 kV cables and 0.6 % of 400 V cables experienced faults. The higher failure rate in cables with higher voltages is explained by the fact that at higher voltages, the percentage of underground lines with respect of the total number of lines increases (e.g. at 11 kV 90 % of the cables are underground and the rest are in overhead lines). Another contributing factor is that underground lines tend to be longer at higher voltages. In the following month the reported percentage of failed 11 kV increased to 15 % (330 km of faulty cables out of a total of 2,200 km) with most of these faults (86 %) observed in streets with severe liquefaction, 8 % of these faults in streets with moderate liquefaction and the rest in streets with minor or no readily-observable artifacts of liquefaction. Figure 13 shows examples of damaged cables. In some cases, the temporary solution to restore service to critical loads, such as water facilities, and some residential electricity users, was to deploy diesel generators. As many as 21 generators were used in this way, most of them deployed in Christchurch eastern suburbs. Another generator brought from Australia was deployed in the Redcliffs area.

Figure 10. The temporary 66 kV line installed from Bromley substation to restore service in the Brighton-Dallington area.

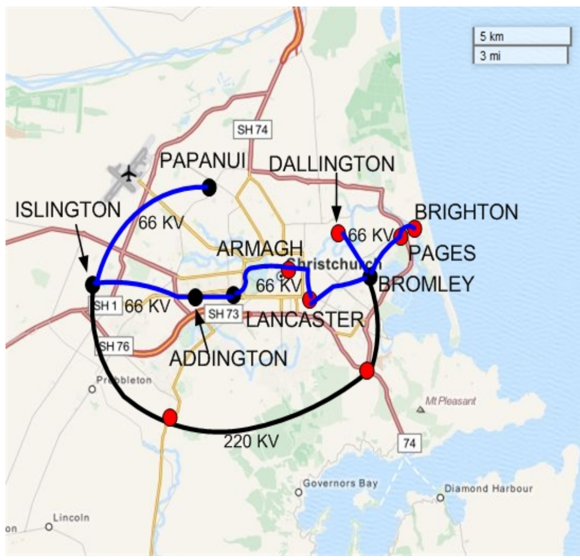

Figure 11. Relevant power distribution infrastructure in Christchurch.

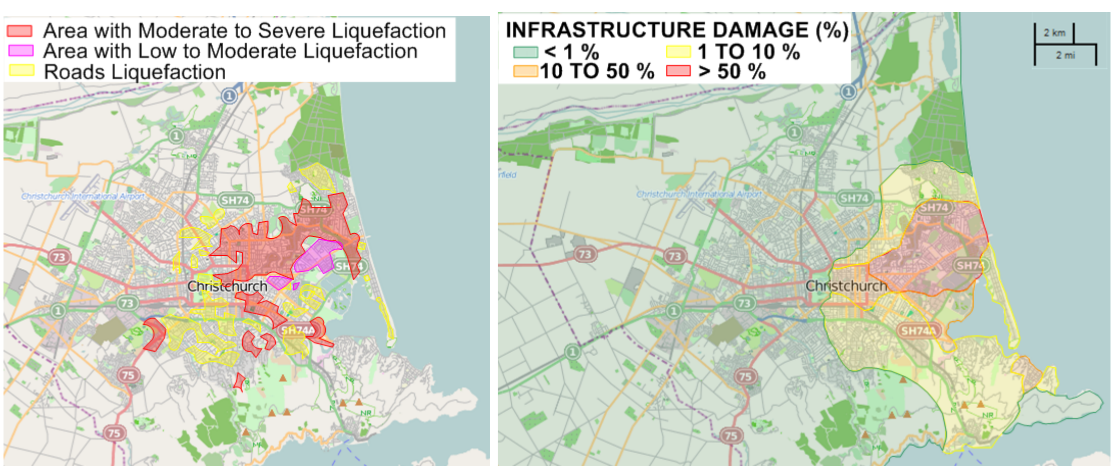

Figure 12. a) Left: Approximate soil liquefaction severity. Map prepared based on (Cubrinovski, 2012). b) Right: General areas with indicated power infrastructure damage severity.

