Performance of Buried High Voltage Power Cables due to Earthquake Loads

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SUMMARY

Buried high voltage power cables failed in many locations in the February 22, 2011 M 6.3 Christchurch earthquake, due to liquefaction. The empirical evidence of these failures is presented. The original design of the cables is considered, and what made the cables so vulnerable. The failure mechanism is described. Recommendations are made for the design of new buried cables in liquefaction zones.

INTRODUCTION

The recent sequence of earthquakes in Christchurch New Zealand resulted in functional damage to more than 400 buried high voltage power cables due to liquefaction. In this paper, we examine the reasons for these failures.

The February 22, 2011 M 6.3 earthquake was the second of four large earthquakes to impact the City of Christchurch, New Zealand, the others being September 2010 (30 buried cable failures), June 2011 (120 buried cable failures) and December 2011. The February 2011 event had the worst impacts to the power grid, resulting in 250 buried power cable failures due to widespread liquefaction. A detailed review of the overall impacts of this earthquake sequence on lifelines is provided in (Eidinger, 2012).

Three power companies serve the greater Christchurch community. Transpower provides regional power transmission, with voltages up to 220 kV. Orion and Mainpower are the two distribution systems for the area, taking power from Transpower's 220 kV grid, and delivering it to the retail customer. All three power companies sustained damage, including damage to office buildings (ground shaking and liquefaction); substation buildings (ground shaking, liquefaction and rock fall); substation yard equipment (ground shaking). The worst overall damage, causing lengthy power outages and costly repairs, was due to failure of buried power cables in the Orion and Mainpower distribution systems, due to liquefaction.

This paper examines just one aspect of the overall power system damage, namely the failure of buried 66 kV power cables in the Orion system. Figure 1 shows a map of the Orion power system, highlighting the liquefaction zones in red (major liquefaction, settlements often 5 to 10 cm, with lateral spreads local up to 1 meter) and yellow (moderate liquefaction, with settlements commonly 2 to 5 cm).

