# PERFORMANCE OF BURIED HIGH VOLTAGE POWER CABLES DUE TO LIQUEFACTION

John M. EIDINGER[1]

[1] President, G&E Engineering Systems Inc., Olympic Valley, California
eidinger@geEngineeringSystems.com

**ABSTRACT**: 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. Nonlinear analyses of buried cables are presented to see how they "theoretically" should perform due to liquefaction. Full scale tests are conducted for unreinforced and reinforced buried cable duct banks to examine their relative capability to absorb the effects of liquefaction. Recommendations are made for the design of new buried cables in liquefaction zones.

**Key Words**: Christchurch earthquake, high voltage buried power cables, XLPE cables, Oil-filled cables, liquefaction

## INTRODUCTION

The recent sequence of earthquakes in Christchurch New Zealand resulted in functional damage to more than 200 buried high voltage power cables due to liquefaction. A similar phenomena occurs to fiber optic and copper communication cables. In this paper, we examine the reasons for these failures, as well as recent full-scale tests of buried power cable duct banks to try to determine cost effective ways to seismically design buried cables through liquefaction zones.

## OVERVIEW OF THE EARTHQUAKE IMPACT ON THE POWER SYSTEM

The February 22, 2011 M 6.3 earthquake was the second of four large earthquakes to impact the city of Christchurch, New Zealand between September 2010 and December 2011. The February 2011 event had the worst impacts, resulting in 182 fatalities, many building failures, and widespread liquefaction. A detailed review of the overall impacts of this earthquake sequence on lifelines is provided in (Eidinger, 2011).

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 locally up to 1 meter) and yellow (moderate liquefaction, with settlements commonly 2 to 5 cm).