Figure 13. a) Left: An apparent crack induced fault in a 11 kV underground cable. b) Right: 66 kV underground line along Armagh street damaged by soil liquefaction (Photo: Orion).

Sudden load loss in most of Christchurch from about 340 MW before the earthquake struck to approximately 60 MW after the shaking passed (Fig. 14 (a)) led also to reactive power imbalances that, in turn, caused voltage rises observed in Transpower substations in the affected area (Fig. 14 (b)). These voltage rises were eventually compensated by reactive power support devices. Load loss also caused a temporary frequency increase in New Zealand's South Island power grid. There was a temporary increase in the power transferred from the South Island to the North Island through the high-voltage direct current (HVDC) 350 kV Inter-Island link which experienced an increase of about 90 MW when the earthquake struck, as shown in Fig. 15 (b). This increase in power supply to the North Island through the HVDC link fulfilled its function of sharing the frequency increase across both islands, limiting the frequency increase in the South Island and creating an acceptable frequency increase in the North Island until regulators acted to balance power generation and demand in both islands. Similar effects were found for the September 4, 2010 earthquake, where the Christchurch load went from about 550MW before the earthquake, to 100MW after the earthquake.

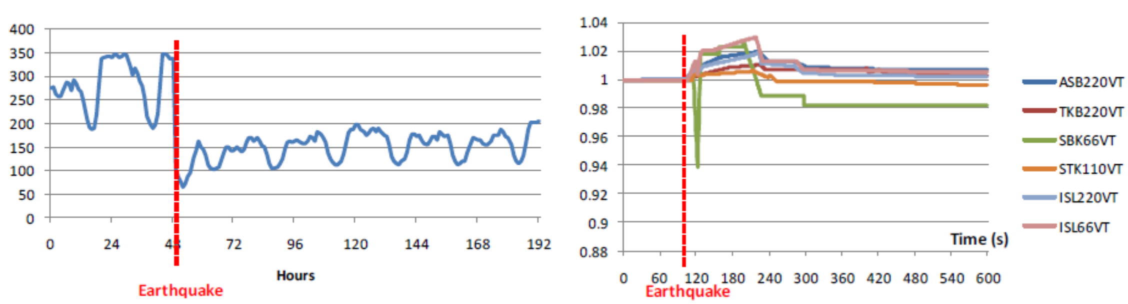

Figure 14. a) Left: Load (MW) in Christchurch on February, 22, 2011. b) Right: Voltage levels (in per unit) in various of Transpower substations in or near Christchurch. (Transpower)

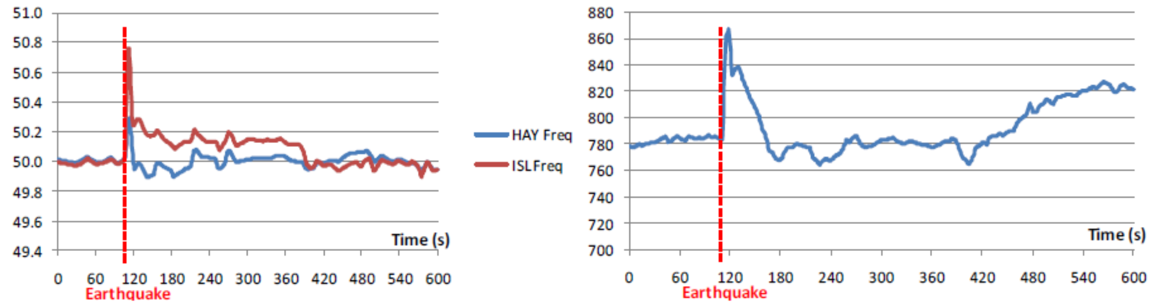

Figure 15. a) Left: Frequency in South Island's power grid at Transpower's Islington (ISL) substation and in North Island's power grid at Transpower's Haywards substation, located south of Wellington. b) Right: Power flow from south to north in the Inter-Islands HVDC link. (Transpower)

The most serious faults were those occurring in Orion's 66 kV lines. As explained in (Eidinger, 2012), factoring in the field observations, the causative movements / forces to cause the 66 kV cable failures are thought to be as follows.

