4 September 2010 and 22 February 2011 Christchurch earthquakes from a transmission infrastructure perspective: asset structural performance and lessons learned

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Abstract

A magnitude 7.1 earthquake struck the Canterbury region of the South Island at 4:36am on Saturday 4 September 2010 causing significant damage to buildings and infrastructure throughout the region. A further magnitude 6.3 earthquake struck the city of Christchurch at 12:51pm on Tuesday 22 February 2011. That earthquake caused a large number of fatalities and widespread damage with the collapse of many buildings in the CBD and significant disruption of lifelines.

These two events challenged the resilience of the transmission infrastructures in the Canterbury and northern South Island region. Some of the most important assets of the South Island grid backbone are located in the Christchurch region with Islington substation, a major node, supplying a high percentage of the load to Christchurch, Nelson, Marlborough and the West Coast. These earthquakes also tested the structural resilience of the transmission grid exit points serving high population areas (nine in the Christchurch region) and Transpower's ability to have them back up and running promptly after these events.

From a seismic perspective substations are the most critical and potentially the most vulnerable infrastructures of our transmission network. Substations are designed to remain operational after rare and severe earthquakes as required by Transpower seismic policy, complying with the latest codes and the Civil Defence Emergency Management Act.

The main purpose of this paper is to discuss the structural performance of the transmission assets during these two events, outlining the damage suffered, and a comparison of the actual performance against the design and expected performance requirements. The two events will be put in perspective with their features (magnitude, spectral accelerations and location) compared.

Finally the paper will outline the key lessons learned from these events from a transmission assets perspective.

1 Introduction

Transpower New Zealand owns and operates the high voltage electricity transmission grid in New Zealand. This includes critical assets, such as Islington substation, in the Canterbury region of the South Island that were affected by the earthquakes of 4 September 2010 and 22 February 2011.

The impact of the both earthquakes on the electrical stability and operation of both the National Grid and regional supply was negligible. Power to the National Grid was unaffected, while power to the feeders into Christchurch City and regional substations was unavailable for up to 4.5 hours while safety checks and minor repairs were made. The supply at the grid exit points was restored at full capacity and n-1 security, except at Bromley substation where supply was restored with n security following the 22 February 2011 earthquake.

The good electrical performance was mirrored by the structural performance of the transmission assets with minor damage being recorded. In most cases, the damage did not affect the operation of the grid and repairs were able to be deferred until after the aftershocks had abated.

This paper outlines the structural performance of Transpower's transmission assets, highlighting examples of damage incurred and drawing comparisons between actual and expected (design) performance. Finally the report identifies key lessons learned.

2 Critical transmission infrastructures during earthquakes

Key transmission assets comprise transmission lines and substations. From experience in New Zealand and overseas, transmission lines are generally resilient to earthquake, as seismic actions on transmission towers are typically less severe than high (design) wind loads. Furthermore transmission lines have reasonably flexible structural systems and can generally accommodate a higher level of ground deformation (liquefaction, surface rupture) than substations structures.

On the contrary, again from past New Zealand and overseas experience, transmission substations are frequently subject to damage from large earthquakes. Substation switchyards generally contain heavy electrical equipment; with most of them containing critical components made of brittle materials such as porcelain or sensitive operational mechanisms. Furthermore the seismic response of some substation equipment can be amplified significantly as they are usually mounted on tall flexible cantilever stands required to provide electrical clearances. New electrical equipment is carefully designed to withstand seismic actions and transmission utilities generally require essential equipment they purchase to be qualified according to international seismic standards. Although small light equipment can generally be replaced by spares promptly after earthquakes, it could take several months to replace some of the largest equipment (e.g. power transformers).

Switchyard equipment is typically controlled and operated from the control/relay building adjacent to the switchyard. Therefore, from an operational point of view, substation buildings are as critical as outdoor equipment they service. The collapse of the control/relay building is likely to prevent the supply of electricity to the distribution network for weeks or months until temporary measures are put in place and some of the repair work is completed.

