Tabled at Hearing 13/03/2013

TRANSPOWER

# 22 February 2011 Christchurch earthquake
# Key findings and lessons learned

**30 June 2011**

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# 1 Executive summary

A magnitude 6.3 earthquake struck the city of Christchurch at 12:51pm on Tuesday 22 February 2011. The *hypocentre*[1] was located at 10 km south-east of the the city's Central Business District (CBD) at a shallow depth of 5km. The earthquake caused a large number of fatalities and widespread damage with the collapse of many buildings in the CBD and significant disruption of lifelines. The Canterbury region was still recovering from damage caused by the 4 September 2010 earthquake when this second event struck.

The objective of this report is to identify the key lessons learned from this event, from a transmission network perspective, and provide recommendations.

The impact of the 22 February 2011 earthquake on the electrical stability and operation of both the National Grid and regional supply was minor. Power to the National Grid was unaffected, while power to the feeders into Christchurch City and regional substations was unavailable for a short period of time while safety checks were carried out. The supply to the grid exit points was restored at full capacity and n-1 *security*, except at Bromley substation where supply was restored with n *security* until some minor repairs were made. Refer to Section 4 for a detailed description of the impact of the earthquake on the transmission network.

Although Transpower was in a position to fully supply power within 5 hours from the event, restoration of power supply to households in Christchurch was constrained by the damage to the distribution network. In particular, Orion suffered extensive damage to its buried high voltage cables network due to *liquefaction* induced ground movement. Power was restored to about 50% of occupied households in the day of the event, 75% after 2 days and 98% after 2 weeks. Refer to Section 5 for a detailed description of the faults on Orion's high voltage burried cable network.

The lessons learned as well as the recommendations are detailed in Sections 6 and 7 respectively and of note are:

- The electricity transmission infrastructure performed generally well, meeting the current performance criteria for such type of rare event.
- This earthquake, as well as the 4 September 2010 Darfield earthquake, highlighted the reliance on existing aged infrastructure that have been designed and constructed prior to Transpower's current seismic policy and latest code requirements.
- The satisfactory performance of Transpower assets during this event does not provide certainty on how well our equipment, systems and buildings would perform in another event of a similar or greater magnitude.
- Buried cables are vulnerable to soil deformations and their failure significantly impedes prompt restoration of supply. Cable repair process usually requires skilled crews, special equipment and is significantly longer than overhead lines repair works. At present there is a lack of comprehensive design and installation practices in the industry to address this risk. Transpower should support and contribute to the development of such practices.

In conclusion, Transpower needs to continue managing seismic risk by removing or replacing existing buildings or items of plant not complying with our seismic policy and to support the improvement of seismic design and construction standards in the high voltage electrical industry.

[1] The terms in italic are explained in the Glossary in Appendix A .

# 2 Introduction

## 2.1 Background

A magnitude 6.3 earthquake struck the city of Christchurch at 12:51pm on Tuesday 22 February 2011. The *hypocentre* was located at 10 km south-east of the the city's Central Business District (CBD) at a shallow depth of 5km. The earthquake caused a large number of casualties and widespread damage with the collapse of many buildings in the CBD and significant disruption of lifelines. In total, 181 people were killed in this event, making the earthquake the second-deadliest New Zealand natural disaster after the 1931 Hawke's Bay earthquake.

This event came at a time when the Christchurch region was still recovering from the magnitude 7.1 earthquake which hit on 4 September 2010.

Following up on the recommendations of the previous earthquake investigation missions (Chile and Darfield earthquakes in 2010), Transpower decided to set up a team to investigate the impact of the earthquake on Transpower's system and identify the key findings and the lessons learned.

## 2.2 Scope

The scope of this report is to describe:

a) The impact on transmission network including:
   - Physical damage
   - System performance and operational response
   - Staff and contractors response.

b) The impact on distribution network, including physical damage, where lessons can be learned from a transmission assets perspective.

## 2.3 Mission team

The team comprised six members from the Wellington office and one external consultant as shown in Table 1 below. The team was assisted by colleagues from the Chrischurch office (Kim Glover and Malcolm Pettigrew) and staff from Transpower's maintenance contractors ABB and Transfield.

**Table 1 : Members of the team**

| Member | Transpower Group | Area of Expertise |
|---|---|---|
| Munyaradzi Chadliwa | Grid Performance<br>Asset Management Engineering / AC stations | Substation electrical operations; asset management engineering. |
| Sarah Dunckley | Grid Performance<br>Asset Management Engineering / Protection and Automation | Protection |
| Wendy Edwards | Corporate Services<br>Risk & Audit | Risk management; business continuity planning; internal audit; information management |
| Philip Hoby | Consultant | Civil; structural; substations; transmission lines |
| Richard Joyce | Grid Project<br>NI Grid Upgrade Cable Project Manager | HV Cables |
| Craig McGhie | Grid Development<br>Asset Development Engineering / Lines | Civil; structural; transmission lines |
| Christophe Tudo-Bornarel | Grid Development<br>Asset Development Engineering / Substation | Structural; substations |

# 3 Christchurch earthquake

## 3.1 Earthquake event

At 12:51 pm on Tuesday 22 February 2011 a 6.3 magnitude earthquake on the Richter scale occurred under the Port Hills near Christchurch. The *hypocentre* was 10km south-east from Christchurch CBD at a shallow depth of 5km. The *epicentre* was located near the Christchurch suburb of Heathcote Valley, see Figure 1 below.

The earthquake caused a large number of fatalities and widespread damage with the collapse of many buildings in the CBD and significant disruption of lifelines. A state of national emergency was declared on the following day.

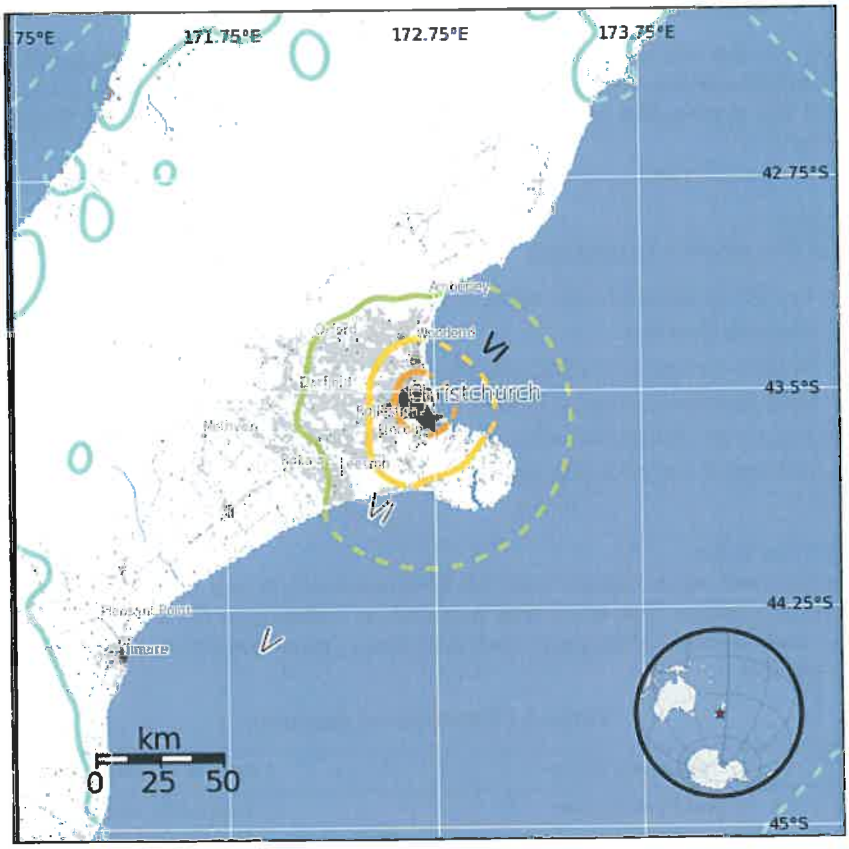



**Figure 1 : Perceived shaking intensities (*Modified Mercalli* scale) (courtesy of USGS)**

The 22 February 2011 earthquake followed nearly six months after the 7.1 magnitude earthquake that shook the Canterbury region on 4 September 2010 causing significant damage to the region but no fatalities.

There are a number of factors that explain why, although smaller in magnitude, the 22 February earthquake caused more damage and fatalities than the September event:

- The *epicentre* was much closer to Christchurch city (10km compared to 40km), and focal depth shallower (5km compared to 10km), therefore a more densely populated area was exposed to more severe shaking, as shown in the Table 2 below.
- The earthquake occurred during lunchtime on a weekday as opposed to the early hours of the morning in the weekend. Most of the working population were concentrated in commercial or office areas.

- The earthquake produced very severe ground motions for an earthquake of this magnitude.

**Table 2 : Estimated population exposed to earthquake shaking (courtesy of USGS)**

| Estimated *Modified Mercalli* Intensity | | VI | VII | VIII | IX | X+ |
|---|---|---|---|---|---|---|
| Perceived shaking | | Strong | Very Strong | Severe | Violent | Extreme |
| Potential damage | Resistant structures | Light | Moderate | Mod./heavy | Heavy | V. heavy |
| | Vulnerable structures | Moderate | Mod./heavy | Heavy | V. heavy | V. heavy |
| 4 September 2010 | | 139,000 | 298,000 | 20,000 | 2,000 | 0 |
| 22 February 2011 | | 50,000 | 63,000 | 228,000 | 92,000 | 0 |

The 22 February 2011 earthquake was felt strongly in the Canterbury region and as far away as Invercargill and Wellington.

## 3.2 Ground motion

The earthquake was characterised by a short duration (severe shaking only lasted 15s) and an unusually high *peak ground acceleration* (*PGA*) for a 6.3 magnitude earthquake.

The *PGA* in Christchurch CBD was on average 0.5g in the horizontal direction (i.e. 0.5 times the acceleration of gravity) and 0.5g in the vertical direction which corresponds to *MM* VIII and was 50% greater than the design loadings for new buildings (500 year *return period* event) [5][2].

**Table 3 : *Peak ground accelerations* recorded within 20km epicentral distance (courtesy GNS)**

| Location | Distance from *Epicentre* (km) | *PGA* (g) | |
|---|---|---|---|
| | | Horizontal | Vertical |
| Heathcote Valley Primary School | 1 | 1.7 | 2.2 |
| Lyttelton Port | 3 | 0.96 | 0.49 |
| Christchurch Cashmere high School | 6 | 0.40 | 0.85 |
| Pages Road Pumping Station – (near Bromley substation) | 6 | 0.67 | 1.9 |
| Christchurch Cathedral College | 7 | 0.48 | 0.80 |
| Christchurch Hospital | 8 | 0.36 | 0.60 |
| Christchurch Botanic Garden | 9 | 0.55 | 0.36 |
| Christchurch Papanui High School – (near Papanui substation) | 12 | 0.21 | 0.21 |
| Templeton School – (near Islington substation) | 19 | 0.13 | 0.16 |

[2] The numbers in bracket refer to the list of references in Section 9.

Some southern and eastern suburbs closer to the *epicentre* experienced even higher levels of acceleration, with the highest recording at Heathcote Valley Primary School of 1.7g in the horizontal direction and 2.2g in the vertical direction, equivalent to *MM* X.

The ground accelerations measured at Heathcote Valley were the highest ever recorded in New Zealand (in comparison the highest reading during the 4 September 2010 event was 1.23g recorded at Greendale). Refer to Table 3 above for a summary of *PGA* recorded in the Christchurch region.

When compared with the 4 September 2010 earthquake, the accelereration from the 22 February 2011 event were much higher in Christchurch and southern and eastern suburbs, up to 6 times the value of the Darfield earthquake, as shown in the Figure 2 below.

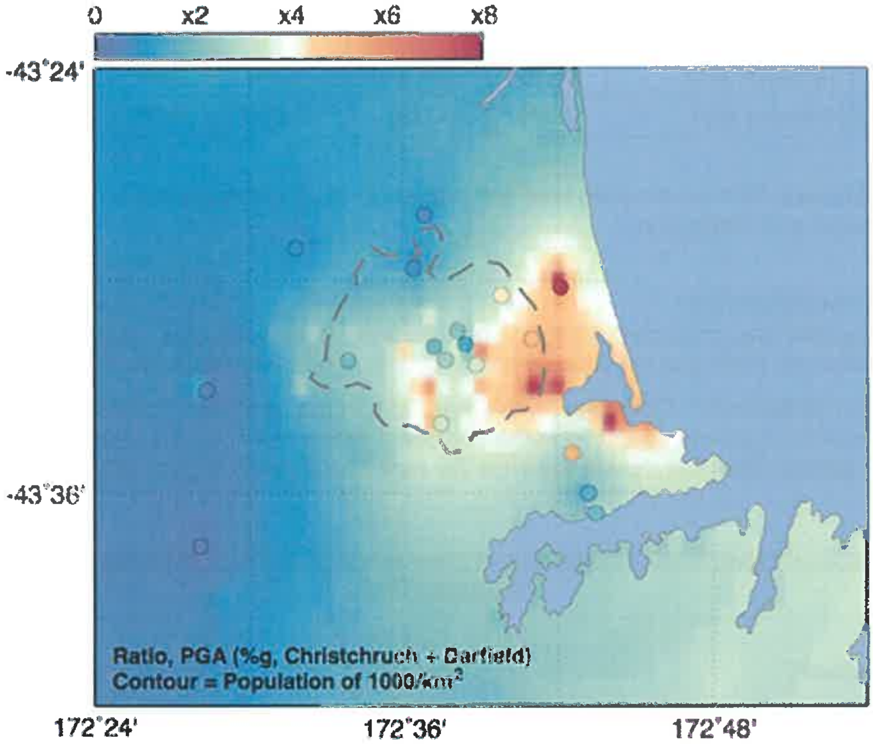



**Figure 2 : Ratio of *PGA* between Christchurch and Darfield earthquakes (courtesy of USGS)**

## 3.3 Geotechnical

The area of Christchurch city and suburbs located on the plains is generally classified as site subsoil class 'D', i.e. deep or soft soil in terms of the New Zealand standard used for determining earthquake loads. The subsoil generally comprises 15-45m deep sediments overlying a 300 to 700m thick inter-layered gravel formation.