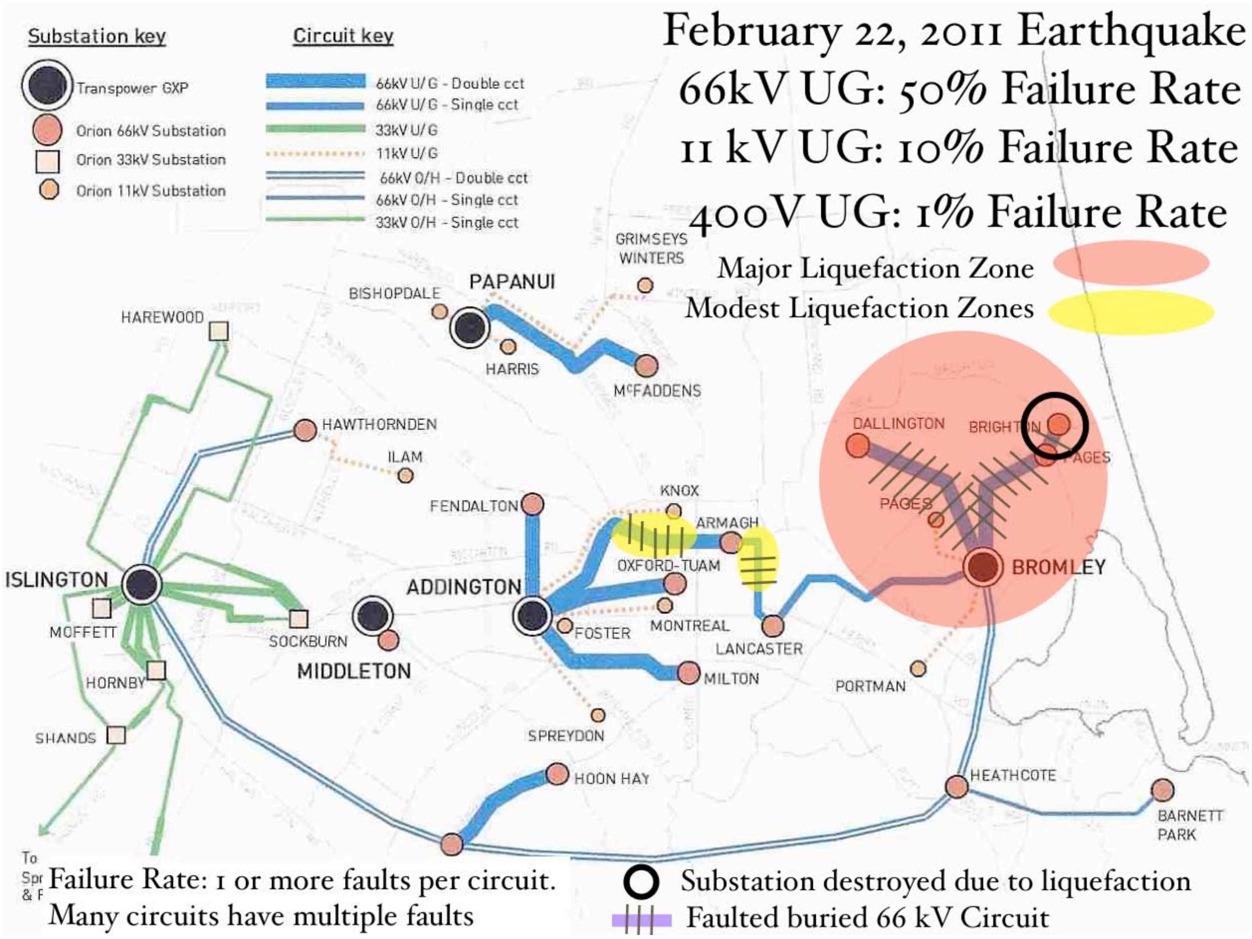

Figure 1. Location of Orion 33 kV to 66 kV Distribution System and Liquefaction Zones

In Figure 1, the red zone in the eastern part of the city suffered the most widespread concentration of liquefaction, and the worst impact to buried power cables. The eastern part of the city is primarily residential. From the Bromley 220 kV – 66 kV substation, there are 5 underground (UG) 66 kV circuits that branch out to 66 kV substations: all these circuits had more than 1 fault; short term emergency repair was to deploy emergency generators at low voltage substations; moderate term repair was to re-energize substations with temporary above-ground cables; the long term permanent strategy (2013 and beyond) is to install new end-to-end 66 kV buried cables. The two yellow zones are drawn over the single Lancaster-to-Armagh 66 kV XLPE-type circuit and the double Addington-to-Armagh 66 kV pipe-type (oil-filled) circuits. These failed and were repaired with new splices at those six locations, and put back into service.

The statistics for the February 22, 2011 earthquake are presented. If one counts by circuit, including all of Orion's system, then 50% of 66 kV underground cables had one-or-more faults; 5.5% of 11 kV (closer to 10% in urbanized Christchurch) and 0.6% of 400 Volt. If one counts

only those circuits located within liquefaction zones, essentially all the 66 kV buried cables failed.
Figure 2 shows the area with power outages, about one day after the earthquake (red lines = no power, blue lines: with power). Almost all of the power outages were due to buried cable failures.