3 An overview of Transpower seismic policy

The current Transpower Seismic Policy TP.GG 61.02 requires all essential substation equipment and substation buildings to remain fully operational and retain security[1] when subject to a "Serviceability Limit State" (SLS) level earthquake[2], that is an earthquake defined as having a return period[3] of 500 years. Essential equipment and facilities shall survive an "Ultimate Limit State" (ULS) event[4], defined as having a return period of 2,500 years, although some repairable damage is tolerated. This applies to all new assets. The policy also extends these requirements to existing buildings. Where existing essential buildings are found to have a seismic capacity less than 75% of new building standard they should be upgraded as near as reasonably practicable to 100% of new building standard, but under no circumstance less than 75%.

Transpower policy is aligned with the requirements from the New Zealand Standard 1170.5:2004 "Structural design actions – Earthquake" for structures having post-disaster functions.

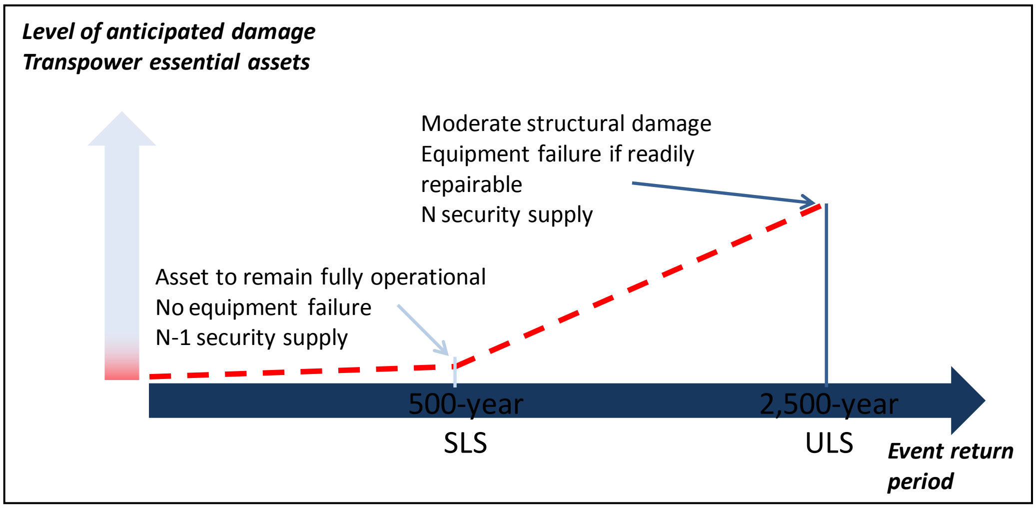

Figure 1: Overview of Transpower seismic policy

The legislative drivers behind Transpower requirements are:

- The Civil Defence and Emergency Management Act 2002 that requires Transpower, as a lifeline utility, to ensure it is able to function to the fullest possible extent, even though this may be at a reduced level, during and after an emergency. Transpower has classified some buildings as "essential facilities", the failure of which could disable a substation with the consequential inability to supply electricity for a considerable period of time.

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[1] 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.

[2] 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.

[3] Return period: a 500-year return period earthquake is the most severe earthquake that statistically is likely to occur during a period of 500 years.

[4] 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.

- The Building Act 2004 and associated regulations that require the establishment and implementation of earthquake-prone building policies.

4 Structural damage following Christchurch earthquakes

Transpower assets suffered relatively minor damage following the 4 September 2010 and 22 February 2011 Christchurch earthquakes. Damage to Transpower substations included minor cracking of reinforced concrete buildings, non-structural building damage such as broken windows, fallen suspended ceiling tiles and light fittings and settlement damage due to liquefaction. Damage to primary plant included failure of candle-stick equipment (one 220 kV current voltage transformer), transformer mounted equipment (one 220 kV surge arrester and one 66 kV bushing) and damage to an 11 kV switchboard – as further described in the following sections.

Figure 2 below shows Transpower substations in the area affected by the 4 September 2010 and 22 February 2011 Christchurch earthquakes and their proximity to the epicentres.