At six different locations (three locations using XLPE-type cables, and 3 locations using oil-filled "pipe type" cables, the observed failure mode of the 66 kV cables was as follows. In all locations, the cables were installed using the "direct burial" method, whereby a trench was dug, the cables laid into the trench, and the cable encased in a weak cement "thermal concrete" backfill; finally the trench filled to the surface to make the road surface. At all locations, the damage occurred to all parallel cables, in less than 10 cm of length; in other words, the damage was concentrated at specific locations, and not randomly disbursed along the length of the cables. At all locations, once the cables were dug up for repair, the observed cable condition was high curvatures (as for example, the three buckled cables highlighted in the red circle in Figure 13b). After the earthquake, the authors field inspected the sites of the cable damage, looking for evidence of liquefaction phenomena nearby, that could explain the ground deformation patterns that led to the damage. From these observations, along with numerical modeling of the cables, the authors make the following comments related to the likely conditions that led to the cable damage and their restorations:

(1) the cable failures are not due to high levels of ground shaking alone. Nearly 100% of cable failures occurred in areas of Christchurch (and nearby Kaiapoi) in locations with readily observed liquefaction. Therefore, the failure phenomena is NOT directly caused by high levels of ground shaking (travelling waves).

(2) the field inspections along the 66 kV cable failures in and near downtown Christchurch (6 total failure locations) showed very modest permanent ground deformations (PGDs) between 1 to 5 cm at or near the actual cable failure locations. Within a 3 km length

through downtown Christchurch, the cables failed at 6 locations (at 5 of the 6 locations, all parallel phases faulted). In downtown Christchurch, with the relatively modest number of 66 kV cable failures, the restoration process was to dig up the damaged cable, cut out the damaged section of cable, and then install a new cable splice, followed by restoration of the thermal backfill and repair of the road.

(3) In eastern Christchurch, where large PGDs were prevalent (5 to 50 cm common), the failures to the 66 kV and 11 kV buried cables were so prevalent as to cause multiple faults on many cables, leading Orion to often abandon-in-place the damaged 11 kV and 66 kV cables in those instances. In eastern Christchurch, with the larger PGDs, the short-term restoration process was to install temporary overhead lines; the moderate term restoration process was to install a new buried transmission cable, routed to avoid the zones thought to have the largest potential for large PGDs in future earthquakes. In some places new cables were laid on a reinforced concrete bed (Orion, October 2012)

We now examine the likely causes of the observed 66 kV cable damage. In all cases, the cables were encased in thermal concrete backfill, sometimes also called "direct burial" method of installation. In all cases, after the thermal concrete was chipped away, the appearance of the damaged cable showed high curvatures (bend radius on the order to 5 to 50 cm). In all cases, there were no large PGDs evident on the roadway above; cracks in the roadways / adjacent curbsides were commonly less than 1 cm. The following paragraphs summarize evidence leading to the posited failure mechanism:

(1) During the strong shaking phase of the earthquake, wave velocities of 40 to 70 cm/sec were prevalent in downtown Christchurch. Using the assumption that cable strain would be equal to the ground strain, and strain being proportional to wave velocity / wave propagation speed, common calculations of cable strain (see ALA 2005) (extension / contraction and bending) cannot show high enough strains / curvatures in the cables to even approach cable failure. This is empirically confirmed as there was essentially no cable damage in western areas of Christchurch that had no liquefaction. Therefore, we conclude that direct burial 66 kV cables (XLPE-type and oil-filled pipe-type) are essentially seismic-robust, where installed in soils not prone to liquefaction (or other PGDs like landslide or surface faulting).