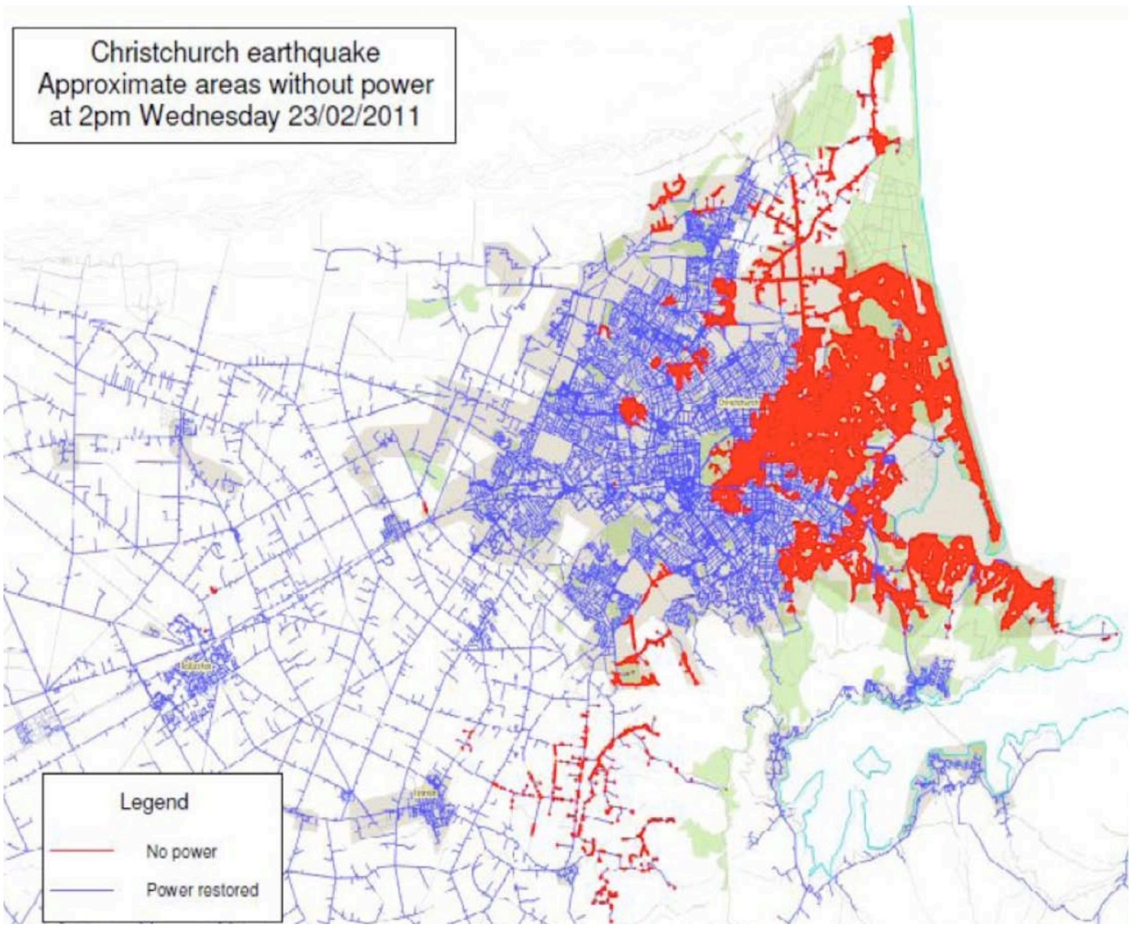

Figure 2. Location of Power Outages, 24 hours Post-Earthquake

The power outages to Orion's 198,000 customers (1 customer – 1 billing account) amounted to about 630,000,000 customer-minutes, due to the February 2011 earthquake.

LOCATION OF CIRCUIT FAILURES

Figure 3 shows the alignment of 66 kV buried circuits in and around the central business district (CBD) of Christchurch, New Zealand. The red stars show the locations where the circuits failed. The blue lines show the circuit alignments. Green areas are parks. The meandering Avon River is highlighted by green parks along either bank. The six circuit failure locations are noted "1, 2, 3, 4, 5, 6". The type of cable at each faulted location is listed as either Oil, or XLPE. Each blue line represents a three-phase circuit. Oil-type cables have all three phases within pipe. XLPE-type cables have three separate cables.