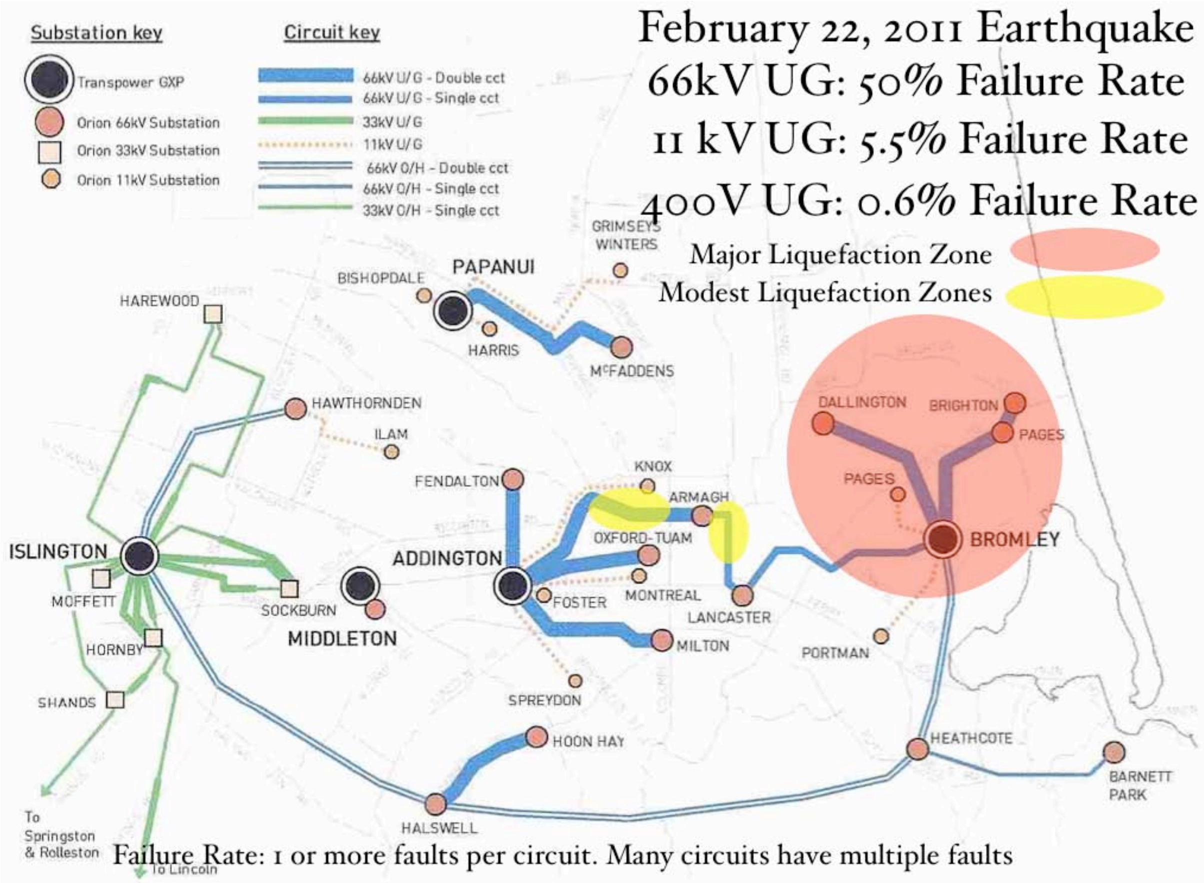


Figure 1. Location of Orion 33 kV to 66 kV Distribution System and Liquefaction Zones (Feb 22 2011)

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 faults; 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 (2012 and beyond) is to install new end-to-end 66 kV buried cables, with some seismic design provision. Exactly what will constitute the seismic design for the new buried cables remains to be determined.

In Figure 1, 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 oil-type circuits. These failed at six locations, were repaired with new splices at those six locations, and put back into service.

In Figure 1, 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 and 0.6% of 400 Volt. If one counts only those circuits located within liquefaction zones, essentially all the 66 kV buried cables failed.

## LOCATION OF CIRCUIT FAILURES

Figure 2 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.