(2) At and near the damaged cable locations, we observed permanent PGDs on the order of 1 cm (common). These small PGDs were manifested by small differential settlements, and also cracks crossing the street transverse to the cable alignments. But, when the damaged

cables were dug up, the damaged condition of the cables did not match the PGDs at the ground surface.

(3) In every case, the dug-up cables showed evidence of the following: First, the cables were stretched in tension, resulting in yielding of the cable and lengthening of the cable. The stretch of the cables were relatively modest (under 5 cm). Second, the thermal concrete surrounding the cables were cracked, transverse to the cables. Third, the cables underwent high curvatures and bending, on the order to 2 to 4 cm in the vertical direction, with resulting bend radius well under 1 meter. With the tight bend radius, the insulation layers (XLPE cable) were squashed, and the pipe (oil-filled cable) was damaged losing its pressure boundary.

(4) In the February 2011 earthquake, Transpower's high voltage system tripped off line within seconds, and therefore the 66 kV cables become de-energized. Once Transpower inspected and re-energized its high voltage system, Orion was able to energize the 66 kV lines; this typically occurred a few hours after the earthquake. It was only when Orion attempted to energize the 66 kV lines that the lines faulted. The dug-up cables showed evidence of complete insulation failure. With the high cable curvatures, the insulation was damaged. Once the insulation is damaged, cable failures can occur within seconds to minutes to days or even months. In the case of the six damaged 66 kV cables in downtown Christchurch, the failures occurred essentially immediately upon attempted restoration of full power. Elsewhere in the Orion system, the rate of cable failures (11kV) was two to four times higher than normal, extending for months after the February 2011 earthquake, suggesting that many operable 11 kV cables (post-earthquake) had sustained insulation damage, taking some time to lead to ultimate failure.

Based on the observed physical condition of the cables, and the observed PGDs at the ground level, we posit the failure process occurred from multiple steps. The following describes the expected failure mechanisms. First, the non-reinforced thermal concrete is cracked from ground strains caused by either strong ground shaking, or PGDs induced by liquefaction. Until the thermal concrete cracks, it is impossible for the cables to undergo the observed deformations. Second, and consistent with the PGD environment, it is apparent that the non-liquefied soil cap (within-which are the power cables) begins to "float" (some people say "slosh") sideways. As the soil cap "floats" sideways, the crack in the thermal concrete opens up, and the cables stretch in tension, to the point that the cables yield. The inside core of the cables, being usually copper or aluminum can readily accommodate modest yielding in tension, although the outer layers (insulation, pressure retaining boundary, etc.) may not. Third, the soil caps continue to "float", and ultimately floats sideways back to more-or-less its original position. As the soil cap returns to its original position, the now-stretched cable cannot recover its original form and length because of the surrounding thermal concrete environment. As a result, the cables go into reverse-curvature, leading to observed high cable curvatures.

In addition to faults in buried cables, service to the eastern suburbs of Christchurch was affected by liquefaction severely damaging the substations in the area, such as Pages substation (Fig. 16) and Brighton substation. In Brighton intense liquefaction led to loss of bearing capacity, which, in turn, resulted in several feet of settlement and tilting of the transformer building (Fig. 17 (a)). In this site the tilting of the foundation was so severe that the substation experienced complete functional failure. Service in this area was restored by the aforementioned overhead line that was installed running from Bromley substation. In Brighton, this line was terminated in a new circuit breaker and transformer, shown in Fig. 17 (b) that stepped down the voltage from 66 kV to 11 kV. Since the earthquake a new substation combining the functions of Pages and Brighton substations was built nearby in soils with reduced severe liquefaction risk. When this substation is complete, the sites of the Pages and Brighton substations will be abandoned.