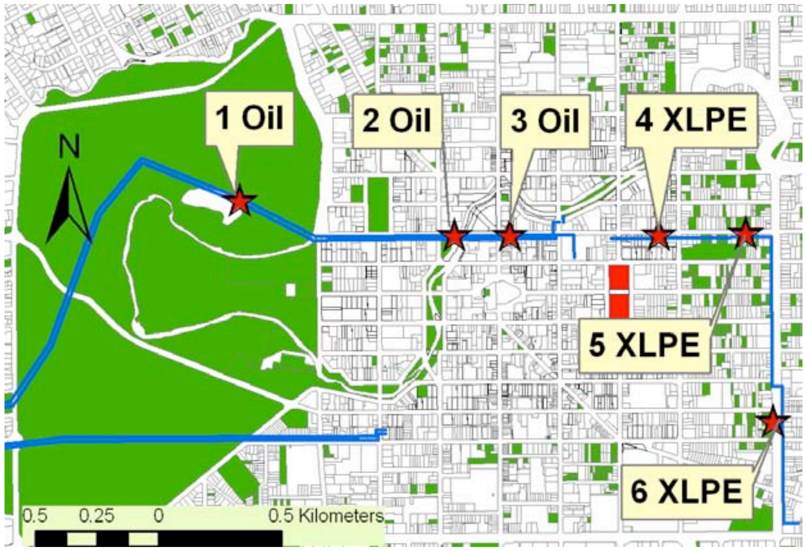

Figure 3. Location of 66 kV Buried Circuit Faults, Central Business District

LOCATIONS 1, 2, 3 – OIL-TYPE CABLES

Figure 4 shows failure Location 1. Figure 5 shows the cross section of the trench design used at Location 1, same as used at Locations 2 and 3. In the field, we observed the actual "230 mm cement-bound sand" and "80 mm red concrete cap" to have the consistency of a moderate strength concrete. Native soil in the top 3 meters, surrounding the cables, are typically moderate strength clays / silts, able to withstand a vertical-cut trench wall. Figure 6 shows the buckled cables, as crews dig them up after the earthquake. Figure 7 shows the cable cross section, comprised of three aluminum conductors (300 mm^2), paper wrapped, with three oil-ducts; all housed within a corrugated aluminum pipe and then with protective plastic outer sheath.

Figure 4. Location 1 – 66 kV Oil-filled Cable

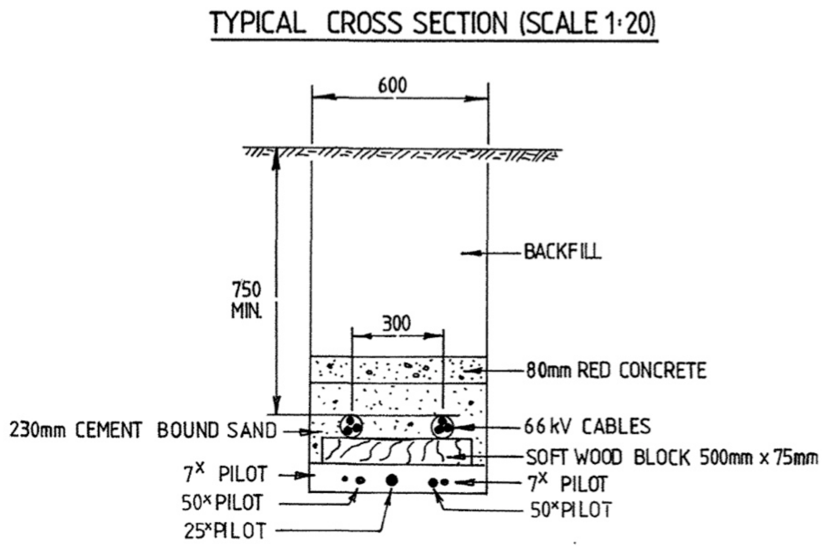

Figure 5. Trench Design 66 kV Oil-type Cable

Figure 6. Exposing the Damaged Oil-Type Cables, Location 1

Figure 7. Oil-Type Cable Cross Section

Figure 8 shows the cut-out section of the oil-type cable, from Location 3. The final deformed shape shows that the cable tried to deform in sharp double curvature. The high curvature led to high strain in the aluminum pipe, tearing it.

Figure 8. Oil-Type Cable (Location 3)

Post-earthquake inspection at Location 1 revealed that the cable alignment was parallel and about 6 meters from the edge of Lake Victoria. Liquefaction occurred under the lake, inducing some settlements, and possibly a very slight lateral spread, as indicated by damage to the retaining wall at the edge of the lake[1]. One buried storm culverts goes under power cable, another over the power cable. Permanent surface level ground deformations in the zone where the cable failed show sudden "knife edge" settlements on the order of 2 cm, gradual lateral soil movements of perhaps 3 cm.