In the western suburbs the deposits are mainly coarse gravels with the groundwater levels between 2-3m below ground surface. In the eastern suburbs, near the coast, silts and sands become more prevalent and the groundwater levels are between 0-2m below ground surface making these areas prone to *liquefaction*.

The earthquake caused significant *liquefaction* in areas throughout the Christchurch southern and eastern suburbs; notably Avondale, Avonside, Bexley, Bromley and Dallington, as shown in Figure 3 below [2]. The *liquefaction* resulted in settlement, *lateral spreading*, sand boils, and a large quantity of ejected silt mud and water ponding onto the soil surface. These suburbs had already suffered *liquefaction* (although not to this scale) during the 4 September 2010 earthquake.

The likelihood of *liquefaction* in the wider Christchurch area in this level of earthquake has been known for more than 15 years, and was documented in detail in studies commissioned and publically disseminated by Environment Canterbury and the Christchurch City Council more than eight years ago [4].

In the foothills of the Port Hills, buildings and properties in the suburbs of Redcliffs, Sumner and Lyttelton sustained damage due to landslides and rockfalls triggered by the earthquake.

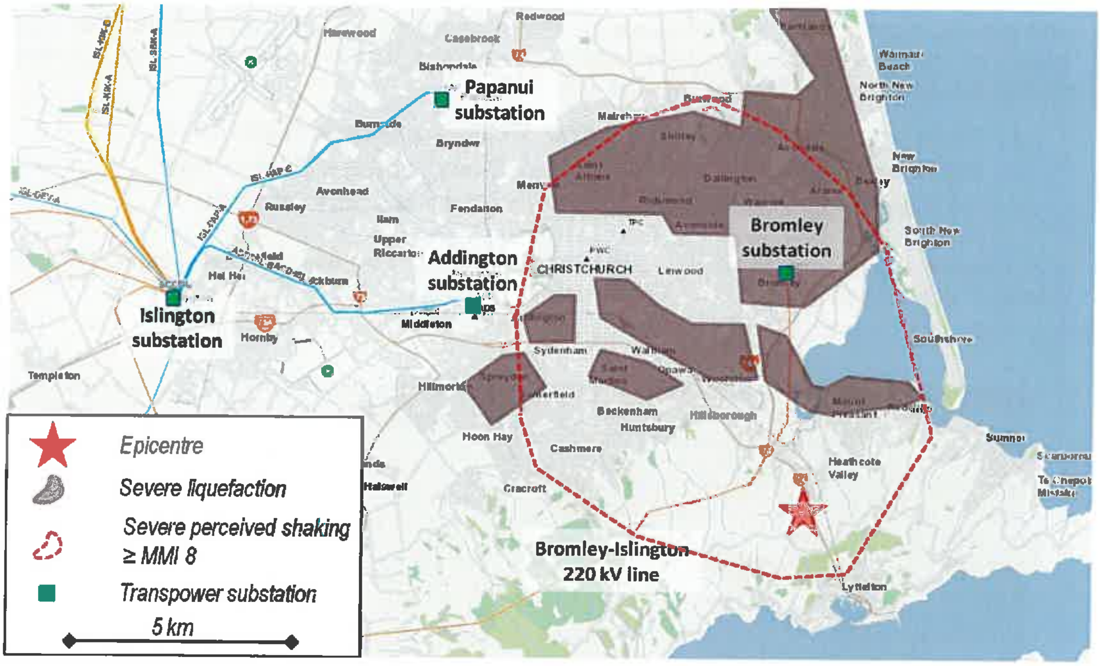



**Figure 3 : Area of observed *liquefaction* and severe shaking**

## 3.4 Damage to buildings and lifelines infrastructures

Damage to buildings and lifelines infrastructure was extensive in Christchurch CBD and southern and eastern suburbs as result of the 22 February 2011 earthquake. As during the 4 September 2010 event, unreinforced masonry (URM) buildings performed poorly throughout the city, with about 62% of all URM buildings in the Christchurch CBD receiving red-tags (not safe to enter and likely to be demolished) as part of the initial assessment [5].

Approximately, 50% of the city was without water for the first days following the earthquake; more than a third of households were without water for over a week. A month on from 22 February 2011, over 95% of occupied units (outside of the cordoned Christchurch CBD) had water, however, a "boil order" was in-place for over six weeks for most of the city due to potential contamination caused by severe damage to the wastewater system. The city relied heavily on a "temporary sewage service" facilitated by chemical and portable toilets to supplement the fractured and fragile wastewater system [5].

**Table 4 : Return of essential services for occupied households in Christchurch area [5]**

| | 1 day after the event | 1 week after the event | 1 month after the event |
|---|---|---|---|
| Electricity | 60% | 80% | 99% |
| Water | 50% | 66% | 95% |
| Sewerage | 40-50% | 50-60% | 80% |

Although the transmission network was largely unaffected and able to provide full supply after few hours following the earthquake, the distribution network was severely damaged with a number of high voltage buried cable faults due to *liquefaction* effects. Electricity was restored to approximately 75% of their households by 24 February; 80% by 26 February, as shown in the Table 4 above [5].

## 3.5 Aftershocks

The main event at 12:51 pm on the 22 February 2011 was followed by a series of aftershocks, most of them located below the Port Hills, as shown in Figure 4 below. The most severe aftershocks (to date) occurred within a few hours following the main event, causing further damage and impeding the rescue activities:

- 01:04 pm, magnitude 5.7, 10 km south of Christchurch at a depth of 6km
- 02:50 pm, magnitude 5.5, 10 km south of Chrischurch at a depth of 5km
- 04:04 pm, magnitude 5.0, 5km from Christchurch at a depth of 12km.

A 5.3-magnitude aftershock on 16 April 2011, the largest for several weeks, caused further damage, including power cuts and several large rock falls.

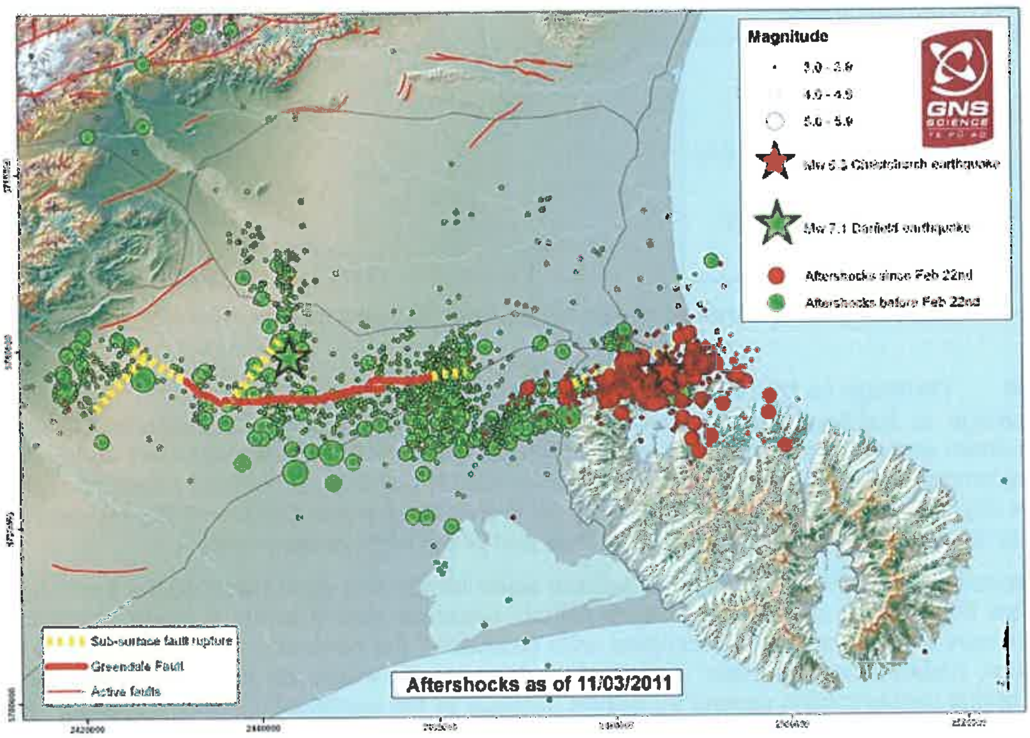



**Figure 4 : Location of the *epicentre* of the aftershocks following the 22 February 2011 earthquake (in red) and 4 September 2010 earthquake (in green) (courtesy of GNS)**

## 3.6 Changes to NZS 1170.5 "Structural design actions – earthquake"

Following the occurrence of these two major events, there is a significant risk that the Canterbury area will be subject to a period of increased seismicity. There may be a period of up to 50 years or more, during which the seismic hazard due to similar events near Christchurch is significantly increased [1].

The assessed risk of another similar earthquake near Christchurch with magnitude 6 to 6.5 event aggregates to approximately 6% on an annual basis. Prior to the earthquakes, this probability might have been assessed as less than 1/100th of this value [1].

**Findings and lessons learned:**

The Structural Engineering Society New Zealand (SESOC) has recommended to the Department of Building and Housing that the "Structural design actions – earthquake actions" Standard NZS 1170.5, defining seismic actions for new structures in New Zealand, should be amended by increasing the hazard factor in the Canterbury region to a minimum of Z = 0.3 (instead of the current value of 0.22), for all buildings and structures having a natural period of oscillation below T = 1.5sec.

GNS has informed Transpower that the current methodology to develop site-specific seismic hazard assessment (SSSHA)in the Christchurch region is still appropriate – using the updated Z factor indicated above rather than engaging GNS for a site-specific study – as explained below.

Site-specific studies by GNS are usually undertaken for sites within 10km from a major fault to ensure the best possible parameter estimates are used (magnitude, recurrence) and to allow modelling of near-fault rupture directivity. Faults are classified as major when capable of producing earthquakes of magnitudes 7.0 or greater and having slip rates of 5mm/year or greater. It is however unlikely that the Greendale and Port hills faults would meet the slip rate criterion.

**Recommendation:**

Transpower should ensure that the new seismic loading values (updated Z factor) are used when designing future projects in the Christchurch region.

# 4 Performance of Transpower assets

## 4.1 Physical damage

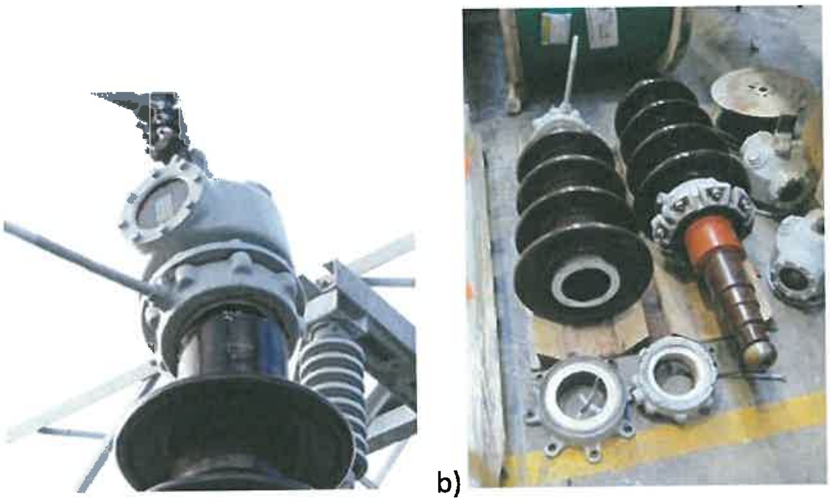
Most of the damage caused by the 22 February 2011 earthquake to Transpower assets occurred at Bromley and Papanui substations with some minor damage at Transpower's Addington warehouse. A number of transmission towers experienced *liquefaction* but were not adversely affected.

### 4.1.1 Damage at Bromley substation

Damage at Bromley substation occurred in the 66 kV and 220 kV switchyards and within the control building. Damage also occurred to two timber pole structures carrying lines between the two switchyards. Significant *liquefaction* occurred in the 220 kV switchyard.

*66 kV switchyard*

Damage to the 66 kV switchyards included two broken 66 kV transformer[3] bushings (refer Figure 5 below) and failure of a 66 kV cable circuit.



a) b)

**Figure 5 : a) 66 / 11 kV transformer bushing (from T2 blue phase) with failure at the top of the insulator; b) the two broken bushings (from T2 red and blue phases), note the insulator from T2 red phase (on the left in the picture) break at the bottom (photos: Transpower)**

There was also evidence that the 66 / 11 kV transformers had moved on their supports and the cast iron housing of a tap changer drive on one of these transformers was broken probably as a result of the relative movement of the transformer with respect to its foundation, as shown in Figures 6 and 7. It is likely that these transformers would have been dislodged from their rails resulting in significant damage had seismic restraints not been fitted.

[3] Manufacturer: AEI, model: 30MVA 66/11 kV, year of manufacture: 1961.