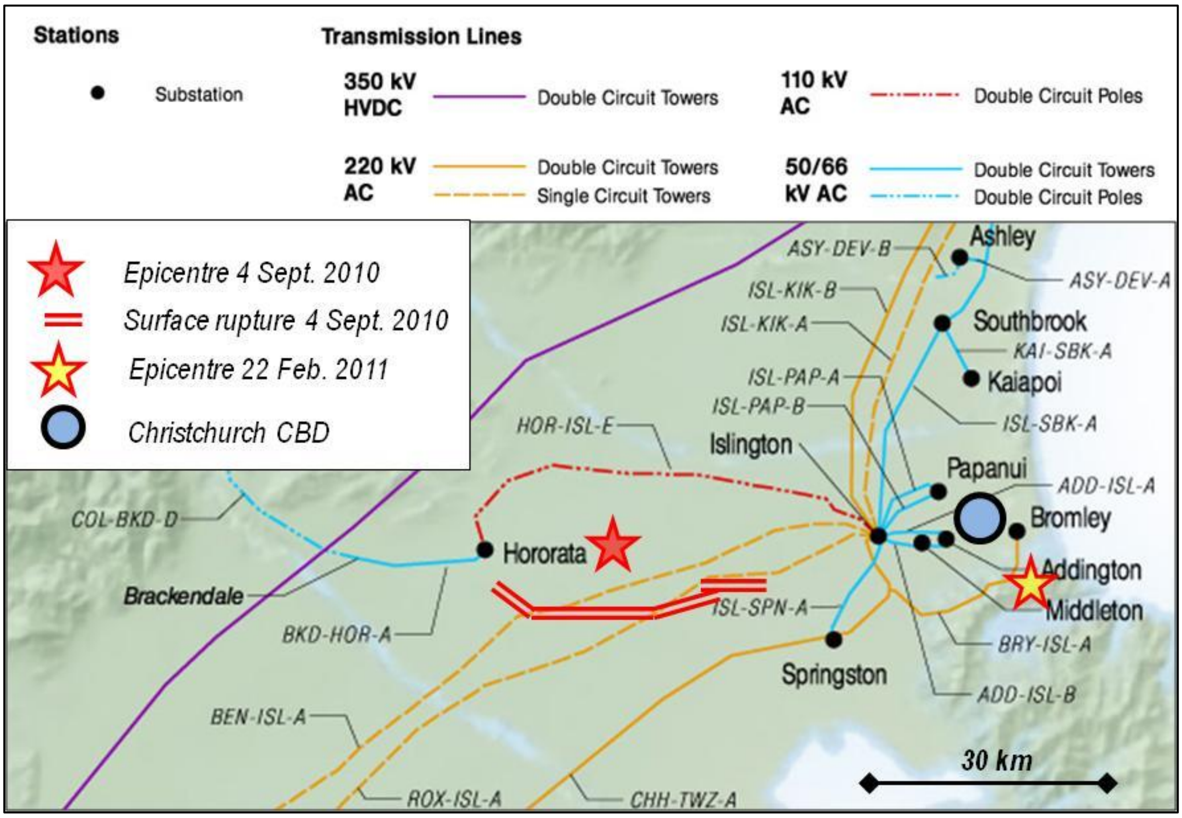

Figure 2: Transpower assets (substations and transmission lines) affected by the 4 September 2010 and 22 February 2011 earthquakes

4.1 Transmission substations

4.1.1 Hororata substation

Hororata is the closest Transpower substation to the 4 September 2010 earthquake epicentre. Intense ground shaking was recorded in the area with Peak Ground Accelerations (PGA) of up to 0.81g being recorded.

The reinforced concrete condenser hall building constructed in the 1940s suffered minor cracking in shear walls and in the legs of the portal frames and a significant number of windows were broken. Unrestrained spare equipment inside the building also sustained damage.

One of the lessons learned from the 1987 Edgecumbe earthquake was that transformers and heavy plant were at risk if not properly seismically restrained. A 10-year retrofit program was subsequently implemented to address the issue. The result of this earlier work is that the transformer banks had been retrofitted with seismic restraints and the restraints performed well during the 04 September 2010 and 22 February 2011 earthquakes, as shown in Figure 3 below.

(a)  (b) 

Figure 3: (Photos: Transpower)
(a) Hororata Substation: transformer banks retrofitted with proper seismic restrains performed well
(b) Edgecumbe substation after the 1987 Edgecumbe earthquake: transformers were not seismically restrained and toppled off their pedestal.

Hororata substation did not suffer any damage following the 22 February 2011 earthquake.