The actual damage to the cable occurred due to high curvature on the exterior aluminum pipe, leading to local wrinkling of the corrugations, pushing inward on the oil tubes / paper wrap. The aluminum pipe tore, releasing the oil and allowing air into the cable. The actual aluminum cores did not appear worse-for-wear.

LOCATIONS 4, 5, 6 – XLPE-TYPE CABLES

The cables used at Locations 4, 5 and 6 are XLPE-type. Cores are 1600 mm^2 copper. Figures 9 and 10 show the typical trench installation and cross section of the cable. Figure 11 shows work crews exposing the fault cable at Location 6.

Figure 12 shows the tell-tale reverse-curvature bend in the XLPE cable from Location 4, with a blow-out hole caused when the cable faulted. Each of the three cables had similar reverse curvature at this location. The high reverse curvature has caused the XLPE insulation around the copper core the wrinkle outwards, tearing the outer copper sheath.

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[1] Post-earthquake, the lake was drained to make repairs / install a water-tight liner system. Once drained, cracks at the bottom of the lake could be observed.

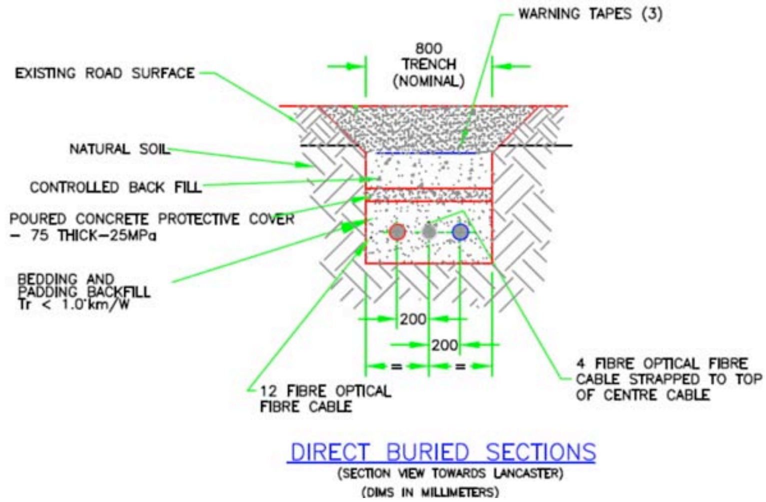

Figure 9. Trench Design 66 kV XLPE-type Cable

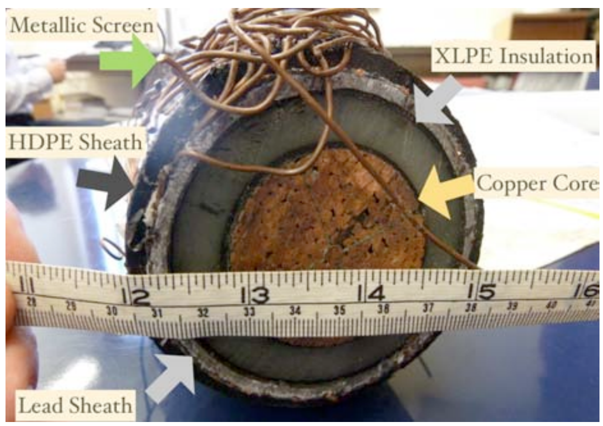

Figure 10. Cross Section, XLPE-type Cable (Top scale in inches, bottom in cm)

Figure 11. Exposing the Damaged XLPE-Type Cables, Location 6

At none of the six locations was the ground deformation "huge", and there were no major ground cracks.