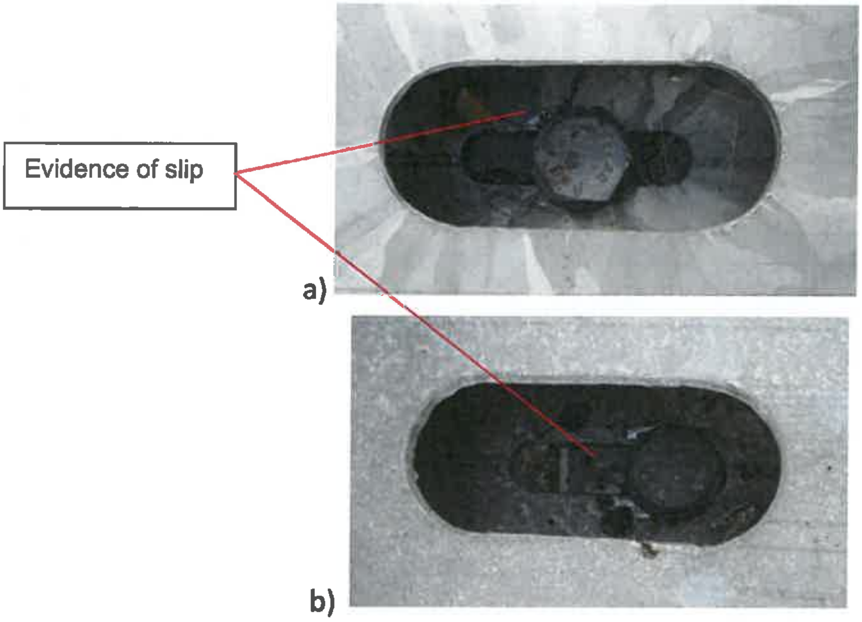


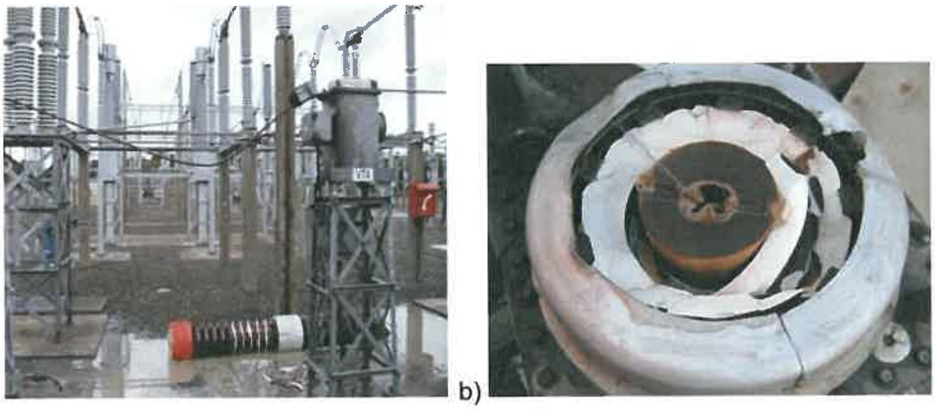

**Figure 6 : a) and b): transformer restraint showing signs of movement (photos: Transpower)**

**Figure 7 : 66/11 kV transformer – broken housing (photo: Transpower)**

*220 kV switchyard*

Damage to the 220 kV switchyard included a broken 220 kV capacitor voltage transformer (CVT)[4], refer Figures 8, 9, 10 and 11 below. 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.

[4] Manufacturer: Asea, model: CPAA 245/1050 N, year of manufacture: 1972.



a) b)

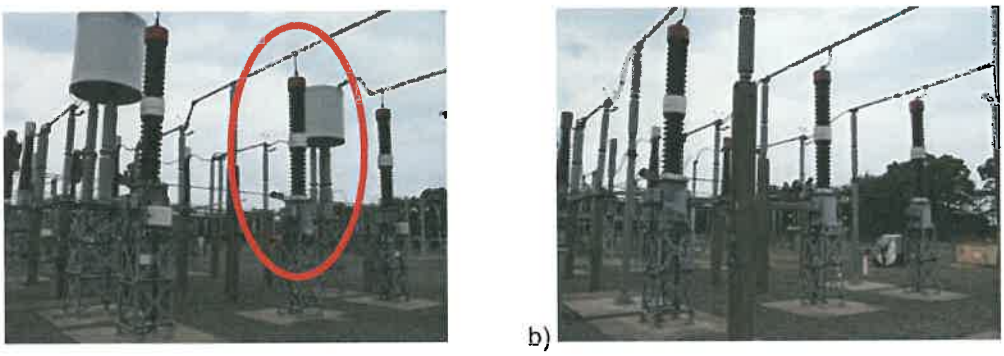
**Figure 8 : a) and b): broken 220 kV CVT insulator mounting showing finger clamps (photos: Transpower)**

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 are known to perform very poorly in earthquakes. Pressure from the finger clamps results in local stress concentration and clamping forces can vary from one clamp to another, so it is possible that the cause of failure is due to stress concentration around the finger clamps i.e. inherent structural weakness rather than due to interaction with the bus connection. It is also possible that the bus bar configuration influenced the failure; the CVTs of the adjacent phases did not fail and both are connected to bus bar supported by line traps quite close to the CVT. These line traps are not present on the phase of the CVT failure which is connected to a longer (more flexible) length of bus bar.

**Findings:**

The original CVT4 straight dropper connecting the equipment to the busbar is an example of arrangement that performs poorly under seismic conditions.

As a general comment, the lack of standardised practice for the installation of flexible conductor and the amount of slack that should be provided was identified as an issue prior to the Darfield and Christchurch earthquakes. The installation of flexible conductor is generally done without proper shape specification other than substation layout drawings and the suitability of the final arrangement relies generally on the experience and judgement of the installation contractor.



a) b)

**Figure 9 : a) original CVT 4 dropper arrangement (circled is the equipment that failed during the earthquake); b) original CVT 5 dropper arrangement (photos: Transpower)**

**Figure 10 : New CVT 4 dropper arrangement and replacement CVT (photo: Transpower)**

**Figure 11 : Undamaged 220 kV breaker bay (photo: Transpower)**

**Recommendations:**

Although the droppers on the two intact phases have been replaced with connections with sufficient slack, it is recommended that all these CVTs (model and model specified above) are replaced as the finger clamp insulator mounting is known to be an earthquake risk. NB: Being about 40 years old, they probably will be replaced soon anyway.

It is recommended that visual inspections be carried out in all substations to identify any flexible connections between equipment that are obviously too tight. It is understood that these inspections are already under way.

It is also recommended that flexible connection design and installation guidelines are completed to ensure appropriate slack is provided with consideration to seismic aspects and electrical clearances. A project has been set up to prepare these guidelines.

Minor spalling of concrete from some bus support stands was observed (Figure 12) but it is believed that this was caused by corrosion of the embedded bolts rather than as a direct result of the earthquake. Note evidence of previous repairs.

**Recommendation:**

It is recommended that these concrete posts be repaired or replaced.

The earth wires between gantries were observed to be slack but it is difficult to know whether this is an indication of permanent movement in the gantries, slip in the termination clamps or it was originally installed this way.

**Figure 12 : Concrete spalling - 220 kV bus support stand (photo: Transpower)**

*<u>Control and relay building</u>*

The control and relay building suffered minor structural damage (cracking of concrete), broken windows, fallen ceiling tiles as shown in Figure 13. One panel (Bay 37) of the 11 kV switchgear, which was racked out at the time of the earthquake, was damaged when the trolley became dislodged from its rails. There was also significant cracking and spalling of the concrete floor slab around the switchgear fixings (see Figure 14). The switchboard will be replaced by a new switchgear building later this year (see section 4.3.4).

a) 

b) 

**Figure 13 : a) and b) dislodged ceiling tiles (photos: Transpower)**

a) 


b) 

**Figure 14 : a) and b) damaged 11 kV switchgear (photos: Transpower)**

### 4.1.2 Papanui substation

The transformer bunds around T4 and the spare transformers were damaged by settlement due to *liquefaction* (refer Figure 15) as occurred in the 4 September 2010 earthquake but the damage due to the 22 February 2011 earthquake was more severe.

a) 

b) 

**Figure 15 : a) and b) settlement of transformer oil bund (photos: Transpower)**

Further settlement occurred around the foundations of the two transmission line terminal structures, see Figure 16. The settlement does not appear to have affected the towers themselves.

**Figure 16 : Settlement around transmission line terminal tower foundations (photo: Transpower)**

The base plates of some support stand legs have separated from their grout indicating that the bolts may have yielded (Figure 17).

**Figure 17 : Support stand showing signs of base plate uplift (photo: Transpower)**

### 4.1.3 Addington warehouse

Damage at the Addington stores included local buckling of the pallet racking structures, collapse of one shelf, a number of local buckling of pallet rack columns (refer Figure 18 below), a broken bushing and fallen or dislodged items.

Shelving damaged in the September earthquake had been replaced with the same system but with a heavier gauge.

Many industrial racking systems in Christchurch suffered similar type of damage and GNS and EQC have concerns about industrial racking and its performance in earthquakes. Generally, it is a poorly regulated area, and not always subject to building consents.

**Recommendation:**

One area of damage that is easily overlooked is the connector tearing or perforations with bearing failure. The beams need to be taken off the racks to observe this. It is recommended that the extent of the inspection already completed be reviewed to see if this has been done. If necessary, load limits should be placed on the racks until Transpower are fully satisfied that the racks are structurally adequate.

a) 

b) 

**Figure 18 : a) and b) local buckling of pallet rack columns (photos: Transpower)**

## 4.2 System performance[5]

Following the earthquake that occurred at 12:51, a Grid Emergency was declared at 13:04 to allow grid reconfiguration and demand management. Multiple feeder and transformer trippings occurred with approximately 248 MW of load being lost in a 30 sec period. The South Island frequency experienced a momentary rise to 50.78 Hz as a result.

This earthquake was managed as a significant event but not one that required major additional resources, given the limited impact on Transpower's assets (and the substantial effect on Orion assets). Approximately 248 MW load was lost across ADD, BRY, ISL and PAP substations. Load in the region has continued to be markedly below the levels seen in the equivalent time period last year. Transpower was able to supply all demand from around 16:30 on the day of the earthquake.

*Transformer trippings during the earthquake*

There were several trippings of non-faulted transformers during the earthquake and during an aftershock on the day of the earthquake. These transformers are listed here.

All of the transformers that tripped during the earthquake at 12:51 tripped from main tank Buchholz protection operation:

- BRY T2 (there were damaged bushings on T2, and these required replacing)
- BRY T3
- BRY T5
- BRY T6
- ADD T7

All of the in-service Bromley transformers tripped during the earthquake, and all connection was lost.

The following transformer tripped during an aftershock at 14:50 on the day of the main earthquake from its On-Load Tap Changer Surge Device:

- SPN T1

There is a mix of Buchholz equipment on the Bromley substation transformers, however all of the existing relays are either designed to be aseismic or have had switches replaced so that they are now considered to be aseismic (this is the case for the CGE devices). The Bromley transformers have the following types of Buchholz protections:

- T2 – AEI
- T3 – Cedaspe
- T5 – CGE
- T6 – Cedaspe

The Addington T7 transformer has the ETI GQ80 Buchholz device fitted which we purchase as our latest standard. The other in-service Addington transformers which also have ETI Buchholz relays remained in service therefore supply was not lost as a result of the T7 transformer tripping.

The Springston T1 transformer tripped during the aftershock due to operation of its On-Load Tap Changer Surge Device which has a non-aseismic mercury switch. The T2 transformer, which has the same type of surge device, remained in service so supply was not lost as a result of the T1 transformer tripping.

Replacement of the Springston T1 transformer device will be completed during an existing scheduled outage in August 2011. Springston T2 is not due to be removed from service for maintenance until 2012, but a separate outage is likely to be scheduled to undertake this work

[5] In sub-sections 4.2 and 4.3 the following site abbreviations are used: BRY for Bromley substation, ADD for Addington substation, PAP for Papanui substation, SPN for Springston substation and ISL for Islington substation.

prior to this. It has been determined that one other Transpower site (Motueka) also has this device installed on its transformer bank and hence the devices there are also scheduled to be replaced.

*Impact of seismic / non seismic rated devices on transformers*

As mentioned above, all of the Bromley and Addington Buchholz relays are specified to be aseismic, or have had switches replaced so that they are less likely to trip during earthquakes. However, these relays spuriously tripped during the earthquake due to ground shaking.

1) Is it advisable that non-faulted transformers trip during earthquake, i.e. can transformer trippings be used to prevent the supply of power to a potentially damaged distribution network?

It is considered undesirable that un-faulted transformers trip during an earthquake. This is because the Buchholz relay is installed only to protect the transformer from internal faults. Feeder protection should be the first protection to operate for faults on any faulted feeders. Then transformer overcurrent and earthfault protection provides backup feeder protection, in the unlikely event that either a feeder protection relay or a feeder circuit breaker fails. Hence, in the usual case where all of the feeder protection operates correctly, any non-faulted feeders would remain in service supplying load. As well as keeping power on, this would also have the benefit of Transpower knowing which feeders are or are not faulted, which would improve our restoration response.

2) Could we have expected the relays not to trip during an event of this magnitude?

Current Transpower purchase specification requires all new relays to be aseismic and not falsely operate at an acceleration of 2.25 g, at any frequency between 2 and 15 Hz. We have asked the manufacturer of the ETI GQ80 relays – the model Transpower purchases as its latest standard - for comment on what acceleration the relays should be resistant to and provide seismic qualification reports for their products. At time of printing, the only test report provided by the manufacturer was a shaking test carried out at acceleration levels significantly lower than those specified.

It is also probable that the performance of the previously purchased aseismic models (e.g. Cedaspe) cannot be ascertained to comply with current Transpower specification.

However, it is likely that at Bromley and Addington substations the actual accelerations applied on the Buchholz relays were greater than the maximum specified value of 2.25g. The acceleration at the level of the Buccholz relays are calculated as the maximum ground acceleration, (in the order of 0.7g horizontally and 1.9g vertically at bromley substation) multiplied by an amplification factor (usually greater than 2.0) that account for the flexibility of the mounting structure.

**Findings**

The performance of the aseismic Buchholz relay during this event is not unexpected as the actual level of acceleration is most probably higher than what the equipment has been specified and tested to.

3) Should Transpower be reconsidering its specification for aseismic relays?

As the current specification of 2.25g may not prevent false operation during rare event similar to the 22 February 2011 earthquake, we may have to reconsider our specification level.

However, we understand from manufacturer's advice that it is difficult to increase the seismic withstand of any new seismically designed Buchholz devices beyond their current design level without permanently decreasing their sensitivity to actual internal transformer faults. It is important to note that these devices have been proven to be very useful in reducing damage during actual transformer faults, and for this reason the risk of permanently desensitising their protection is not considered acceptable.

Also strong earthquakes such as this one are uncommon, and hence the inconvenience created by non-faulted transformer trippings during such a rare earthquake can be deemed as acceptable.

Inversely, the false operation of transformer relays during aftershocks or small earthquakes is probably not acceptable given that the recurrence of such event is much higher. The fleet of aseismic relays installed in Christchurch substations remained stable during the 4 September 2010 and 22 February 2011 earthquakes aftershocks, inferring that the current level of compliance allows satisfactory performance during aftershocks and lower magnitude earthquakes.

**Findings**

The current level of specification allows satisfactory performance during aftershocks and lower magnitude earthquakes but may not prevent false operation during large earthquakes.

It is understood that increasing the specified level of acceleration to ensure correct performance of Buchholz relays during rare and large earthquakes will have a detrimental effect on the sensitivity of the devices to actual internal transformer faults.

It is understood that only shake table tests would provide some assurance on the performance of the relays devices during rare and large earthquake.