4.1.2 Islington substation

Islington is the main nodal substation in the south island and was the largest and most important of Transpower substations that were affected by the 4 September 2010 earthquake.

A surge arrester mounted on the SVC9 red phase transformer at Islington was damaged. The failure of the surge arrester did not result in an immediate outage even though the porcelain housing had cracked at the base, as shown below in Figure 4. Only very minor superficial cracking damage occurred to the reinforced concrete buildings at the substation.

(a)  (b) 

Figure 4: Islington Substation (Photos: Transpower)
(a) overview of the SVC transformer banks
(b) close-up on the surge arrester that failed.

Islington substation did not suffer any damage following the 22 February 2011 earthquake.

4.1.3 Papanui substation

The southern end of the switchyard was affected by liquefaction following the 4 September 2010 earthquake. Settlement resulting from the liquefaction damaged the oil containment bund to transformer T4 as shown in Figure 5 below. The foundations of the terminal towers on both ISL-PAP A&B 66kV lines were strengthened in 2008 with the addition of 20m deep steel screw piles. Although the liquefaction around the tower foundations was extensive there was no discernable damage to the foundations.

Failure of the eyebolt attaching the red phase of the terminal span of the ISL-PAP B 66 kV transmission line circuit 4 to the substation gantry structure caused a fault as the conductor fell down onto another phase. The shortness of the terminal span (15m) and tightness of the conductors to achieve clearance contributed to the failure. The eyebolt was subsequently replaced by a spring bolt as shown in the photo below.

Only very minor cracking occurred to buildings at the substation, with the exception of the concrete floor slab of the earthing equipment shed, which broke in two and will need to be replaced.

(a)  (b) 

(c) 

Figure 5: Papanui Substation (Photos: Transpower)
(a) termination span; cct1 is in the foreground, cct3 and cct4 are in the background
(b) eye nut attachment to gantry identical to the one that failed
(c) T4 bund cracked due to differential settlement.

Papanui substation did not suffer any further damage following the 22 February 2011 earthquake.

4.1.4 Bromley substation

Bromley substation sustained negligible structural damage and minor soil liquefaction during the 4 September 2010 earthquake. However, located only 5km from the 22 February 2011 earthquake epicentre, the substation suffered structural damage to 4 items of equipment due to intense ground shaking, as shown in Figure 6 below. The 220kV CVT and 66kV bushings were replaced with spares. A new 11kV switchgear building is to be constructed, to enable replacement of the existing damaged but serviceable switchgear. The damage at Bromley did not prevent supply of power, but did reduce the system to n security until the CVT was replaced.

The switchyard was affected by intense liquefaction effects without apparent damage to equipment foundations.