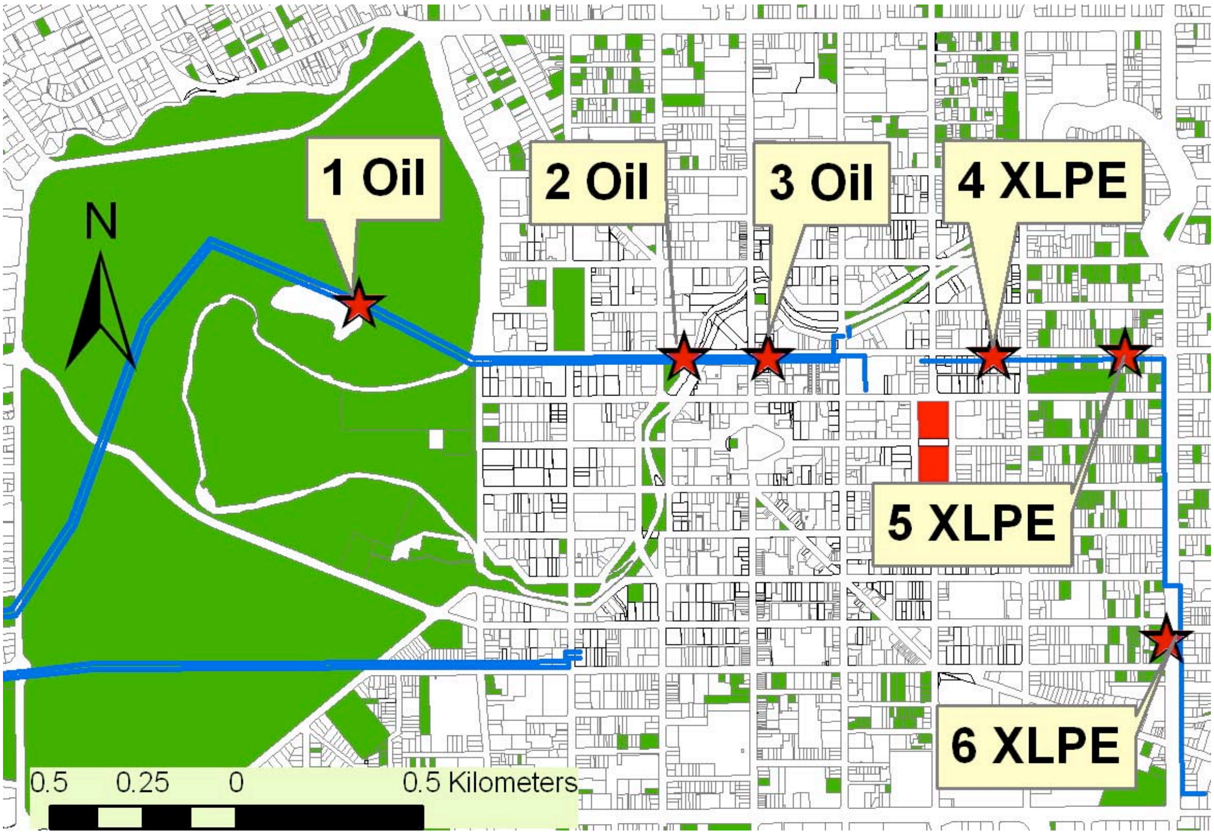


Figure 2. Location of 66 kV Buried Circuit Faults, Central Business District, Christchurch (Feb 22 2011)

## LOCATIONS 1, 2, 3 – OIL-TYPE CABLES

Figure 3 shows failure Location 1. Figure 4 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 5 Shows the buckled cables, as crews dig them up after the earthquake. Figure 6 shows the cable cross section, comprised of three aluminum phases (300 mm^2), paper wrapped, with three oil-ducts; all housed within a corrugated aluminum pipe and then with protective plastic outer sheath.