**Recommendation:**

Transpower should decide whether it is required for relays not to falsely operate during rare and large earthquake. If that is the case, the specified acceleration levels should be reviewed and the performance of relays shall be demonstrated by shake-table tests reproducing the as-installed arrangement of the device.

4) Should Transpower reconsider the relay model it currently purchases?

From the available information we have from the two Christchurch earthquakes and from design specifications and comments from the manufacturers, it is considered that there is no benefit in replacing any of the types of aseismic Buchholz relays at Bromley or Addington, or any of these types of devices at other sites.

There is also no clear benefit in reconsidering the model Transpower currently purchases, unless it is decided that relays should remain stable during rare and large earthquake.

**Recommendation:**

We recommend that we continue to purchase the ETI relays for new Buchholz relay installations, unless it is decided that relays should remain stable during rare and large earthquake.

*Feeder trippings during the earthquake*

There were also numerous feeder trippings during the earthquake. The substations affected are Addington, Islington, Kaiapoi and Papanui. This is likely to be due to genuine faults caused by the earthquake, and it is considered that the feeder protection has performed reliably and is stable.

*Subsequent related trippings*

On 6 March 2011, Bromley T4 tripped. At the time, the transformer was on hot-standby, which is its usual operating configuration. The tripping was due to a fault in the pitch-filled cable termination box for LV circuit breaker number 39. Because the transformer was on hot-standby there were no operating issues due to the tripping, and the damage was able to be fixed within a few days and the transformer returned to hot-standby. As the cable box was filled with pitch, the pitch required melting before any repairs could be done. The fault was likely to be due to damage to the low voltage switchgear, which was sustained during the earthquake and subsequent aftershocks.

## 4.3 Response and recovery

The full list log of Transpower response activities is provided in Appendix B . The following section provides information on the system response and recovery as well as the short and long term remedial strategies. All timescales in the Figures 19 to 25 below are in seconds, with the earthquake happening at t = 110 seconds.

### 4.3.1 System response

*Loss of load*

The total loss of load at the main grid exit points in the Christchurch region were as follow (refer to the Figure 19 below for variation of load with the time):

- Bromley (BRY) loss of 90 MW; the load dropped to zero in two stages i.e. at 420 seconds (8 mins) and 510 seconds ( 8.5 mins) after the earthquake,
- Addington (ADD) loss of 80 MW,
- Papanui (PAP) loss of about 80 MW,
- Springston (SPN) loss of 5 MW.

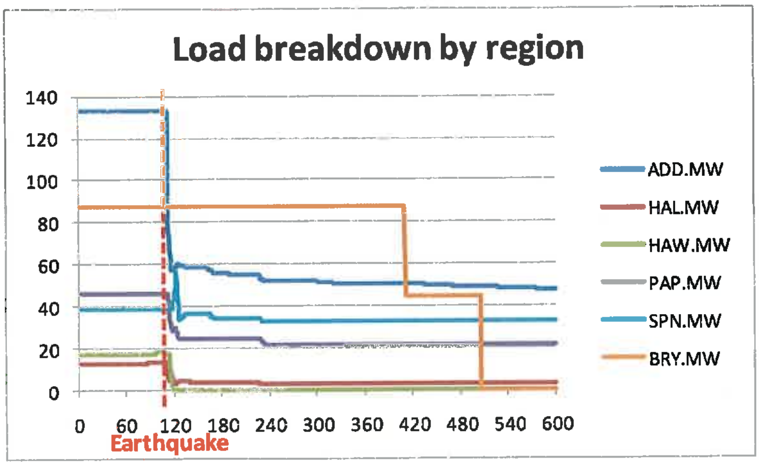



**Figure 19 : Load loss breakdown by region (data: Transpower)**

The loss of load on the interconnecting transformers T6 and T7 at Islington is shown in the Figure 20 below. Note: ISL T3 was out of service at the time of the event.

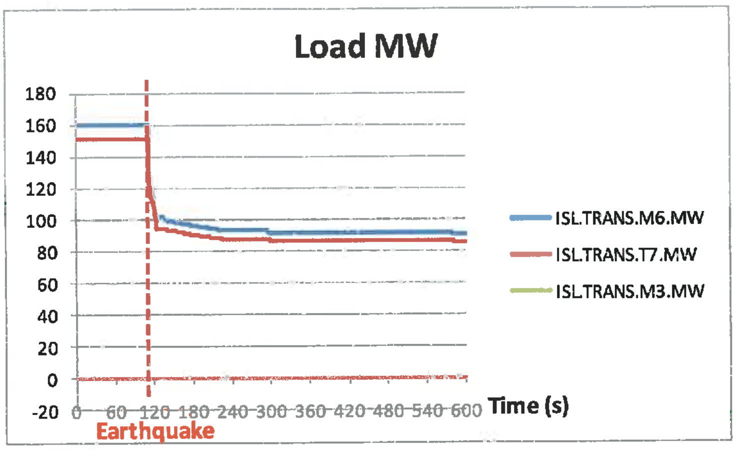



**Figure 20 : Load at Islington reduced from about 160 MW to approximately 90 MW in 2 minutes after the earthquake (data: Transpower)**

*Islington substation voltage*

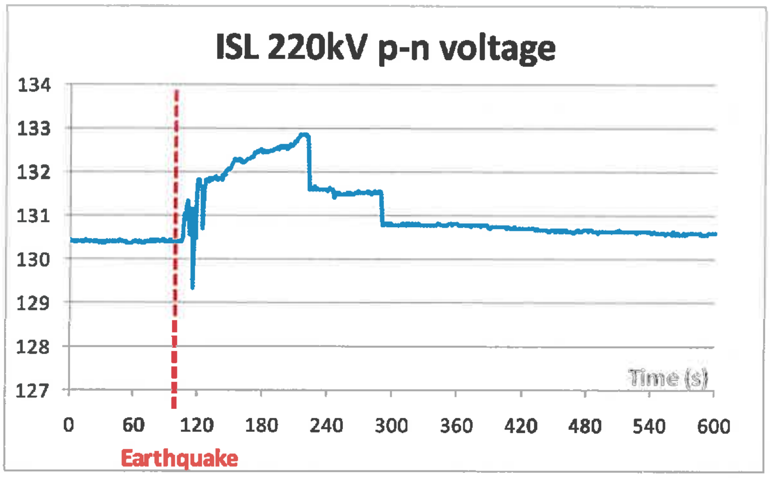



**Figure 21 : Islington 220 kV p-n voltage (data: Transpower)**

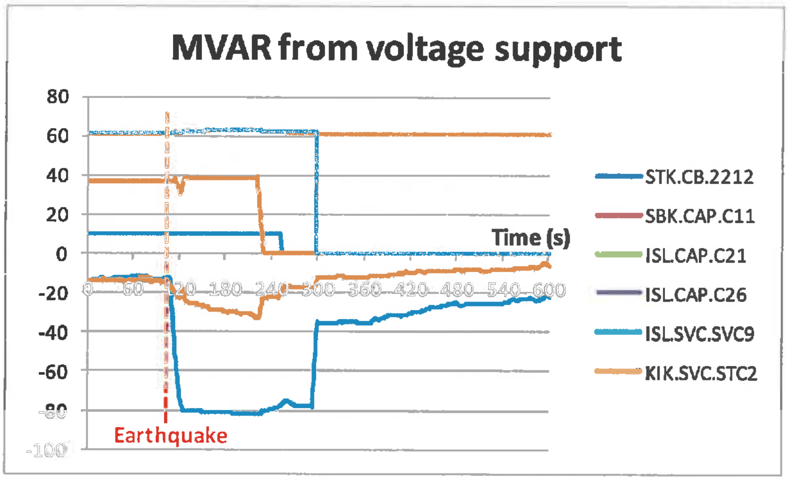
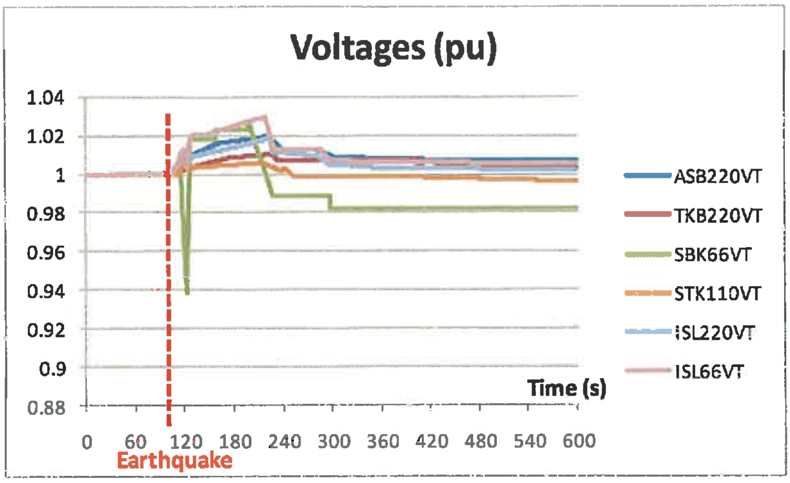



**Figure 22 : MVAR from voltage support (data: Transpower)**

The loss of load caused the ISL bus voltage to rise, followed by two distinct downward steps. The first at about t = 200 seconds was from the operator turning off the 35 MVAR capacitor bank C11 at Southbrook substation (SBK). The second at t = 300 seconds was from the operator turning off the C26 capacitor bank at ISL, which caused SVC9 to reduce its amount of inductive load. The operator also switched out C33 10 MVAR cap at Stoke substation (STK) at around t = 240 seconds, which may have caused the slight dip in ISL voltage.

*Bus voltages*

Bus voltages in the Figure 23 below are normalized to their initial pre-quake values. The ISL 66 kV bus had worse voltage regulation than the 220 kV, as expected. A comparison of PMU voltages versus traditional measurement voltages is also shown.

a)


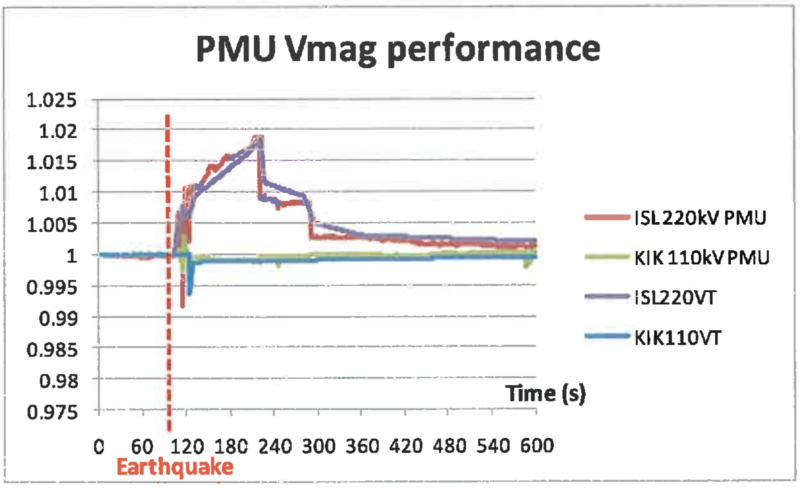

b)



**Figure 23 : a) and b) 110 and 220 kV Voltage Regulation (data: Transpower)**

*Frequency response*

Loss of load caused South Island frequency to rise. HVDC power flow north increased, causing North Island frequency to also spike, as shown in Figure 24 and 25 below.

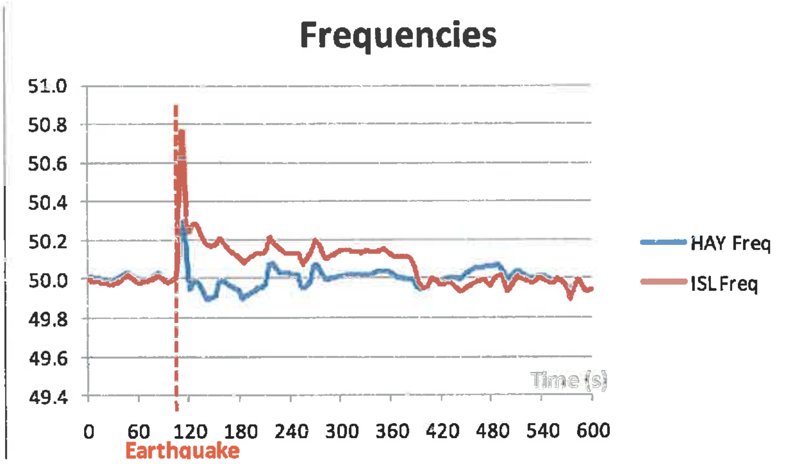



**Figure 24 : Frequency rise at Islington and a frequency spike at Haywards (data: Transpower)**

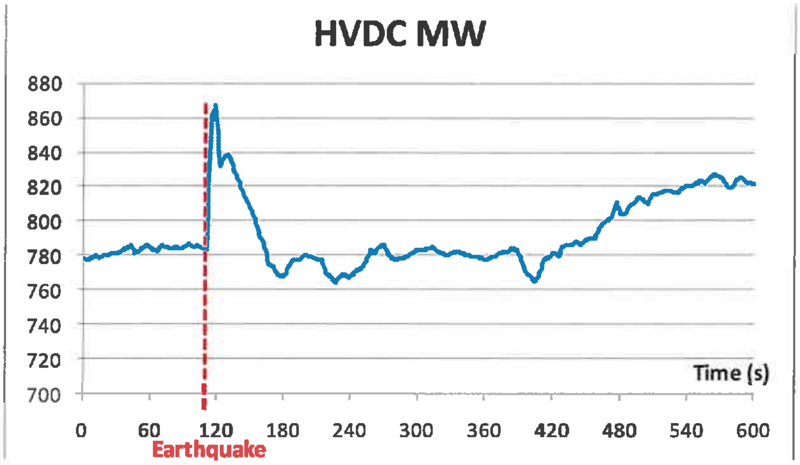



**Figure 25 : Power increase in HVDC link (data: Transpower)**

### 4.3.2 System recovery

The load took some time to recover to pre-quake levels, as shown in Figures 26 and 27 below. All timescales in the Figures 26 and 27 below are in hours, with the earthquake happening at t = 48 hours.