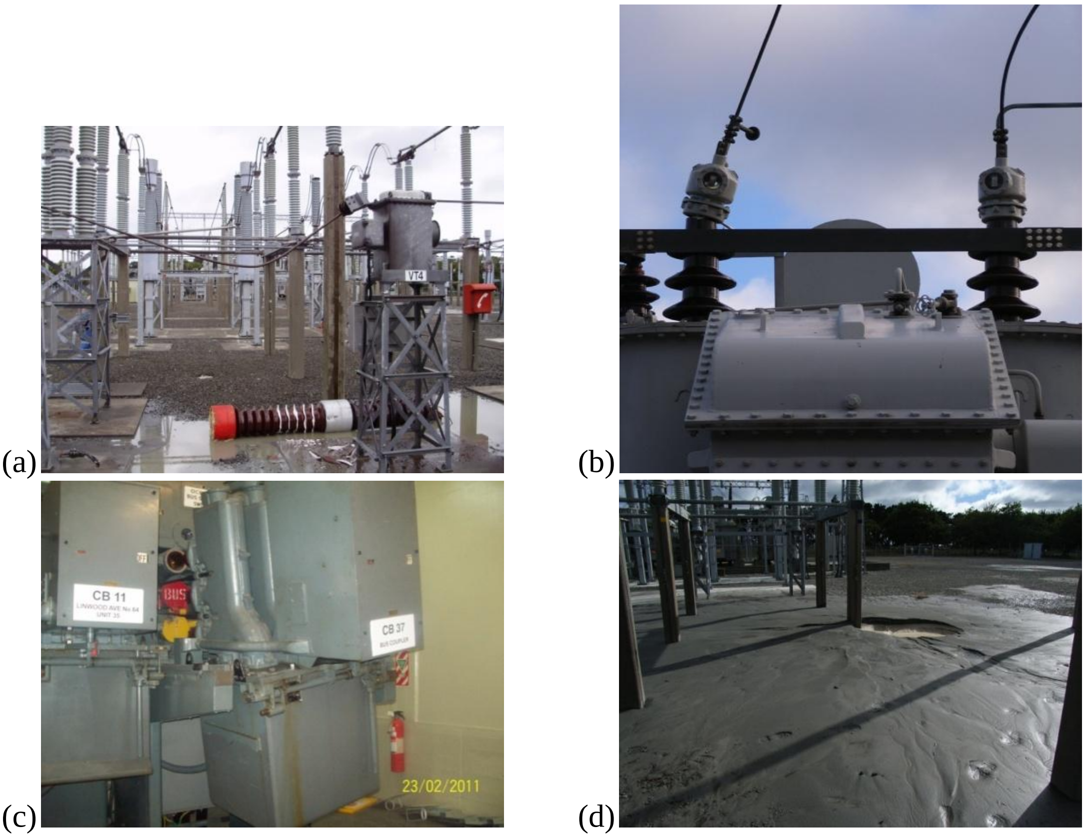

Figure 6: Bromley Substation (Photos: Transpower)
(a) 220 kV failed current voltage transformer
(b) failed 66 kV transformer bushing, snapped at its top
(c) damage to a 11 kV switch board with hold-down bolts pulled out of concrete; the switchgear remained operational during and after the earthquake
(d) severe liquefaction in switchyard with silt, sand and water erupting from ground; this did not cause significant damage to switchyard foundations.

4.2 Transmission lines

A number of transmission towers were affected following the 4 September 2010 earthquake by surface rupture, liquefaction induced settlement and/or lateral spreading resulting in tilting towers; suspension insulators being pulled out of alignment and in once case, a bent earth peak as detailed in Sections 4.2.1 and 4.2.2 below. This moderate level of damage did not have any effect on the performance of the lines during or after the earthquake. It confirms what has been noticed after similar earthquakes overseas that the transmission lines are generally more resilient to seismic events than substation assets.

Although further liquefaction affected the Bromley – Islington A 220 kV line following the 22 February 2011 earthquake, it did not cause any further damage and did not affect the performance of the line.

4.2.1 Bromley – Islington A line (220kV)

Following the 4 September 2010 earthquake extensive liquefaction occurred in the area between towers 44 and 64 causing differential settlement of tower footings resulting in tilting of towers 44, 53 and 54. Tower 44 was temporary guyed to concrete blocks; no other immediate actions were required. Intense liquefaction also occurred following the 22 February 2011 at towers 1, 2 (close to Bromley substation) and Tower 11 without causing apparent damage. Refer to Figure 7 below.

(a)  (b) 

Figure 7: Bromley-Islington A line (Photos: Transpower)
(a) Tower 44 with liquefaction leaving gaps around footings - 4 September 2010 earthquake
(b) Tower 1 with effects of liquefaction: ejected silt and soil settlement – 22 February 2011 earthquake.

4.2.2 Roxburgh – Islington A and Benmore – Islington A lines (220kV)

The earthquake of 4 September 2010 originated on the previously unknown Greendale fault. The fault trace crossed both ROX-ISL A and BEN-ISL A 220kV transmission line routes with strike-slip displacements of up to 4m in the surface rupture zone. This caused additional distance to be added between towers 1013 to 1028 on ROX-ISL A line and towers 597 to 605 BEN-ISL A line, resulting in increased conductor tensions and insulators pulled out of vertical alignment

(a)  (b) 

Figure 8: Roxburgh-Islington A line
(a) Surface rupture passing at short distance from tower A1022 (courtesy of GNS)
(b) Misaligned suspension insulators at tower A1022 (Photos: Transpower).

Refer to Figure 8 above for examples of ground rupture and insulator swing. In addition, towers 600 and 601 on the BEN-ISL A line sustained structural damage in the form of bent earth peaks as shown in Figure 9 and will need to be repaired. The damage did not affect the performance of the lines and did not require immediate actions. The insulators shall be re-clipped in the vertical position following cessation of the aftershocks, subject to confirmation of acceptable conductor tensions.