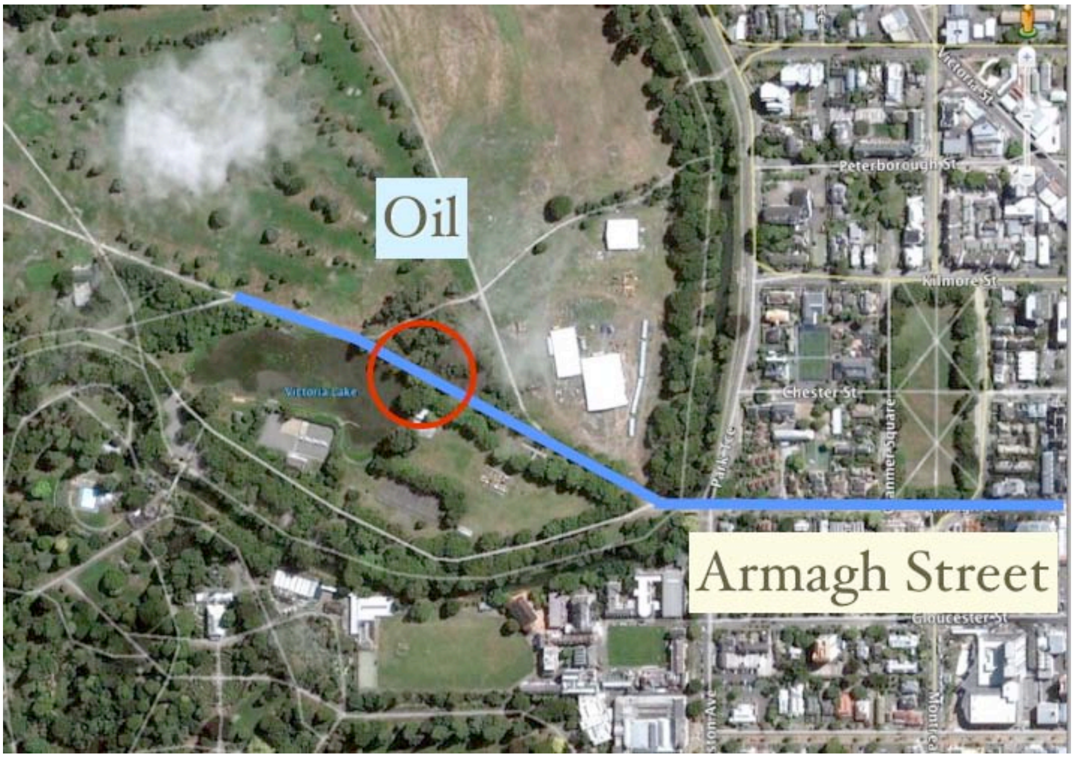


Figure 3. Location 1 – 66 kV Oil-filled Cable

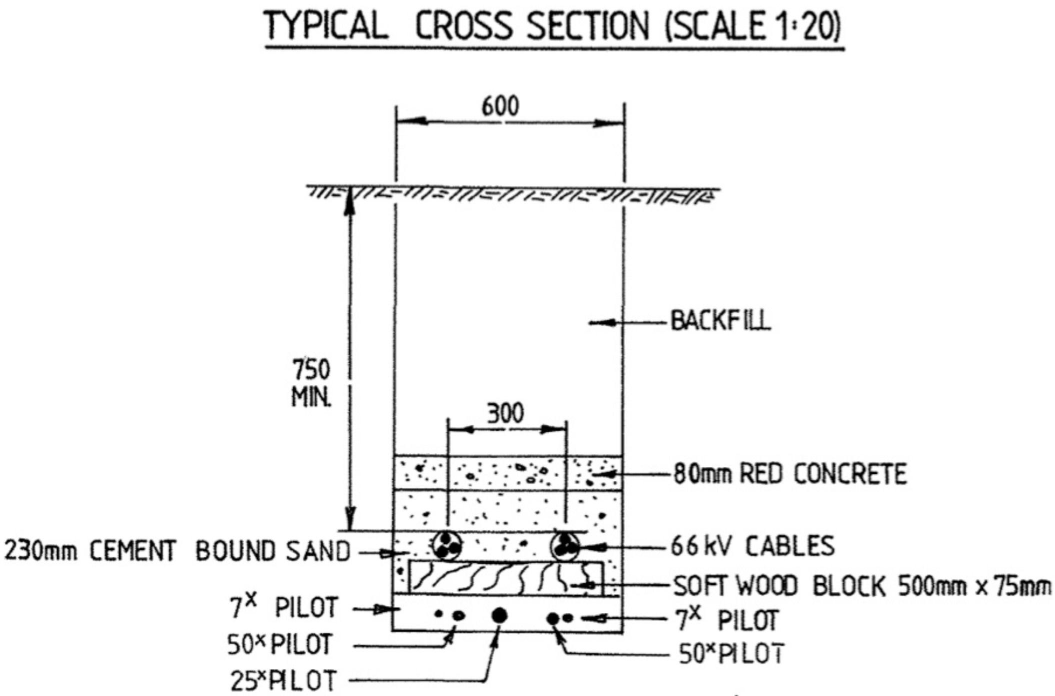


Figure 4. Trench Design 66 kV Oil-type Cable

Figure 5. Exposing the Damaged Oil-Type Cables, Location 1

Figure 6. Oil-Type Cable Cross Section

Figure 7 shows the cut-out section of a oil-type cable, from Location 3. The final deformed shape shows that the cable tried to deform in sharp double curvature, to accommodate a shear across the cracked thermal concrete cross section. The high curvature lead to high strain in the aluminum pipe, tearing it. Post-earthquake inspection of the roadway surface at Location 3 showed street-level knife-edge type vertical settlements on the order of 2 cm; no lateral spreads.

Figure 7. 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. One buried storm culverts goes under power cable, another over the power cable one installed likely before, and one after, the cable installation. 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 damage pattern of the cable shows a classic "nonlinear beam on nonlinear soil" pattern, expressed mostly of vertical settlement. 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 8 and 9 show the typical trench installation and cross section of the cable.