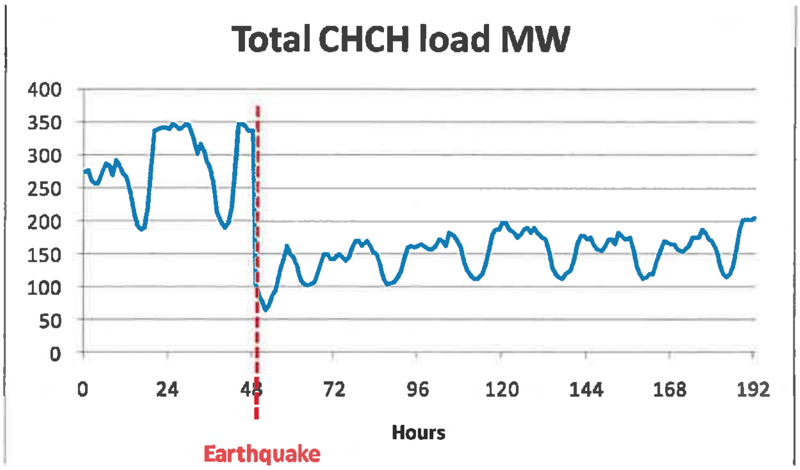



**Figure 26 : Pre and post earthquake Christchurch total load (data: Transpower)**

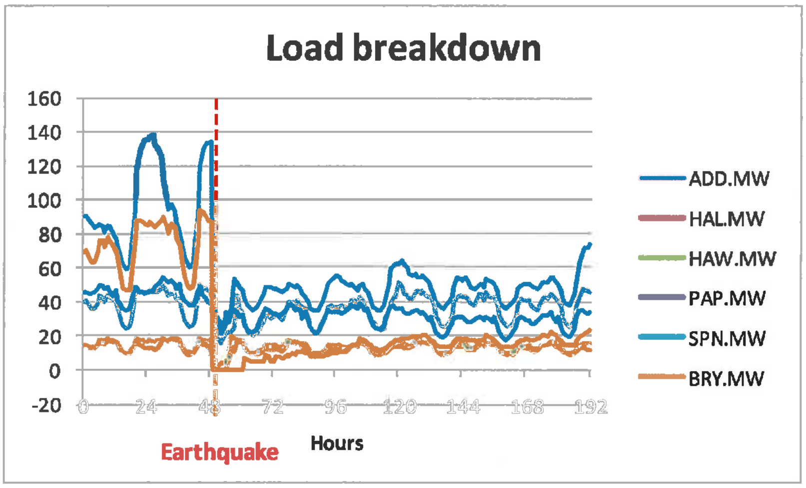



**Figure 27 : Breakdown of pre and post earthquake Christchurch load drop by site (data: Transpower)**

### 4.3.3 Short term remedial strategy

*Bromley 11 kV switchboard*

Interim measures were taken to ensure that the Bromley substation, an important point of power supply for the Christchurch region, remains in operation. Temporary repairs have been carried out to enable the equipment to be returned to service, and bracing has been installed at the front and rear of the panels to hold the switchgear onto the foundations, and to enable the circuit breakers to be safely racked out and isolated. Partial Discharge testing to evaluate the condition of the 11 kV switchboard following quake was carried out twice in February 2011 and four times in March 2011 and the result were satisfactory.

a)  b) 

**Figure 28 : a) and b) Bromley bracing installed at the front and rear of the switchgear panels (photos: Transpower)**

*Bromley 66 kV switchyard equipment*

T2 bushings were replaced by using bushings from the spare Transformer on site. This means that Bromley 66 kV no longer has a spare transformer.

*Bromley 220 kV switchyard*

Disconnectors DS804, DS817, DS894 and DS896 went out of alignment. Outages were planned to realign and close.

BRY Broken 220 kV Capacitive Voltage Transformer VT4 was recovered from site and sent to ABB ware house for scrapping.

**Figure 29 : Broken capacitive voltage transformer, VT4, removed from Bromley substation and replaced (photo: Transpower)**

### 4.3.4 Long term remedial strategy

*Bromley 11 kV switchboard*

Transpower is fast-tracking the construction of a new substation building and the installation of new switchgear to ensure power supply to the Christchurch area remains secure. The damaged switchboard will be removed. Transpower has already awarded the civil works contract. The solution meets the customer (Orion) requirements of two extra 11 kV circuit breaker panels in addition to what is there. The building is expected to be commissioned, along with new switchgear during the third quarter of 2011. The switchboard has been sourced from the Timaru project which will now wait for a new switchboard to be manufactured.

*Bromley 66 kV switchyard*

The replacement spare for T2 bushings are to be sourced.

## 4.4 Structural damage vs. performance requirements

Although the vast majority of Transpower's buildings affected by the 22 February 2011 earthquakes were designed prior to Transpower's current policy and no major strengthening work has been carried out, they met or exceeded the current performance criteria. The equipment failures sustained at Bromley substation are considered to be tolerable given the age of the assets and are regarded as meeting the current performance requirements for this magnitude of event.

Transpower's Bromley substation, the nearest substation to the 22 February 2011 earthquake *epicentre* (5km), experienced very strong horizontal and vertical ground shaking. GNS recordings at Pages Road pumping station (1.5km from Bromley substation with same ground conditions) provide a good indication of the level of acceleration experienced at the substation. The earthquake *response spectra* correspond to Transpower's current *ultimate limit state* level (*return period* 2500 year) for the 0.0 to 0.3s period range, refer Figure 30 below.

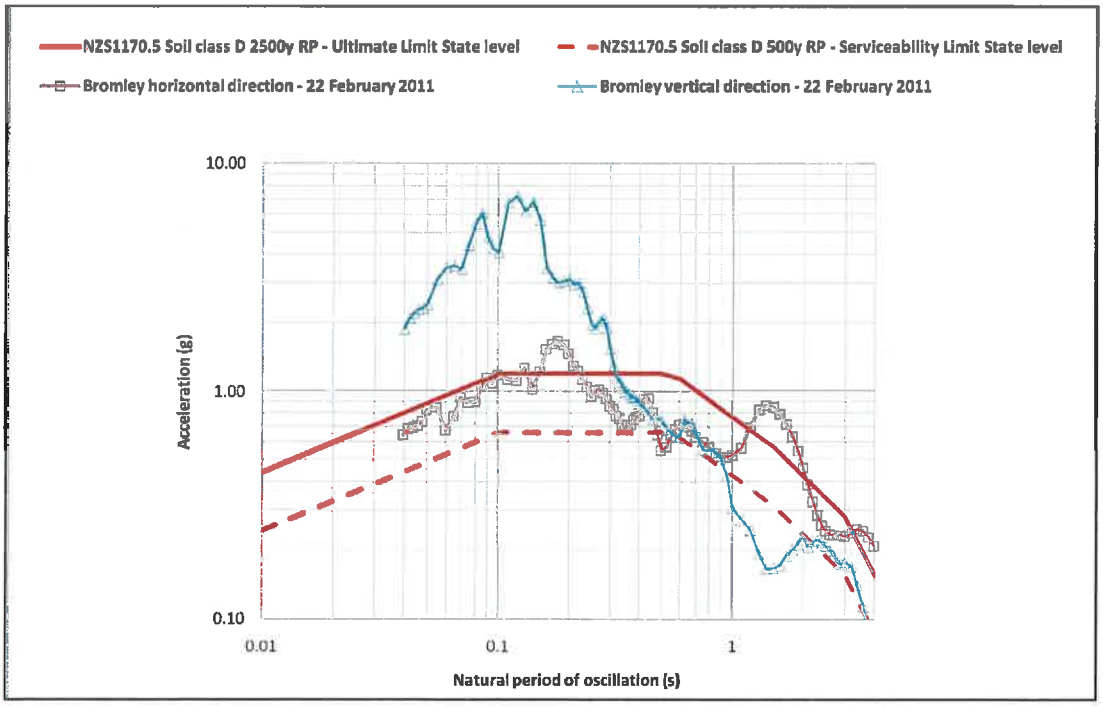



**Figure 30 : 22 February 2011 earthquake - Bromley substation. *Response spectra* at 5% of critical damping (from GNS) compared with NZS1170.5 *ULS* and *SLS* requirements for the site**

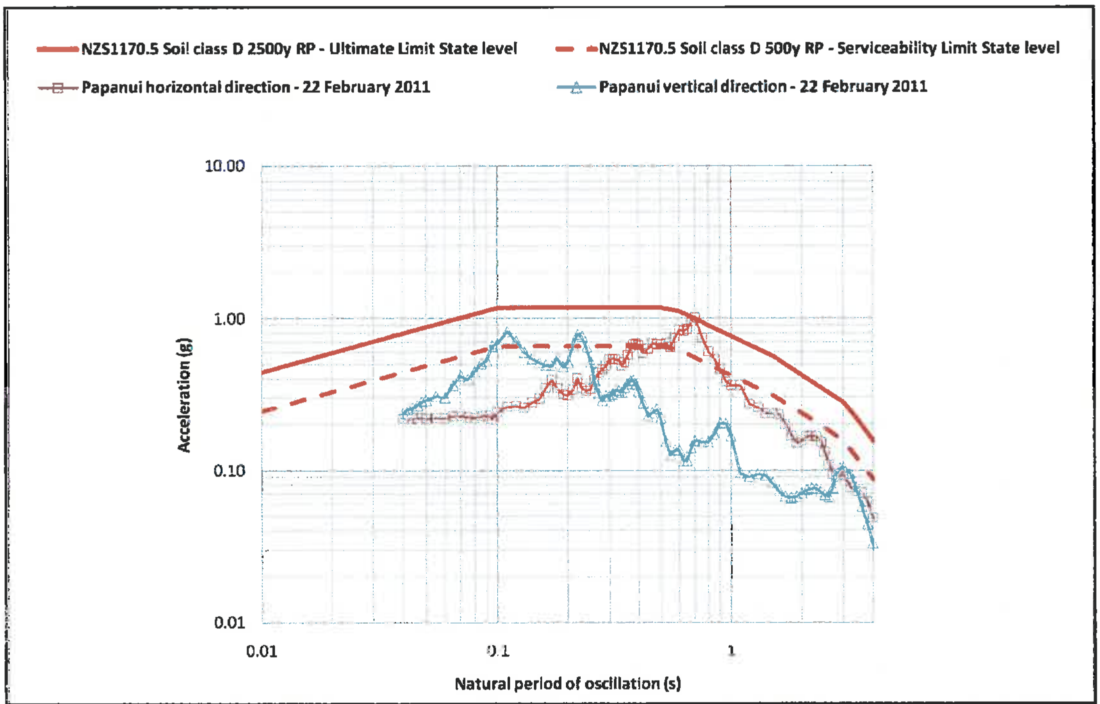



**Figure 31 : 22 February 2011 earthquake - Papanui Substation. *Response spectra* at 5% of critical damping (from GNS) compared with NZS1170.5 *ULS* and *SLS* requirements for the site**

At Bromley no significant damage to the buildings was sustained and, as described above, some switchyard equipment failed. Spares were available and the failed equipment was replaced promptly, which is tolerated by Transpower policy for *ULS* events. Equipment failures reduced the *security* contingency to n instead of n-1; again this is tolerated by the seismic policy. Hence buildings and equipment met the current performance criteria at *ultimate limit state level*.

During the 22 February 2011 earthquake, the substations north and west from the CBD (Papanui, Addington, Islington) generally experienced shaking corresponding to Transpower's current *serviceability limit state* level (*return period* 500 years) for the 0.0 to 0.3 second period range. Figure 31 above shows the *response spectra* at Papanui substation (4km north of the CBD). Although not necessarily designed for this level of earthquake loading, the substations structures and equipment performed well and met the current performance criteria at *serviceability limit state* level with the exception of the spurious transformer trip at Addington substation.

Most of Transpower substation assets have been designed or purchased on the basis of seismic requirements generally less severe than the current requirements. In that respect, the assets have performed well despite not having been designed to current seismic standards. Inherent strength margins and seismic restraints retrofit programme are likely to have contributed to the good performance.

**Findings and lessons learned:**

This earthquake, as well the 4 September 2010 event, did highlight Transpower's reliance on aged infrastructures. However, their good performance in this event does not provide certainty on how well our equipment, systems and buildings would perform in another event of same or greater magnitude, particularly if the *epicentre* is closer to a substation.

**Recommendation:**

Transpower needs to continue to reduce the risk by removing or strengthening existing buildings or items of plant not complying with our seismic policy and to support the improvement of seismic design and construction standards in the electrical industry.

## 4.5 Transpower organisational response

As with most businesses in Christchurch, Transpower had staff in a number of locations:

- in the Show Place Office (referenced below as Christchurch office),
- in the Addington Warehouse
- at the Islington Regional Operating Centre

In addition, some staff were at work, but out of the office at the time – on site or elsewhere.

Islington Regional Operating Centre (ROC)

The Regional Operating Centre was fully operational at the time of the event. They reported much less disruption than for the 4 September 2010 event and were able to continue working throughout the event and the following days. Infrastructure services (electricity, water, sewerage) were not disrupted for this site. As a precaution, a portable toilet was organised for the site, at a later date, in case the city sewerage system disruption became more extensive, but this was not required.

Addington warehouse

Damage, racking and unsecured pallets at the Addington warehouse made the site unsafe to work in, although no injuries were sustained during the event. Staff were advised they were not required on site until the site was safe. Where projects required equipment from the warehouse a procedure was established for access to equipment while ensuring the safety of staff.

The site was inspected by John MacKenzie (a structural engineer contracted by Transpower's Christchurch office) to assess the structural safety of the building and its contents. It was quickly established that the building was structurally safe but the nature of the damage to the contents was of primary concern. A work plan was established to safely bring all inventory to ground level, remediate the shelving, and reshelv inventory in a more appropriate configuration taking account of the nature of the inventory and the frequency of access. This work took some weeks. Inventory in the yard was restacked and restrained as appropriate. In addition to putting right the damage from the earthquake the opportunity was taken to dispose of inventory no longer required. Actions taken at this site were then applied to other warehouse sites as appropriate.

Christchurch office

Staff in the Christchurch office took shelter from the earthquake under desks or in door frames. Once the shaking had stopped, staff evacuated the building. Having ascertained everyone was out of the building, staff were sent home, although significant road traffic congestion impeded progress. A number of managers stayed at the site, making contact with employees who were off site, crews who were checking equipment, and management at Head Office.