(a) 

Figure 9: Benmore-Islington A line (Photos: Transpower)
(a) Earth peak bent on tower 600.

5 Structural damage vs. performance requirements

Although the vast majority of Transpower's buildings affected by the 4 September 2010 and 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. However, the few equipment failures sustained during the 4 September 2010 earthquake are regarded as not meeting the current performance requirements, although they did not significantly impact of the operation of the grid and supply of electricity to the feeders in the Canterbury region. The damage suffered during the earthquake of the 22 February 2011 was to be expected given the much larger peak ground accelerations experienced in Christchurch City.

Hororata, the nearest substation from the 4 September 2010 epicentre (15km), experienced strong horizontal and vertical ground shaking. From GNS recordings at Hororata School the earthquake response spectra[5] correspond approximately to 75% of Transpower's current Ultimate Limit State level (return period 2500 years) for the 0.0 to 0.3s period range where most of substation structure and equipment fall, see Figure 10 below. Only minor damage to the building was sustained. There was no equipment failure. Hence, the building and equipment met the current performance criteria. The ground shaking at Hororata resulting from the 22 February 2011 earthquake was well below the SLS level earthquake as shown in the spectral response, Figure 10 below, and as such no damage was sustained.

[5] 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.

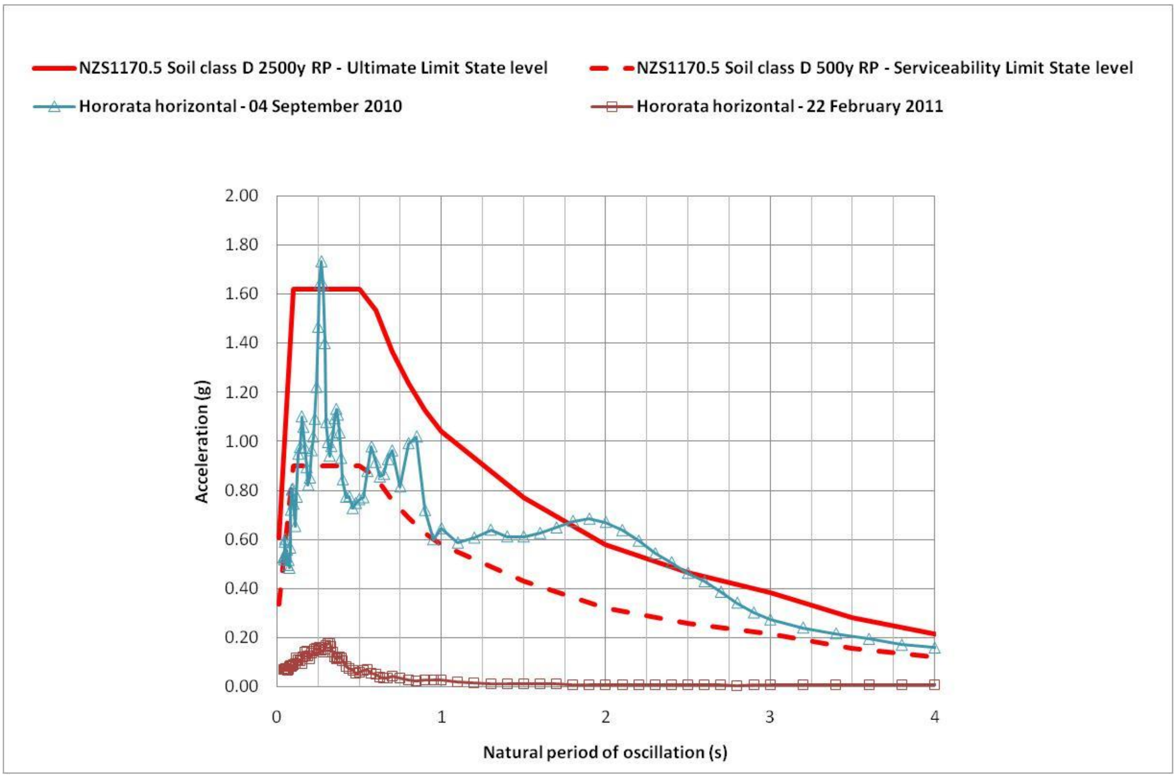

Figure 10: 4 September 2010 and 22 February 2011 earthquakes - Hororata substation. Response spectra at 5% of critical damping (from GNS) compared with NZS1170.5 ULS and SLS requirements for the site