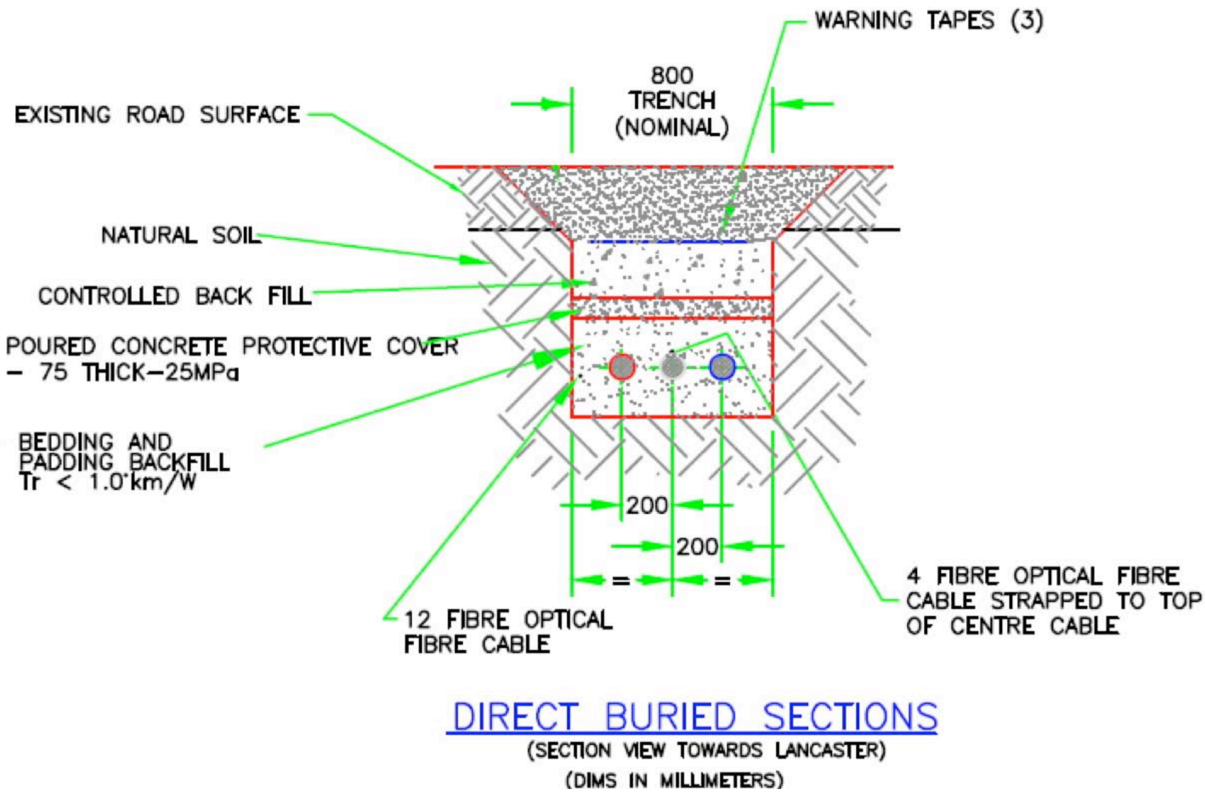


Figure 8. Trench Design 66 kV XLPE-type Cable

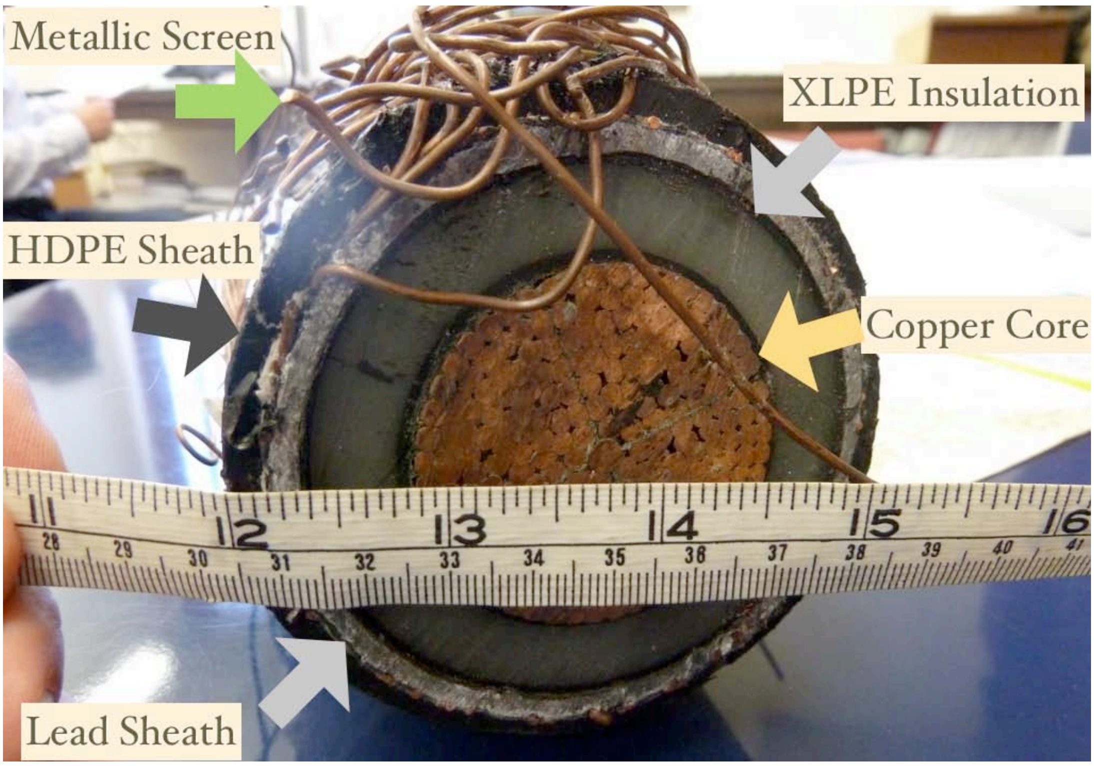


Figure 9. Cross Section, XLPE-type Cable (Top scale in inches, bottom in cm)

Figure 10 shows work crews exposing the fault cable at Location 6.

Figure 10. Exposing the Damaged XLPE-Type Cables, Location 6

Figure 11 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. Figure 12 shows this cable after the outer HDPE coating is removed. The high reverse curvature has caused the XLPE insulation around the copper core the wrinkle outwards, tearing the outer copper sheath.

It appears that the damage to the cables at these 6 locations was due to the effects of liquefaction. Why do we say this? The following observations are made:

Ground shaking. The level of ground shaking varied throughout Christchurch in this earthquake. In the areas with buried 66 kV cables, the motions were typically 40 to 70 cm / sec. Assuming a wave propagation speed of perhaps 3.5 km/sec, and the cable moves with the ground, we get a ground strain of 0.0002. This should produce a maximum stress in the aluminum (or copper) on the order of 10% of yield. While locally the ground velocities might have been twice as high owing to normal variations of motions over distance, it is not credible to posit that the motions would have been high enough to cause yielding in the metal.

At none of the six locations was the ground deformation "huge", and there were no major ground cracks. Figure 13 shows Location 5; the remaining locations are not all that much different with respect to damage to the streets / sidewalks.

Figure 11. Failed XLPE-Type Cable, Location 4

Figure 12. Failed XLPE-Type Cable, Location 4

Figure 13 shows the buckling of the XLPE-type cables at Location 5.

Figure 13. Failed XLPE-Type Cable, Location 5

## ESTIMATED PERMANENT GROUND DEFORMATIONS

We field surveyed each of the 6 locations. With the exception of Location 1 we observed no lateral spreads. At all 4 of the 6 locations, we can 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 are is clear evidence, within 50 m of the damaged cables, of liquefaction, as expressed by sand boils.

In discussions with Orion, it was observed that multiple people who looked at the damage locations could not discern any particular reason why the cables broke at those specific locations. Figure 14 shows the street in the vicinity of Location 5: no major ground deformations are observed.