No injuries were sustained during the event, however, there was disruption to the office site with air conditioning ducting coming through the ceiling space in the reception area, papers sliding off desks and shelves, and unrestrained equipment moving from its usual location (refer Figure 32 below).

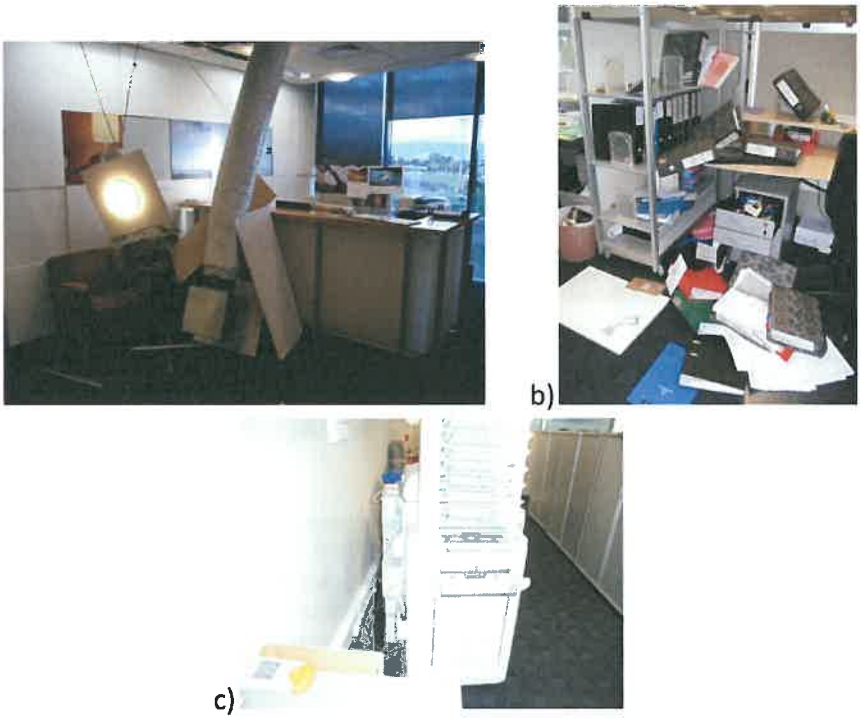



**Figure 32 : a), b) and c) Transpower Christchurch office (photos: Transpower)**

While the office itself was essentially undamaged, it was two days before a structural assessment was conducted due to the unavailability of assessors through the building owner. In the end, Opus were requested to do an assessment, the result of which was that the building was determined as safe to occupy. Since then it has been decided that a more formal arrangement with Opus should be entered in to so that an early assessment of facilities can be undertaken following a similar event. This arrangement has also been offered to maintenance contractors.

Management determined early on that it needed to maintain close contact with all of the Christchurch staff in the following days. On the afternoon of the earthquake, the GM Grid Performance and the Chief Executive requested a staff contact list for Christchurch staff and later in the afternoon they attempted to make telephone contact with all staff, to find out how they and their families were. Many staff later reported how much they appreciated this early contact.

Until the office reopened, Christchurch managers made contact with staff at least daily. In addition:

- Information was put on the 0800 What To Do number so that staff could have access to up to date information about the status of the Christchurch Office
- Emails and text messages were sent to Christchurch staff providing them with regular updates. This continued for some days until staff was able to come back to work.
- An Intranet page was established with Transpower specific information plus links to official Civil Defence sites.

Managers report communication with field crews and staff was a little difficult in the early stages post event. The mobile phone network was congested, but this was not unexpected, so manager attempted to use FleetLink radios to communicate with field crews. In some instances, it appears that the radio network was not operational. At the time of writing this report, this is still under investigation.

Satellite phones were used in some cases for management communication. These were found to be effective, but it has been determined there are insufficient portable satellite phones. A proposal is being developed to increase the number and availability of satellite phones.

With respect to communicating with staff, managers found that text messaging was more reliable. Managers found that personal contact lists (from records in the HR system) were out of date in some cases or did not contain mobile phone contact information. In addition, some staff chose to take their families out of town and notified their line manager (who was not from the Christchurch office), but failed to notify a Christchurch Office manager. These things reduced the certainty of wellbeing information for individual staff in the short term. Staff across the company are now regularly reminded about keeping their contact information in the HR system up to date.

**Recommendation:**

Staff contact lists should be regularly updated and should contain mobile phone numbers (company and personal phones) as text messaging was found to be the most effective way of communication. Transpower should develop a coordinated approach on FleetLink radio and satellite phone use for management communication and communication with maintenance contractors after disruptive events.

Within three days of the event, management formed a small "Earthquake Recovery Team" whose purpose was to provide support and assistance to the managers and staff in Christchurch. This group had a phone conference every couple of days to ascertain the current situation and determine what support and assistance was required. As some of the managers lived outside the city, their water systems were not disrupted, so they provided fresh water for other staff to take home for the first few weeks.

Many of the actions taken for the 22 February 2011 earthquake differed to that of the 4 September 2010 earthquake mainly due to the "felt" severity of the event, and the personal impact of the event given that it occurred during working hours. In September 2010, much of the recovery activities centred around staff being ready to return to work, as the assessment of the office building could be done during the weekend. In February 2011, this assessment work was done during the week, meaning staff were at home when they might otherwise have been at work. This placed some pressure on the need to return facilities and buildings to service sooner than for the previous event.

# 5 Distribution network

## 5.1 Orion

Orion manages the distribution network across Christchurch City and the suburbs affected by the 22 February 2011 earthquake. The network, comprising mainly 66 kV and 11 kV underground cables (as shown in Figure 33 below), suffered major outages and they estimated that the impact was ten times greater than the 4 September 2010 earthquake and there was significant damage to the cable network. The following high level information was provided by Orion on damage to their cable circuits:

- All major 66 kV cables supplying Dallington & Brighton zone substations failed (2 zone substations out of 51 )
- 50% of 66 kV cables suffered multiple damage
- 5.5% of 11 kV cables suffered multiple damage
- 0.6% of LV cables suffered multiple damage

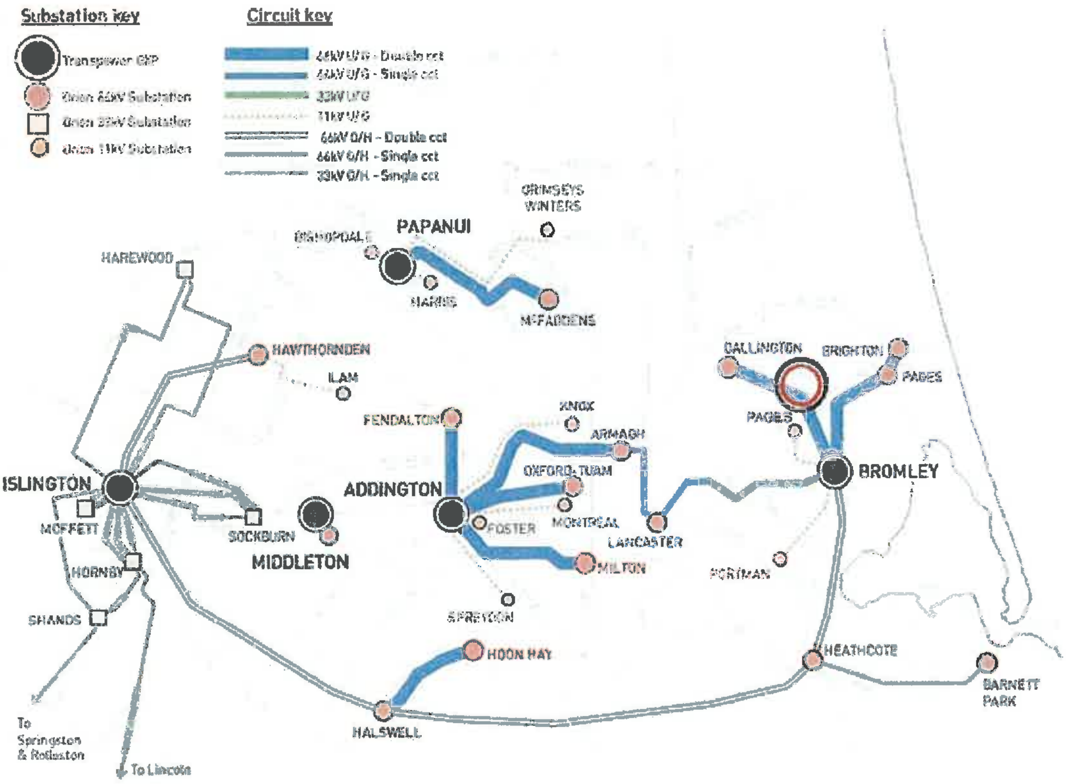



**Figure 33 : Orion Single line distribution network (courtesy of Orion)**

### 5.1.1 Physical damage

All types of cable suffered damage i.e. it was not possible to say that any particular cable variant was less susceptible to damage when compared to any other; and the was no discernible pattern to the areas/ground conditions where cables were effected. Below are a number of photographs of damage sustained (Figure 34, 35 and 36).

**Figure 34 : 66 kV XLPE cable and associated protection optical fibre cables on Fitzgerald Avenue. Note: cable did not fault at this location (courtesy of Orion)**

a)

b) 

**Figure 35 : 66 kV XLPE cable fault position, a) initial exposure and b) internal cable damage (courtesy of Orion)**

**Figure 36 : Typical 11 kV Cable Damage (courtesy of Orion)**

A number of these photographs have been shared with other overseas utilities and cable engineers and the consensus view is the extent and the type of damage is unique.

### 5.1.2 Response and recovery

By necessity the initial response has been on locating the various cable faults and repairing these, the principal method being cutting out of the damaged section and inserting a new piece of cable with two repair joints. However, a number of the older 66 kV oil filled cable circuits had to be abandoned and temporary lines installed on an emergency basis.

### 5.1.3 Recommendations

**Recommendations:**

Whilst Transpower has only a limited number of underground cable assets, it is currently implementing a large number of 220 kV XLPE insulated cable projects in Auckland and a number of these are or planned to cross the South Auckland Landslip Zone.

The following actions are recommended to improve Transpower understanding of the risks to its 220 kV underground cable circuits assets:

1) Sponsor a study of the damaged 66 kV cables either uniquely or in conjunction with other utilities (NZ or overseas) or IEEE 693-Consortium. A suggested brief is given in Appendix C This was provided by Cable Consulting International Mr. Brian Gregory a pre-eminent EHV cable expert who is based in the UK.

2) Leading from Item (1) above, develop technical standards that could be used to mitigate the probability of damage to underground cable circuits during a significant seismic event. Note: It is understood that PG&E and BC Hydro have put in place separate investigation initiatives in this field. We could benefit from coordinating our activities.

3) Place a much greater emphasis on geotechnical studies during the development of 220 kV cable circuits and develop appropriate policies.

4) All optical fibre cables should be installed within separate plastic ducting, i.e. not buried direct – in Christchurch all these cables have now had to be abandoned and alternative protection communication paths sought.

# 6 Key findings and lessons learned

**General**

- This earthquake, as well the 4 September 2010 event, has highlighted the reliance of Transpower transmission network on aged infrastructures.
- This event has also highlighted the potential issue of repairability of some aged equipment after an earthquake due to the lack of readily available spares (such was the case of the 66 kV transformer bushings that broke at Bromley substation).
- The satisfactory performance of Transpower assets during this event does not provide certainty on how well our equipment, systems and buildings would perform in another event of a similar or greater magnitude.

**Seismic risk assessment**

- The seismicity (the frequency or magnitude of earthquake activity) over a region can change following an earthquake event. As a result of the 4 September 2010 and 22 February 2011 events, New Zealand structural design standards are likely to be amended to account for an increased seismic hazard in Christchurch region.

**Flexible conductors**

- The very short straight connection between the CVT4 and rigid bus at Bromley substation was identified as a possible cause of the failure of the CVT.
- As a general comment, the lack of standardised practice for the installation of flexible conductor and the amount of slack that should be provided was identified as an issue prior to the Darfield and Christchurch earthquakes.

**Buchholz relays**

- The current level of specification allows satisfactory performance of aseismic Buchholz relay during aftershocks and lower magnitude earthquakes but may not prevent false operation during large earthquakes.
- It is however understood that increasing the specified level of acceleration to ensure correct performance of Buchholz relays during rare and large earthquakes will have a detrimental effect on the sensitivity of the devices to actual internal transformer faults.

**High voltage cables**

- Buried cables are vulnerable to soil deformations and their failure significantly impedes prompt restoration of supply. Cable repair process usually requires skilled crews, special equipment and is significantly longer than overhead lines repair works. Damaged cables may require construction of temporary overhead lines to reroute power supply during the repair works.

**Communications**

- A variety of communication mechanisms need to be used to keep in touch with staff. In this event, text messaging was more effective than phone communication due to the network being congested. Other methods, such as 0800 What To Do and and intranet page were also effective mechanisms, although not direct as text messaging
- A variety of communication mechanisms need to be used to keep in touch with field crews. There is limited use of radios at present but this will improve once it is made more explicit in the maintenance contactors agreements. In addition, an increase in the number of satellite phones will provide a strong alternative should it be required.

# 7 Recommendations

The following actions are recommended to improve Transpower understanding of the risks to its assets and the system as a whole, from a major earthquake event and to mitigate or reduce these risks as is reasonably practicable. This list also provides ecommendations aimed at improving the emergency preparedness and the organisational response following a disruptive event of similar amplitude:

**General**

- Transpower needs to continue to reduce the risk by removing or strengthening existing buildings or items of plant not complying with our seismic policy and to support the improvement of seismic design and construction standards in the electrical industry

**Seismic risk assessment**

- Transpower should ensure that the new values for seismic actions are used when designing future projects in the Christchurch region

**Flexible conductors**

- It is recommended that visual inspections be carried out in all substations to identify any flexible connections between equipment that are obviously too tight. It is understood that these inspections are already under way.
- It is also recommended that flexible connection design and installation guidelines are completed to ensure appropriate slack is provided with consideration to seismic aspects and electrical clearances. A project has been set up to prepare these guidelines.

**Equipment replacement**

- It is recommended that all instrument transformers with insulators held by "finger clamps" are replaced as this type of clamping is known to perform poorly during earthquakes.