Three other substations were damaged south and south east of Christchurch. One of those that had been seismically reinforced and shown in Fig. 18 was damaged by a falling rock. Service in the area of this substation was restored by bypassing this substation. Another of the upgraded URM substations that failed was the St. Andrews Hill substation. This is the only one of 268 upgraded URM substations that failed during this earthquake from inertial overload due to PGA values that likely exceed well over 0.5g. Eventually, this substation was demolished and was replaced by a slab mounted transformer shown in Fig. 19. Despite this single upgraded URM substation failure, it can be considered that the reinforcement program was highly successful. Examples of undamaged reinforced URM substations are shown in Fig. 20. At least one other of these reinforced URM substations (Fig. 21) experienced considerable settlement due to soil liquefaction but it remained operational.

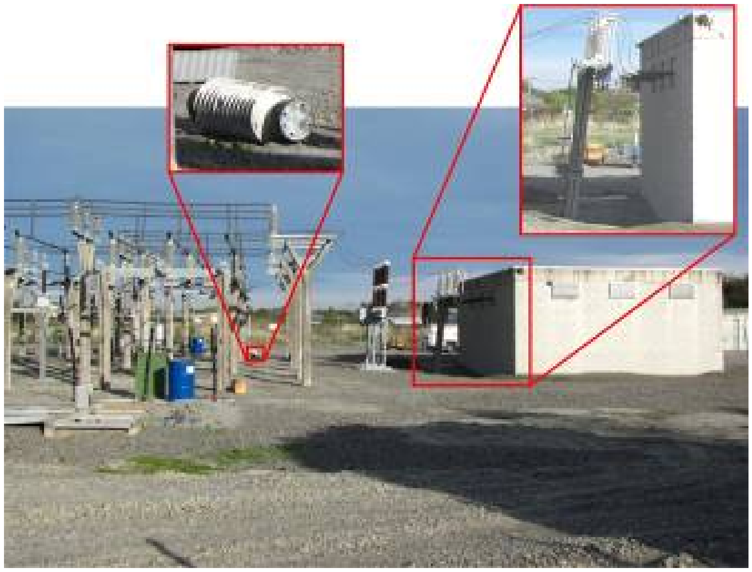

Figure 16. Damage from soil liquefaction at Pages substation. The details show a damaged bushing (left) and tilted supporting structure at the conductors entrance to the transformer building (right) which had experienced a small settlement.

Figure 17. Brighton substation. a) Left: Significant settlement and sinking of transformer buildings. b) Right: Circuit breaker and transformer at the end of the temporary line shown in Fig. 10.

Figure 18. Damaged substation building by rock fall in Sumner. a) Left: Exterior. b) Right: Interior.

Figure 19. Slab mounted transformer installed on the slab where St. Andrews URM substation building used to stand before it was damaged by the February 22, 2011 earthquake.

Figure 20. Two examples of seismically reinforced URM substations good performance. Notice the damage in the home next to the substation shown in the photo on the left.

Orion encountered additional difficulties in the central business district (CBD). In addition to work involved disconnection of several buildings requested by Civil Defense or other reasons, Orion experienced damage in its CBD administrative and operations buildings. Orion's Main building was extensively damaged and the adjacent office building in the CBD (Fig. 22) had moderate damage. These problems were addressed by relocating Orion's operation to a backup control centre and by establishing portable accommodation on site within the CBD Red Zone.

Although damage to Orion's underground infrastructure was significant, damage to overhead lines was minor with 80 poles that tilted but none of them toppled or broke. Since Mainpower's grid had little damage during this event, Mainpower resources were used to assist Orion restoration work primarily in the eastern suburbs of Christchurch.

Figure 21. Settlement due to liquefaction at a seismically upgraded URM substation.

Figure 22. Orion's office building next to Orion's main building. Operations in these buildings needed to be relocated.

With respect to Orion's pre-earthquake preparedness and post-earthquake restoration efforts, the following is highlighted.