Figure 12. Failed XLPE-Type Cable, Location 4

ESTIMATED PERMANENT GROUND DEFORMATIONS

We field surveyed each of the 6 locations. With the exception of Location 1 we observed no permanent lateral spreads in excess of 1 cm, but there was clear evidence of "transient lateral spreads". At 4 of the 6 locations, we observed up to 2 cm of "knife edge" settlements nearby, as expressed by cracked sidewalk curbs or other cultural features. Nearby single family residential structures showed slight to moderate damage (most were "green tagged".) One older unreinforced masonry structure had partial collapse near Location 2, but that is not surprising given the high levels of shaking (PGA about 0.5g).

At all 6 locations, there is clear evidence, within 50 m of the damaged cables, of liquefaction, as expressed by sand boils.

FAILURE MECHANISM

It appears that the damage to the cables at these 6 locations was due to the effects of liquefaction. Why do we say this?

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, over 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 in Figure 11, with closeout and "blow-out" in Figure 12). After the earthquake, we 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 following were the likely conditions that led to the observed cable damage:

- The cable failures were not due to high levels of ground shaking alone. Nearly 100% of cable failures occurred in areas of Christchurch (and nearby Kaipoi) in locations with readily observed liquefaction. Therefore, the failure phenomena is not directly caused by high levels of ground shaking (travelling waves).
- The field inspections along the 66 kV cable failures in and near downtown Christchurch (6 total failure locations) showed very modest permanent ground deformations (permanent ground deformations, PGDs, between 1 to 5 cm) at or near the actual cable failure locations. Over 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.
- 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 highest potential for large PGDs in future earthquakes.

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. We posit that the failure process was in two steps:

- 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).

- 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.
- 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.
- Based on the observed physical condition of the cables, and the observed PGDs at the ground level, we posit the following failure mechanism. First, strong ground shaking leads to high enough strains in the non-reinforced thermal concrete to crack the concrete (thesis 1); or PGDs induced by liquefaction cracks the concrete (thesis 2). 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 continues 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 must shorten back into its original position, clearly impossible within the thermal concrete environment. Therefore, the cables go into reverse-curvature, leading to high cable curvatures and spalling of the thermal concrete (as observed).
- In the actual February 2011 earthquake, Transpower's high voltage system tripped off line within seconds, and therefore the 66 kV cables became de-energized. Once Transpower inspected and re-energized its high voltage system, Orion was able to energize its 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: Orion notices a sudden drop in oil pressure for the oil-filled cables 2 to 3 hours after the earthquake. The dug-up cables showed evidence of complete insulation failure. With the high cable curvatures, the insulation was damaged. Once the insulation is damaged, XLPE-type 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.

CONCLUSIONS

Based on the empirical evidence the following preliminary design recommendations are made for 66 kV (or higher) buried cables in liquefaction zones:

- If at all possible, avoid the liquefaction zone; or use overhead circuits in liquefaction zones.
- Direct burial in moderately-strong thermal backfill concrete can result in cable failures. Failure rates observed are about 2 faults per cable per km, given transient lateral spreads and permanent settlements on the order of 2 to 5 cm. Buried cables in zones that had higher settlements (5 to 10 cm+ with some permanent lateral spreads), had a higher rate of failures as to warrant outright replacement rather than repair.

- Where buried cables are required in liquefaction zones, a reinforced concrete thermal backfill can control curvatures and prevent sharp knife-edge offsets, and a PVC (or HDPE) conduit with inside diameter 1 to 2 cm larger than the cable and inside of the conduit can materially improved cable performance. Reinforcement (either steel, or possibly with fiber reinforcement, designed to resist shear failure and provide crack control) should be used for such direct burial situations, especially if there is no PVC conduit. Where PVC conduits are placed within the thermal concrete, the cemented PVC joints can be expected to crack under high bending action, which will make it difficult to pull through replacement cables that are sensitive to external abrasion.

REFERENCES

[1] Eidinger, J., editor, "Christchurch earthquake sequence of 2010-2011." *Technical Council on Lifeline Earthquake Engineering*: URL http://www.geEngineeringSystems.com, 2012.

[2] ALA, Seismic Guidelines for Water Pipelines, American Lifelines Alliance, http://www.americanlifelinesalliance.com, March 2005.