The substations closer to the CBD area during the 4 September 2010 earthquake or north and west from the CBD during the 22 February 2011 earthquake generally experienced shaking corresponding to Transpower's current Serviceability Limit State level (return period 500 years) for the 0.0 to 0.3s period range. The Figures 11 and 12 below shows the response spectra at Papanui substation (4km north of the CBD) and Bromley substation (5km east of the CBD) for both earthquakes respectively. 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 terminal span failure at Papanui substation and the 220kV surge arrestor failure at Islington during the 4 September 2010 earthquake.

However, Bromley, the nearest substation from 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 12 below.

At Bromley no 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 that is tolerated by the seismic policy. Hence buildings and equipment met the current performance criteria at ultimate limit state level.

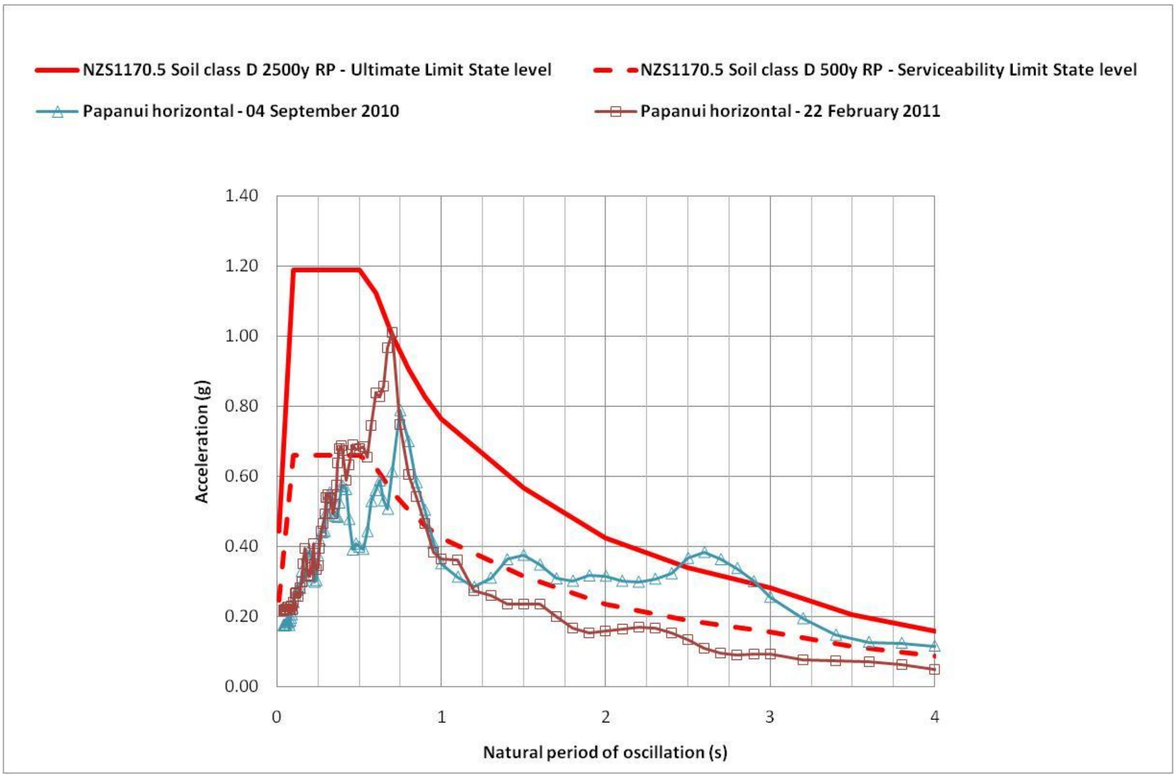

Figure 11: 4 September 2010 and 22 February 2011 earthquakes - Papanui Substation. Response spectra at 5% of critical damping (from GNS) compared with NZS1170.5 ULS and SLS requirements for the site