**Buchholz relays**

- Transpower should decide whether it is required for relays not to falsely operate during rare and large earthquake. If that is the case, the specified acceleration levels should be reviewed and the performance of relays shall be demonstrated by shake-table tests reproducing the as-installed arrangement of the device.
- It is recommend that we should continue to purchase the ETI model relays for new Buchholz relay installations, unless it is decided that relays should remain stable during rare and large earthquake.

**High voltage cables**

- The following actions are recommended to improve Transpower understanding of the risks to its 220 kV underground cable circuits assets:

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  2) Leading from Item (1) above, develop technical standards that could be used to mitigate the probability of damage to underground cable circuits during a significant seismic event. Note: It is understood that PG&E and BC Hydro have put in place separate investigation initiatives in this field. We could benefit from coordinating our activities.

  3) Place a much greater emphasis on geotechnical studies during the development of 220 kV cable circuits and develop appropriate policies.

4) All optical fibre cables should be installed within separate plastic ducting, i.e. not buried direct – in Christchurch all these cables have now had to be abandoned and alternative protection communication paths sought.

**Communications**

- Staff contact lists should be regularly updated and should contain mobile phone numbers (company and personnal phones) as text messaging was found to be the most effective way of communication.
- Develop a coordinated approach on FleetLink radio and satellite phone for Transpower internal communication and communication with maintenance contractors after disruptive events.

# 8 Acknowledgements

The authors would like to thank staff of Transpower, Transfield, ABB, Orion and GNS for their assistance.

# 9 References

The following references were used for this report:

[1] Society of Structural Engineering (SESOC), Christchurch seismic design load levels, interim advice, April 2011.

[2] Liquefaction map, 22 February 2011 earthquake, Misko Cubrinovsky and Merrick Taylor, University of Canterbury, retrived from the NZSEE database.

[3] Fact sheet "Why buildings respond differently to earthquakes", IPENZ, March 2011

[4] Fact sheet "Christchurch earthquake – an overview", IPEN, March 2011

[5] Preliminary observation of the impacts of the 22 February Christchurch earthquake on organisations and the economy: a report from the field (22 February – 22 March 2011), Joanne R. Stevenson, Hlekiwe Kachali, Zachary Whitman, Erica Seville, John Vargo, & Thomas Wilson, University of Canterbury, Christchurch

# Appendix A Glossary

**Epicentre**: It is the point on the Earth's surface that is directly above the point where the earthquake originates.

**Hypocentre**: It is the position where the strain energy stored in the rock is first released, marking the point where the fault begins to rupture. This occurs at the focal depth below the *epicentre*.

**Lateral spreading (*Liquefaction* induced)**: It describes a lateral displacement of gently sloping ground as a result of earthquake-induced pore pressure built up or *liquefaction* in a shallow underlying deposit. Surface displacement proceed down-slope or towards a steep free face (such as a stream bank) with the formation of fissures and scarps. Horizontal displacement in lateral spread can range up to several meters with smaller associated settlements.

**Liquefaction (soil)**: It describes a phenomenon whereby a soil substantially loses strength and stiffness in response to an applied stress, usually earthquake shaking or other rapid loading, causing it to behave like a liquid. The phenomenon is most often observed in loose sandy soils. Liquefaction can cause damage to structures in several ways. Buildings whose foundations bear directly on sand which liquefies will experience a sudden loss of support, which will result in drastic and irregular settlement of the building. Liquefaction causes irregular settlements in the area liquefied, which can damage buildings and break underground utility lines where the differential settlements are large. Pipelines and ducts may float up through the liquefied sand.

**Modified Mercalli Intensity 7 (or MM VII)**: Difficult to stand or walk. Noticed by drivers of cars. Furniture broken. Damage to poorly built masonry buildings. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, unbraced parapets and porches. Some cracks in better masonry buildings. Waves on ponds.

**Modified Mercalli Intensity 8 (or MM VIII)**: Steering of cars affected. Extensive damage to unreinforced masonry buildings, including partial collapse. Fall of some masonry walls. Twisting, falling of chimneys and monuments. Wood frame houses moved on foundations if not bolted, loose partition walls throw out. Tree branches broken

**PGA**: Peak ground acceleration is a measure of earthquake acceleration on the ground and an important input parameter for earthquake engineering. Unlike the Richter magnitude scale, it is not a measure of the total size of the earthquake, but rather how hard the earth shakes in a given geographic area.

**Response spectrum**: A response spectrum is a plot of the peak response (usually acceleration) of a structure depending on the period (or frequency) of its main natural mode of oscillation and its intrinsic damping. Thus, if the natural period of a given structure is known, then the peak response of the structure can be estimated by reading the value from the response spectrum for the appropriate period.

**Return period**: It is an estimate of the interval of time between events of a certain intensity or size.

**Serviceability Limit State**: States that correspond to conditions beyond which specified service criteria for a structure or structural element are no longer met. The criteria are based on the intended use and may include limits on deformation, vibratory response, degradation or other physical aspects.

**Security**: a term used to describe the ability or capacity of a network to provide service after one or more equipment failures. It can be defined by deterministic planning criteria such as (n), (n-1), (n-2) security contingency. A security contingency of (n-m) at a particular location in the network means that m component failures can be tolerated without loss of service.

**Ultimate limit State**: States associated with collapse, or with other similar forms of structural failure. This generally corresponds to the maximum load-carrying resistance of a structure or structural element.

# Appendix B Log of Transpower response activities

TRANSPOWER ICAR - TP495

| ID | Version | Type |
|---|---|---|
| 7563 | Submitted | MER |
| **Event Date Time** | **Submitted Date Time** | |
| 22/02/2011 12:52 | 24/02/2011 01:20 | |
| **Region** | **Primary Location** | **Other Locations** |
| SI | BRY-ISL-1 | ADD,BRY,ISL,KAI,PAP |
| **Interruption** | **ITC No** | **Cause** |
| Yes | 7561 | Trippings due to 6.3 Earthquake 5km deep 10km south of ChCh |

**Description**

ADD T7, Feeders 42,62,122,142,172, BRY T5, T6, T2, T3, Feeders 92,122,142,182, ISL Feeders 222, 242, 932, KAI Feeders 4 & 7 tripped due to intial Earthquake.
Relay prot operated for ISL 222 & 242 O/C CBF & 932 Trip CCT 1 & 2 fail operated. KAI 4, 6 & 7 O/C Time operated

**Background**

NIL

**CB Operations**

ADD 72 30 42 62 122 142 172. BRY 802 492 842 532 162 38 62 35. ISL 222 242 932, KAI 4, 7

**Connected Parties Affected**

MainPower New Zealand Limited,Orion New Zealand Limited

**Protection Information**

ADD T7, BRY T2, T5,T6 Buch trip T3 HSB oper, ADD 42,62,142,172, BRY 92,122,142,182 1 Trip received, BRY492,532 Inst O/C,

| **Weather Code** | **Lightning?** |
|---|---|
| Some rain. Up to moderate winds | No |
| **Distance to Fault** | **Location of fault (Tower, Distance from)** |

**Distribution (Mandatory)**

MER_Recipients

**Distribution (Others)**

Lines S2 - Transfield Christchurch (Fax),Stations S3 - ABB Christchurch (Email),Stations S4 - Transfield Christchurch (Fax)

## Sequence

| Description | Date |
|---|---|
| ADD feeders Tripped during earthquake 42,62,122,142,172 all 66 kv ORN feeders | 22/02/2011 12:52 |
| ISL 66KV Fdrs 222, 242 Tripped ORN advised | 22/02/2011 12:52 |
| Earthquake centered at Lyttelton 6.3 magnitude. | 22/02/2011 12:52 |
| ADD T7 Tripped. Was 112 MW now 32 MW 80 MW lost. | 22/02/2011 12:52 |
| ISL 33 kv feeder tripped 932 advised ORN | 22/02/2011 12:52 |
| BRY T6, T5, T2, T3 Tripped LOS 66kv was 57 MW 11kv was 30 MW | 22/02/2011 12:52 |
| KAI 11 kv Feeders 4 & 7 tripped | 22/02/2011 12:55 |
| BEN T1 & T3 Earthquake bucholz alarms Contractor to inspect | 22/02/2011 12:55 |
| Called ABB to inspect BRY T5, T6, T2, T3, ADD T7 | 22/02/2011 12:59 |
| Requested TSL to inspect all their CHCH stations for earthquake damage | 22/02/2011 13:00 |
| Advised MPW KAI 11 kv feeders 4 and 7 Tripped | 22/02/2011 13:04 |
| Grid Emergency declared for ISL BRY PAP Grid Configuration | 22/02/2011 13:04 |
| Another Strong Canterbury earthquake SO and GAM advised | 22/02/2011 13:04 |
| SPN 1172, 1222 33kv feeders tripped. | 22/02/2011 13:06 |
| RFS BRY T4 after tripping of BRY T5 & T6 OS 4069 | 22/02/2011 13:06 |
| BRY - Contractor advised CVT 812 fallen over and staff leaving area due to Tsunami threat. | 22/02/2011 13:11 |
| EARTHQUAKE SMS and IRN Text sent. | 22/02/2011 13:15 |

TRANSPOWER **ICAR - TP495**

| | |
|---|---|
| Updated MPW on trippings and asked if any other problems in their network RCS could assist with | 22/02/2011 13:24 |
| Advised by J Hastie lines patrols under way for Christchurch circuits | 22/02/2011 13:26 |
| Call Care phoned to advise of Earthquake 6.3 and Tsunami warning. FTB notified. | 22/02/2011 13:34 |
| FTB and OTB warned of potential Tsunami | 22/02/2011 13:37 |
| Advised ADD T7 and site inspection completed. ADD T7 found no faults. ADD 147, 256 134 56 will require reclosing | 22/02/2011 13:45 |
| KAI 4 feeder RTS OS 4091 | 22/02/2011 13:46 |
| CTO Submitted for ISL 66 BS D ,PSO for ISL 66 BS change was ending 22/02/11 now 23/2/11 at 1700 hrs due to Earthquake | 22/02/2011 13:51 |
| Station inspections at KAI completed and no faults found | 22/02/2011 13:51 |
| Station inspections at BEN and OAM completed and no faults found | 22/02/2011 13:51 |
| Advised B Cox of BRY T5,T6,T2,T3 all tripped, ADD T7 tripped | 22/02/2011 14:02 |
| RTS ADD T7 & Select ADD T5 to HSB OS 4092 | 22/02/2011 14:16 |
| Station inspections at TIM & TMK completed and no faults found | 22/02/2011 14:31 |
| Station inspections at WTK STNS completed and no faults found | 22/02/2011 14:41 |
| BRY stn Inspection started delay due to traffic and communication problems | 22/02/2011 14:45 |
| Failure due to telecomms leased cct faulty at CHCH due to earthquake affecting COB RTU | 22/02/2011 14:50 |
| SPN T1 Tripped during another earthquake | 22/02/2011 14:50 |
| BEN T1 T3 Earthquake bucholz alarms Contractor again called for inspection | 22/02/2011 14:51 |
| NCC Advised of SPN T1 tripped during earthquake | 22/02/2011 14:56 |
| Lineman report all Canterbury CCTS flown over and all OK | 22/02/2011 15:00 |
| Station inspections at SBK completed and no faults found | 22/02/2011 15:01 |
| Reported to NCC BRY T5 & T6 OK,BRY T2 HT bushing broken, and CVT 812 fallen over with droppers detached | 22/02/2011 15:03 |
| ABB Reported BRY T2 HT bushing broken, and CVT 812 fallen over with droppers detached | 22/02/2011 15:03 |
| BEN T1 & T3 inspected OK | 22/02/2011 15:07 |
| Advised K Glover of BRY T5,T6,inspection and CVT 812 on side, ADD T7 tripped & RTS | 22/02/2011 15:20 |
| ADD 62 feeder Closed by ORN and tripped Flags Inst O/C | 22/02/2011 15:25 |
| ASY Contractor reports all okay | 22/02/2011 15:45 |
| PAP Contractor reports PAP T3&T4 foundation pads & Security fence have sunken into the ground rest of the station okay | 22/02/2011 15:49 |
| CTO Submitted for BRY-ISL 1 Manualled outage from 1600 to 2000 23/02/11 due to earthquake damage | 22/02/2011 15:57 |
| Opened BRY 72, 112, 172 to Clear 66KV Bus OS 4098 | 22/02/2011 16:08 |
| BRY-ISL 1 RFS OS 4094 | 22/02/2011 16:12 |
| EARTHQUAKE SMS Text sent | 22/02/2011 16:26 |
| CTO Submitted for BRY T5 out from now until 23-02-11 22:00 out on NCC request | 22/02/2011 16:51 |
| Contractor reports TWR 48 all OK on ISL-PAP 1 | 22/02/2011 16:54 |
| ISL 222 & 242 Closed By ORN, Hawthornden 1 & 2 RTS | 22/02/2011 17:00 |
| EARTHQUAKE SMS Text sent | 22/02/2011 17:01 |
| BRY 64 Opened due to T2 fault OS 4102 | 22/02/2011 17:07 |
| Instructed ORN to clear BRY 11KV Bus prior to livening after bank trippings during earthquake | 22/02/2011 17:10 |
| BRY T6 and 66KV Bus RTS OS 4101 | 22/02/2011 17:12 |
| Advised ORN BRY 66 & 11 Kv BS available to take load, ORN advised RCS no load will be applied till tomorrow | 22/02/2011 17:18 |
| BRY T3 and 11 KV Bus RTS OS 4103 | 22/02/2011 17:18 |
| BRY T4 RTS OS 4104 | 22/02/2011 17:25 |
| EARTHQUAKE IRN and SMS text sent | 22/02/2011 17:29 |
| CTO Submitted for BRY T5 was ending at 2100 now 1800 hrs | 22/02/2011 17:31 |
| BRY T5 RTS OS 4105 | 22/02/2011 17:33 |
| Station inspections at HOR completed and no faults found | 22/02/2011 17:55 |
| Advised GEN now ended for ADD, ISL, PAP, BRY stations | 22/02/2011 17:56 |
| BRY 92 Tripped on close OS 4108 Item 1 Cancelled | 22/02/2011 19:22 |
| BRY 122 Tripped on close OS 4109 Item 1 Cancelled | 22/02/2011 19:27 |
| BRY 172 Closed OS 4110 | 22/02/2011 22:37 |
| BRY 172 Tripped, O/C Neutral Time , ORN & NCC Security advised. | 22/02/2011 23:41 |
| BRY 172 RTS OS 4111. ORN Proving a cable on their system between Lancaster Park & Armagh St Subs. | 22/02/2011 23:44 |