(1) Beginning in the mid-1990s, following a lifeline review, Orion undertook to seismically strengthen all of its URM distribution substation buildings. Some 260 such buildings had been strengthened prior to the 2010-2011 earthquake sequence. This cost about $6 million to accomplish. This mitigation effort was very fortunate, as with only 1 exception, all the strengthened URM buildings (only exposed to ground shaking) performed well, likely saving $30 to $50 million in post-earthquake repair costs, and hugely increased power outages and impacts to the community. Orion recognized that liquefaction issues were likely an issue, and decided, in the mid-1990s, to try to mitigate this by improving its network by installing more parallel cables, thus trying to accommodate cable failures by using parallel cables. However, it would be fair to say that the mid-1990 lifeline study did not factor the occurrence of local earthquakes that would produce ground motions in excess PGA > 0.5g being common, nor the weakness of direct-burial cables in liquefaction zones.

(2) In the September 2010 event, Orion had $4 million in repair costs. In the February 2011 event, Orion had $40 million in repair costs (short term repairs), and an estimated $70

million in intermediate term costs to install new cables; customer power outages were about 640,000,000 customer minutes (1 customer = 1 billing account). In the June 2011 event, Orion had $4 million in repair costs.

(3) In the long term, it is apparent that Orion (and other power utilities) needs to re-assess the seismic weaknesses of buried power cables, especially those using direct burial installation methods. As of mid-2013, there are no international standards for the design of buried power cables in liquefaction zones, although there are now some efforts by leading power companies to investigate. The long term approach to deal with this kind of hazard could include the following. First, use overhead transmission and distribution lines through zones prone to liquefaction (or landslide / surface faulting). While overhead installations are about 80 to 90% less costly than underground cables, they can be prone to high wind / ice failures, and many communities are adverse to the unsightly overhead cables. Second, it is now readily apparent that an industry guideline on the seismic design of buried power cables, and perhaps after some years of experience, an industry standard, could be very useful. Such a guideline should cover evaluation of existing cables, and also design of new cables. Simple requirements to seismically-retrofit existing cables are possibly not likely to be cost effective (perhaps costing 50% to 100% of a new cable cost), but adding in seismic design features for new cables is likely to involve only marginal (perhaps 10%) extra cost. As cables age, they become less reliable, and ultimately need to be replaced; at that time, suitable seismic-design features should be factored into the design. Adding network redundancy, especially as part of the build-out of a network to support increased loads, is a very promising strategy.

POWER INFRASTRUCTURE PERFORMANCE DURING THE JUNE 13, 2011 EARTHQUAKE

Transpower and Mainpower had no noticeable issues with this earthquake. Orion had some power outages mostly in the New Brighton and Mount Pleasant areas but these outages were cleared within 24 to 48 hours after the earthquake. In general damage was much lighter than in the February 2011 earthquake. During this event no damage was observed in the 66 kV cables. Still, the transformer on the Brighton substation for the temporary line to Bromley settled about 5 cm, but did not cause the line to trip offline.