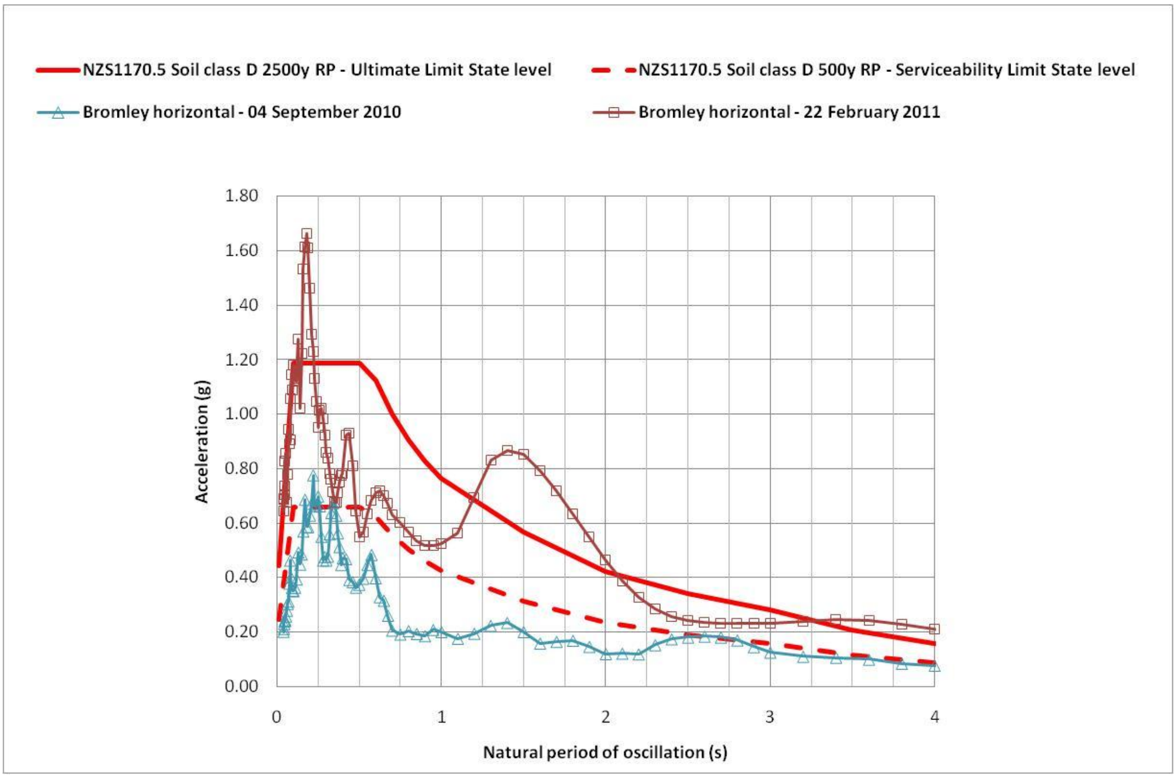

Figure 12: 4 September 2010 and 22 February 2011 earthquakes - Bromley substation. Response spectra at 5% of critical damping (from GNS) compared with NZS1170.5 ULS and SLS requirements for the site

6 Lessons learned – from an asset structural performance perspective

- Overall Transpower assets did not suffer serious damage and system interruption was minimal.
- These events highlighted the reliance on existing aged transmission infrastructures. Although most were designed and installed prior to Transpower's current seismic policy, they met or exceeded the current performance criteria.
- The implementation of the lessons learned following the 1987 Edgecumbe earthquake, the seismic restraint retrofit programme, was demonstrably worthwhile.
- Transpower needs to continue to reduce the risk by removing or strengthening existing buildings or items of plant not complying with our current seismic policy.

7 Conclusion

In conclusion, the electricity transmission infrastructures performed well, meeting Transpower current performance criteria.

Most of our 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 even better than what they were strictly designed or expected to. Design margins, good construction workmanship, adequate maintenance and seismic restraints retrofit programme are likely to have all contributed to the good performance.

These events did highlight the reliance on existing aged infrastructures. Unfortunately their good performance these events does not provide certainty on how well our equipment, systems and buildings would perform in another event of similar or greater magnitude.

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.