## Comment Log

| Comment Text | Date | User |
|---|---|---|

Run By: coxb Page 2 of 3 Report Date: 11/05/2011 07:52

TRANSPOWER **ICAR - TP495**

| | | |
|---|---|---|
| Linked to event #11244 | 04/03/2011 16:13 | Malcolm Pettigrew |
| Form submitted | 24/02/2011 01:20 | Don Fraser |
| ORN 66KV and 11 KV feeders will be restored very slowly due to ORN having to check each cable | 23/02/2011 14:56 | Terry Hocking |

# TRANSPOWER ICAR - TP495

| ID | Version | Type |
|---|---|---|
| 7610 | Submitted | GOR |
| **Event Date Time** | **Submitted Date Time** | |
| 22/02/2011 12:52 | 01/03/2011 23:14 | |
| **Region** | **Primary Location** | **Other Locations** |
| SI | BRY | |
| **Interruption** | **ITC No** | **Cause** |
| No | | BRY DISCONNECTORS 817, 867 AND CVT 812 DAMAGE DURING EARTHQUAKE |

**Description**

BRY CVT 812 ( VT 4 ) WAS DISCOVERED ON ITS SIDE AFTER THE EARTHQUAKE INSPECTION, ALSO DISCONNECTOR 817 WAS NOT FULLY CLOSED AND DAMAGED, AS WAS BRY 867 DAMAGED

**Background**

EARTHQUAKE NEAR CHCH

**CB Operations**

BRY 812 ISL 432 for cct, BRY T5 & T6 802, 842, 532, 492

**Connected Parties Affected**

**Protection Information**

NIL

| Weather Code | Lightning? |
|---|---|
| Some rain. Up to moderate winds | No |
| **Distance to Fault** | **Location of fault (Tower, Distance from)** |

**Distribution (Mandatory)**

Jireh Consultants,Richard Prins

**Distribution (Others)**

Stations S3 - ABB Christchurch (Email)

## Sequence

| Description | Date |
|---|---|
| BRY T6, T5, T2 and ADD T7 Tripped on Bucholz operation, BRY T3 HSB operation, BRY T4 CBs remained closed | 22/02/2011 12:52 |
| Earthquake centered at Lyttelton 6.3 magnitude. | 22/02/2011 12:52 |
| Called ABB to inspect BRY T5, T6, T2, T3, ADD T7 | 22/02/2011 12:59 |
| BRY STN Inspection started, delay due to traffic and communication problems | 22/02/2011 14:45 |
| ABB Reported BRY T2 HT bushing broken with droppers detached , and CVT 812 ( VT 4 )fallen over | 22/02/2011 15:03 |
| Advised K Glover of BRY T5,T6,inspection and CVT 812 on side, ADD T7 tripped & RTS | 22/02/2011 15:20 |
| CTO Submitted for BRY-ISL 1 Manualled outage from 1600 to 2000 23/02/11 due to earthquake damage | 22/02/2011 15:57 |
| BRY-ISL 1 RFS OS 4094 | 22/02/2011 16:12 |
| Transferred OC 267A to R Johnson on BRY 812 | 23/02/2011 12:35 |
| CTO Submitted for BRY 807-817-897 BRY DIS 827 (CLO) Manualled outage from 1400 to 1600 to fix BRY 817 | 23/02/2011 12:39 |
| CTO Submitted for BRY-ISL 1 was ending 20:00 23/02/11 now 20:00 24/02/11 Contractor repairing CVT 812 | 23/02/2011 14:14 |
| RFS BRY 807-857 220 BS | 23/02/2011 14:37 |
| BRY 807-857 220 BS Transferred OC 269A to R Johnson | 23/02/2011 14:38 |

TRANSPOWER **ICAR - TP495**

| | |
|---|---|
| CTO Submitted for BRY 807-817-897 BRY DIS 827 (CLO) was ending 1600 now 20:00 24/02/11 Fault on BRY 817 | 23/02/2011 14:48 |
| Received OC 269B from D Munaka on BRY 807-857 220 BS | 24/02/2011 16:10 |
| CTO Submitted for BRY 220BS 827-847-917, BRY T6, BRY C6A. Manualled outage 08:00 25/02/11 to 16:30 for BRY 867 repair. | 24/02/2011 17:42 |
| Received OC 267B from R Johnson on BRY 812 | 24/02/2011 18:30 |
| PTP received for BRY VT 4 Test liven via BRY 812 OS 4150 | 24/02/2011 19:14 |
| CTO Submitted for BRY ISL 1 was ending at 2000 now 2030 hrs due to commissioning switching | 24/02/2011 19:20 |
| RTS BRY 220 BS 807-857, and Open BRY 827 OS 4122 | 24/02/2011 19:53 |
| BRY CVT 4 Test liven via BRY 812 OS 4150 | 24/02/2011 20:11 |
| ISL BRY 1 RTS OS 4097 | 24/02/2011 20:14 |
| BRY T6 and BRY C6A. RFS OS 4151 | 25/02/2011 08:01 |
| BRY 220 BS 827-847-917 RFS. OS 4151 complete. | 25/02/2011 08:26 |
| BRY 220 BS 827-847-917. Transferred OC 4152A to D Munyaka. | 25/02/2011 08:32 |
| CTO Submitted for BRY 220BS 827-847-917, BRY T6, BRY C6A. End time was 16:30 now 18:30. Work not completed. | 25/02/2011 14:10 |
| CTO Submitted for BRY 220BS 827-847-917, BRY T6, BRY C6A. End time was 18:30 now 19:30. Work not completed. | 25/02/2011 17:27 |
| BRY 220 BS 827-847-917. Received OC 4152B from D Munyaka. | 25/02/2011 18:55 |
| BRY 220 BS 827-847-917 RTS. OS 4153 | 25/02/2011 19:22 |
| BRY T6 and BRY C6A. RTS OS 4153 | 25/02/2011 19:26 |

## Comment Log

| Comment Text | Date | User |
|---|---|---|
| Linked to event #11244 | 07/03/2011 07:57 | Malcolm Pettigrew |
| Form submitted | 01/03/2011 23:14 | Wayne Burton |
| DAMAGE TO CVT 812 and 817 and 867 was done during the earthquake refer to MER 7563 | 26/02/2011 01:41 | Terry Hocking |

# TRANSPOWER ICAR - TP495

| ID | Version | Type |
|---|---|---|
| 7609 | Submitted | GOR |
| **Event Date Time** | **Submitted Date Time** | |
| 22/02/2011 12:52 | 03/03/2011 16:19 | |
| **Region** | **Primary Location** | **Other Locations** |
| SI | BRY | |
| **Interruption** | **ITC No** | **Cause** |
| Yes | 7562 | EARTHQUAKE NEAR CHCH |

**Description**

TRIPPING OF T2, AND T3 66KV TO 11KV SUPPLY, TOTAL LOS TO BRY 66KV AND 11KV BUSES

**Background**

EARTHQUAKE

**CB Operations**

BRY BANKS T3 and T4 CBs 62,35,162,38 and BRY T5 and T6 CBs 842,532,802,492

**Connected Parties Affected**

Orion New Zealand Limited

**Protection Information**

BRY T6, T5, T2 and ADD T7 Tripped on Bucholz operation, BRY T3 HSB operation, BRY T4 CBs remained closed

| Weather Code | Lightning? |
|---|---|
| Some rain. Up to moderate winds | No |
| **Distance to Fault** | **Location of fault (Tower, Distance from)** |

**Distribution (Mandatory)**

Jireh Consultants,Richard Prins

**Distribution (Others)**

Stations S3 - ABB Christchurch (Email)

## Sequence

| Description | Date |
|---|---|
| Tripping of BRY T6, T5, T2, T3 , Total LOS OF 66kv was 57 MW and 11kv was 30 MW due to 6.3 Earthquake | 22/02/2011 12:52 |
| Called ABB to inspect BRY T5, T6, T2, T3, banks | 22/02/2011 12:59 |
| Grid Emergency declared for ISL BRY PAP Grid Configuration | 22/02/2011 13:04 |
| BRY - Contractor advised CVT 812 fallen over and staff leaving area due to Tsunami threat. | 22/02/2011 13:04 |
| EARTHQUAKE IRN and SMS Text sent. | 22/02/2011 13:15 |
| Advised B Cox of BRY T5,T6,T2,T3 all tripped | 22/02/2011 14:02 |
| BRY STN Inspection started delay due to traffic and communication problems | 22/02/2011 14:45 |
| ABB Reported BRY T2 HT bushing broken, and CVT 812 fallen over with droppers detached | 22/02/2011 15:03 |
| Reported to NCC BRY T5 & T6 OK,BRY T2 HT bushing broken, and CVT 812 fallen over with droppers detached | 22/02/2011 15:03 |
| Advised K Glover of BRY T5,T6,inspection and CVT 812 on side, ADD T7 tripped & RTS | 22/02/2011 15:20 |
| CTO Submitted for BRY T2 was starting at 1700 hrs ending at 21:00 23/02/11 Broken HV bushing | 22/02/2011 16:35 |
| BRY 64 Opened due to T2 fault OS 4102 | 22/02/2011 17:07 |
| Advised ORN BRY 66 & 11 Kv BS available to take load, ORN advised RCS no load will be applied till tomorrow | 22/02/2011 17:18 |
| BRY T3 and 11 KV Bus RTS OS 4103 | 22/02/2011 17:18 |
| BRY T6 and 66KV Bus RTS OS 4101 | 22/02/2011 17:18 |
| CTO Submitted for BRY T2 was ending 21:00 23/02/2011 now 21:00 24/02/11 Broken HV | 23/02/2011 14:46 |

TRANSPOWER ICAR - TP495

| | |
|---|---|
| bushing | |
| CTO Submitted for BRY T2. End time was 21:00 24/2/11 now 03/03/11 21:00. Structural assessments to be done. | 24/02/2011 17:52 |
| Received OC 4128B BRY T2 from R Johnson | 03/03/2011 14:45 |
| CTO Submitted for BRY T2 end was 2100 now 1530 | 03/03/2011 14:51 |
| BRY T2 RTS OS 4239 | 03/03/2011 15:15 |

## Comment Log

| Comment Text | Date | User |
|---|---|---|
| Linked to event #11244 | 07/03/2011 08:03 | Malcolm Pettigrew |
| Form submitted | 03/03/2011 16:19 | Chris McClelland |
| MER 7563 contains more detail about total earthquake trippings and restoration of supply | 23/02/2011 23:42 | Terry Hocking |

# Appendix C Suggested studies on faulted 66 kV cables

Collect background information: i) what was load and calculated temperature just before the earthquake; if the cable was near to its operational temperature then there is a remote chance that a little of mechanical strain memory of the earthquake may still be present in the XLPE, just like an un-shrunk heat shrink tube. ii) was the DTS equipment operational, this is potentialy very interesting as, depending on the memory storage, if any, an optical expert might be able to work out what strain occurred in the fibres just before they snapped.

1) Get a panel of expert analysts together to examine cables, who have their own and who have contact with other expert establishments as well as cable experts to plan what to do, as it is unlikely that another set of earthquake samples will become available soon and as the results may well help to form the basis of recommendations (NZ, CIGRE etc) on cable and installation design and perhaps on a special proving test.

2) Try to avoid tests that wipe the mechanical and thermal memory and contaminate the sample, such as transparentisation in hot oil.

3) Get a professional photographer to photo the samples from all angles with and without a new slim metric steel rule present. These will be ideal for technical publications and presentations and for appropriate persons in your companies to 'dine out' on.

4) If there is enough of the electrical faulted sample remaining, then look to see if pre-fault fracture morphology is present (i.e. the 'mirror' and 'hackle' fracture faces of initial elastic and rapid brittle failure).

5) Measure and digitally record the outer shape of the samples using a high quality 3D electronic measuring table to obtain a 3D image of the sort that medical people use for the human head, using laser light for example.

6) Use X-radiography, not gamma radiography, as the former has much better definition. You will need a powerful fixed installation X-ray set to penetrate a lead sheath, but we used to do this on sub sea cables. If you can perform 3D tomography and take a digital record, much as the medical people do these days. This will show you what has happened to the conductor and if you are lucky what has happened to the screen thicknesses.

7) 3D ultrasonic inspection could be applied on the extruded cable core to see if the insulation and insulation/interfaces have sheared. A tiny shear plane of only 12 Angstroms will reflect perfectly. The IPEC Ultrasense equipment was quite capable of doing this ten years ago, although I understand that the company has moved on.

8) Only at this stage decide where to slice the samples.

9) Microtoming and leather slicing (a blade in a 'shaping' machine) are the standard cutting methods. Small samples can be examined by SEM and EDX on the same machine to look at the microstructure to see if the morphology has been disrupted and dislocated on the molecular level (whether the folded chains have been stretched open). The act of cutting smears the surface, so a chemical etching process or Nitrogen rupture technique is required to prepare the samples. The people I know who can do this are Reading (BICC sponsored the morphological research) University and Southampton (the Reading expert moved here) and and ERA. Samples would be looked at in several orthogonal planes.

10) Optical microscopy inspection by polarised light shows the inherent morphology from extrusion, the flow and knit lines from the particular triple die. Samples from the damaged area and a remote area would be compared to see if the material had been stretched and if so in what direction.

11) The standard cable tests would be performed, but to greater precision. Hot sets and ageing tests to look at degree of cross-linking (has fission of the links occurred) compared to a remote sample.

12) DSC analysis and thermo-gravimetric analysis heats the samples and analyses the memory of the stored energy.

13) Standard dynamic mechanical tests for rubber and plastics subject the sample to high frequency mechanical strain and measure the 'real' component of deformation (viscous part of the material that produces heat loss) and 'apparent' part (elastic component that stores recoverable energy).

14) In a similar way dielectric spectroscopy subjects a small sample to a low electric stress and subjects it to a frequency scan to characterise the particular sample (real and imaginary components of loss i.e. its power factor/loss tangent).

15) You could lathe cut and produce a swiss roll tape to measure the 'electricals' and bd strength, but I think that this could wreck the sample for the detailed mechanical and morphological testing.