CONCLUSIONS

Although peak ground acceleration recordings during the main events of the 2010 and 2011 sequence of earthquakes provide evidence of the strong shaking that affected Christchurch, power infrastructure performance showed relatively satisfactory performance. In all the three main events, power transmission grids presented considerable resiliency with service being restored within a day of the events thanks to a relatively little to moderate damage. TCLEE damage assessment teams were able to observe that most of Transpower's equipment for 220 kV and higher were well installed, substantively meeting the intent of IEEE 693 (high zone), including substantial anchors. In the three substantial earthquakes, damage to high voltage (220 kV) equipment was relatively minor—in particular one broken CVT, one broken surge arrestor, several out-of-alignment disconnect switches, plus possibly some additional failures in the weeks following the main shocks. One of the reasons that explains this performance characterization is found through TCLEE damage assessment teams, which were able to observe that most of Transpower's equipment for 220 kV and higher were well installed, substantively meeting the intent of IEEE 693 (high zone), including substantial anchors. Another reason for the documented high-voltage system performance is that only one 220 kV substation (Bromley) was exposed to PGA much over 0.5g. Still, the sporadic damage observed to some 220 kV equipment, seems to indicate the difficulty of seismically qualify all of 220 kV equipment. Nevertheless, the performance of substation equipment was relatively satisfactory and accepted standards, such as IEEE 693 seem to have been followed well. At the lower voltages, the TCLEE damage assessment teams observed failure of 4 substation buildings: one due to extremely strong shaking (likely PGA > 0.9g), one due to rock avalanche and two due to liquefaction, resulting in nearly total damage to all equipment. Yet, these 4 failed facilities were a small fraction of the total inventory (more than 250), because of Orion's prior seismic mitigation efforts. Significant load drop during both the September 4, 2010 and February 22, 2011 events caused a temporary increase of the South Island’s power grid frequency. The HVDC transferred additional power to the North Island as designed, ameliorating the frequency deviation of the South while increasing the North Island frequency by an acceptable amount. The power flow control advantages provided by HVDC lines over conventional alternate current high-voltage transmission lines allowed this power sharing to occur with minimal system instability. Longer outages were also avoided during the September, 4, 2010, when two important 220 kV transmission lines powering Islington substation from the south west remain functional even though surface fault offsets occurred between a few towers.

Damage to power distribution networks was also relatively minor except in the February 22, 2011 earthquake. As it was commented, damage to almost all unreinforced masonry substation buildings was prevented thanks to a seismic upgrade program that was implemented in the years before the earthquake. Yet, considerable damage was observed in underground cables in areas with intense liquefaction. Hence, it is suggested here that in high liquefaction potential areas cable engineered solutions be found or planners should avoid the use of underground cables as much as possible. Although some poles also suffered liquefaction and lateral spread effects by tilting, no pole was reported to have toppled and even when poles could have failed, overhead lines tend to be not only less vulnerable to ground failures, but when damaged they can be repaired much faster than underground cables. If underground cables still need to be installed, a reinforced concrete thermal backfill could be used to limit damage in future earthquakes. The approach that have been followed by both Orion and Mainpower to address damage in underground cables has been to replace affected sections in the cables damaged during the earthquakes, and to have their maintenance and material logistical plans prepared to manage the expected future higher failure rate in underground cables caused by earthquake-induced stresses. In addition, Orion has been installing a 66 kV ring around Christchurch to enable power re-routing capabilities in case one path fails (Orion, October 2012). In some areas these cables have been laid on a reinforced concrete bed to improve their resistance to earthquake-induced damaging actions. However, the potential for earthquake-caused future faults in lower voltage portions of the grid remains as, to the best of the author's knowledge, no other programs to reduce failure of underground cables in future earthquakes have been implemented. One alternative to address such potential faults implemented by Orion have been to install back up diesel generators on the Queen Elizabeth II Park (Orion, March 2012). This approach suggests the potential for broader application of permanent distributed generation (e.g. photovoltaic panels) in microgrids to help mitigate the effect of earthquake damage, as previously indicated in (Kwasinski, 2010) and (Kwasinski, 2012). Careful planning and periodic evaluations of soil conditions should be carried out in substations located in highly liquefiable soils in order to prevent settlement and sinking like in Brighton substation. In case no other location is possible or the substation cannot be relocated, liquefaction mitigation measures need to be carried out. Due to access limitations in Christchurch central business district, Orion's control center needed to be relocated. Disaster planning for electric utilities needs to include contingency plans to relocate control centers or establish redundant control center in another location with automatic control transfer in case of an emergency.

It is expected that the observations made in this paper will serve to motivate further analysis on various research topics covered as part of the description of power grid performance during this sequence of events. In particular, further research needs include detailed study of buried cable failures and performance of substation equipment with respect to IEEE 693-class equipment. Based on Orion's decision of a diesel generator-based local back-up plant, future research could also explore unconventional electric power generation and distribution approaches including, but not limited to, microgrids, backup local generation plants and distributed energy storage.

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