Ongoing work to superimpose Lidar-based movements (differential between locations measured after the September 10 2010 event and the February 22 2011 event) remains to be done.

## FAILURE MECHANISM

A series of nonlinear structural analyses of buried cable were performed to try to duplicate the field observations in Christchurch. Based on these analyses, and in combination with the field observations, the causative movements / forces to cause the cable failures are thought to be as follows. A combination of traveling waves (peak velocities of perhaps 40 to 70 cm/sec) and local differential settlements (locally 2 to 5 cm) create high bending moment about the horizontal axis of the unreinforced cemented sand / concrete thermal backfill. Before the concrete cracks, the cables are fine.

Figure 14. Street at Location 5

With increasing bending moment, the induced tensile stress in the concrete finally finds a "weak spot" and the concrete cracks, with the depth of the crack about mid-way through the cross section. High compressive forces occur in the cables as the cable pipes try to behave "like reinforcing". These high compressive forces may cause spalling of the sides of the cemented-bound sand. Within a minute (or a few minutes) after the start of ground shaking, liquefaction-induced pore pressures begin to dissipate, and the ground settles into its final position. By that time, the earthquake bending-moment-caused crack in the thermal concrete then allows the differential settlement to accumulate along the crack, resulting in a shearing action of the now-divided two pieces of unreinforced concrete. The crack in the top "soil cap" allows for "sloshing" of the top ground layer, and when the two parts "come back together", high compressive forces occur in the thermal concrete, forcing the cables to buckle sideways (towards the Lake) and downwards / upwards. The corrugated cables, being anchored within the concrete either side of the crack, cannot slip; the XLPE cables might slip a bit into the concrete. The 2 cm to 5 cm of resulting "knife edge" shearing offset of the thermal concrete.

The net effect was that the shearing action across the cracked concrete was enough to locally crush the power cable, or to put the cable into reverse bending over a short enough crack-width zone so as to locally wrinkle a lead sheath within the cable; the buckled aluminum or lead sheath crushed the internal insulation around the copper / aluminum core, leading to a short (fault).

## TEST PROGRAM AND DESIGN IMPLICATIONS

A test program for full scale duct bank specimens is now being conducted at Berkeley, California, sponsored by Pacific Gas and Electric. The test specimens include four 150 mm diameter (6-inch) ducts (either PVC or HDPE) supported on spacer grids every 1.5 m (5 feet) within unreinforced (or reinforced) concrete, about 0.8 m x 1 m in cross section. As of writing this paper, complete results are not yet available, but initial tests on two specimens show the following.

Unreinforced duct: as soon as imposed bending moment on the concrete duct bank exceeds the tensile cracking strength, a large crack forms in the concrete. As the imposed displacement is increased to force increased curvature on the 150 mm ducts within (but preventing any shearing), the ducts maintain their circular cross section sufficiently so as to prevent crushing of the power cable within, even through rotations of 5 degrees.

Reinforced ducts. The internal reinforcement includes steel to resist bending and shear due to liquefaction; with extra shear reinforcement to assure that bending controls. Tests show the steel-reinforced duct bank easily absorbs the cracking via ductile performance of the reinforcing bars; there is no significant shear deformation on the internal ducts. Internal PVC ducts do crack at their joints; this damage would not likely damage an existing XLPE cable within, but might preclude pulling a new XLPE cable, until such time that the cracked PVC is identified and repaired.

Based on the empirical evidence, coupled with nonlinear analyses and tests, 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 settlements on the order of 2 to 5 cm. Buried cables in zones that had higher settlements (5 to 10 cm+ with some lateral spreads), had a high enough number 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. Reinforcement (either steel, or possibly with fiber reinforcement) should be used for such direct burial situations. Where ducts are placed within the thermal concrete, the cemented PVC joints can be expected to crack under high bending action.

## CONCLUSIONS

Unreinforced thermal concrete should not be used either for direct burial or duct-bank-type burial of 66 kV (or higher) cables in zones prone to liquefaction.

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