Bulletin of the New Zealand Society for Earthquake Engineering, Vol. XX, No. Y, Month 2017

IMPACT OF THE KAIKŌURA EARTHQUAKE ON THE ELECTRICAL POWER SYSTEM INFRASTRUCTURE

Yang Liu[1], Nirmal-Kumar Nair[1], Andrew Renton[2] and Stuart Wilson[3]

(Submitted *March 2017*; Reviewed *April 2017*; Accepted *May 2017*)

ABSTRACT

This paper summarizes the impact the 2016 Kaikōura earthquakes have had on electrical transmission and distribution infrastructure performance. It also provides background context to the distribution network operator, MainPower's, prior earthquake preparedness following the 2010 earthquakes in the region.

INTRODUCTION

The M_w7.8 Kaikōura earthquake that occurred at 12:02 a.m. on 14th of November 2016 struck the upper South Island of New Zealand with effects spreading to Wellington and Christchurch. In the immediate aftermath, the earthquake caused loss of the electricity supply to almost 7,000 homes and businesses located in Hanmer Springs, Kaikōura, Waiau, Culverden, Cheviot and the surrounding areas. Power was restored to much of the main townships by the end of the day.

MainPower New Zealand Limited (MainPower) owns the distribution and sub-transmission electricity systems in Kaikōura. National electricity transmission assets operated by Transpower New Zealand Limited (Transpower) were also affected by the earthquake. This paper firstly presents an overview of the regional electricity transmission and distribution network, which is then followed by some background information about the Kaikōura earthquake. Thereafter the major operational impact and damage to Transpower's network are identified, followed by a discussion on the mitigation actions taken. Finally detailed information on the impact of the earthquake on MainPower's distribution network assets is discussed. The distribution network's preparedness in regards to seismic events following the Canterbury Earthquake Sequence is also analysed in the context of the observed damage to electricity assets. This is followed by a discussion of the interdependency impacts with communication infrastructure.

REGIONAL TRANSMISSION AND DISTRIBUTION

Transmission and Distribution services to within, and across the Christchurch and North Canterbury regions are provided by Transpower and MainPower respectively.

Crossing the region as it heads north from Benmore Power Station to the South Island cable station is Transpower's overhead high-voltage direct-current (HVDC) transmission line.

Due to its generation resource imbalance between South and North Island, New Zealand has power flow transfers between the islands by a bi-pole HVDC transmission system. Transmission of power through the rest of the country is carried by an alternating current (AC) transmission system. The HVDC Inter-Island link therefore transports hydro power produced from South Island, which accounts for almost 60 percent of the total generation, to the North Island where the major population is inhabited. The transmission line passes through Weka Pass into the Amuri district, travelling north through the region, west of Culverden, to Hanmer Springs. From here, the line turns north-east and travels through Molesworth Station into Marlborough and down the Awatere River valley, before turning north to meet State Highway 1 through the Dashwood and Wards Passes. The line travels east of Blenheim, meeting the eastern coast of the island at Cloudy Bay, and travelling up the coast into the Marlborough Sounds.

The majority of electricity provided to the Christchurch and North Canterbury region is supplied from generation in the south via Transpower's 220kV network.

From the Christchurch Islington substation three 220kV transmission circuits supported on single and double circuit lattice steel towers traverse North Canterbury stopping at Grid Exit Point (GXP) substation Waipara and Culverden on their way north to Kikiwa substation in the Nelson region. Islington, Waipara and Culverden provide points of interconnection between the main 220kV transmission network and the regional 66kV network, as shown in Figure 1.

The regional 66kV network consists of a double circuit tower line that runs from Islington in the south to Waipara in the north via smaller 66kV GXP substations of Southbrook and Ashley. A spur 66kV Connection is provided at Transpower's GXP substation at Culverden for MainPower's line to Kaikōura, as shown in Figure 3.

[1] *Research Engineer, University of Auckland*
[2] *Corresponding Author, Associate Professor, University of Auckland, N.Nair@auckland.ac.nz*
[3] *Senior Principal Engineer, Transpower New Zealand Ltd.*
[4] *Grid Manager Development, MainPower New Zealand Ltd.*

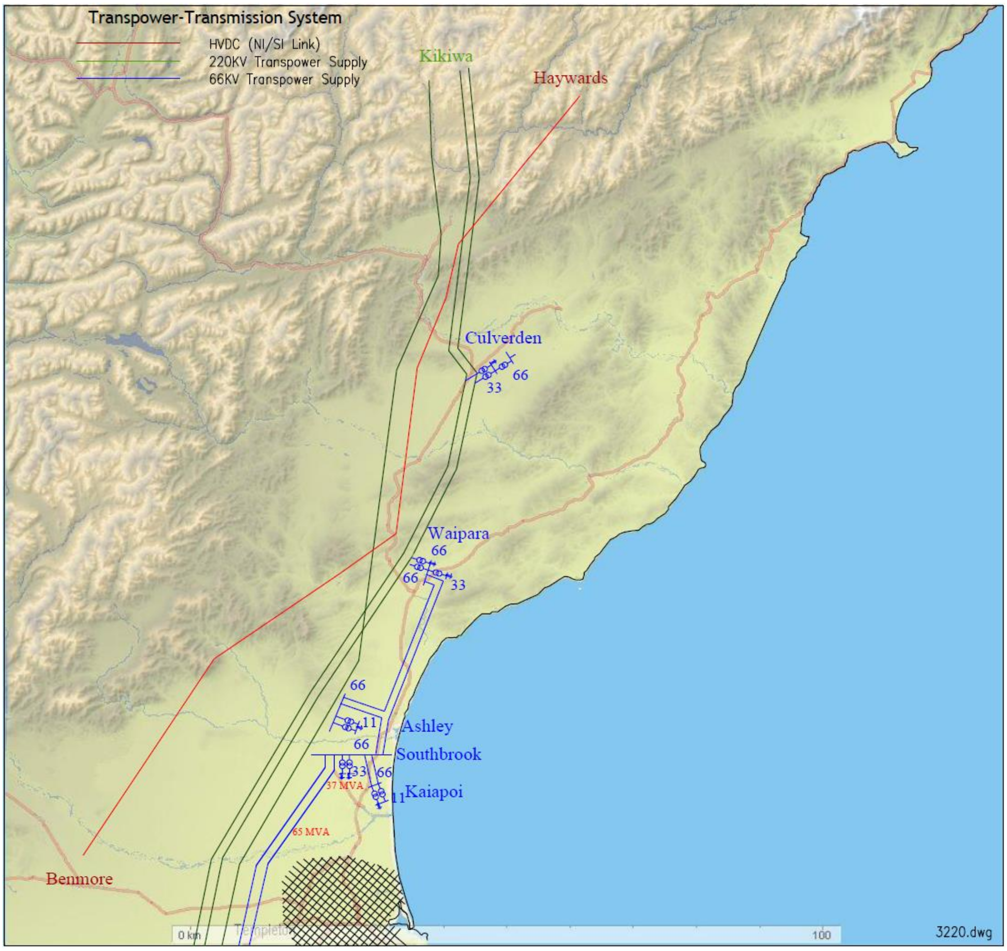

Figure 1: Transpower Transmission System on the eastern coast of the South Island of New Zealand.

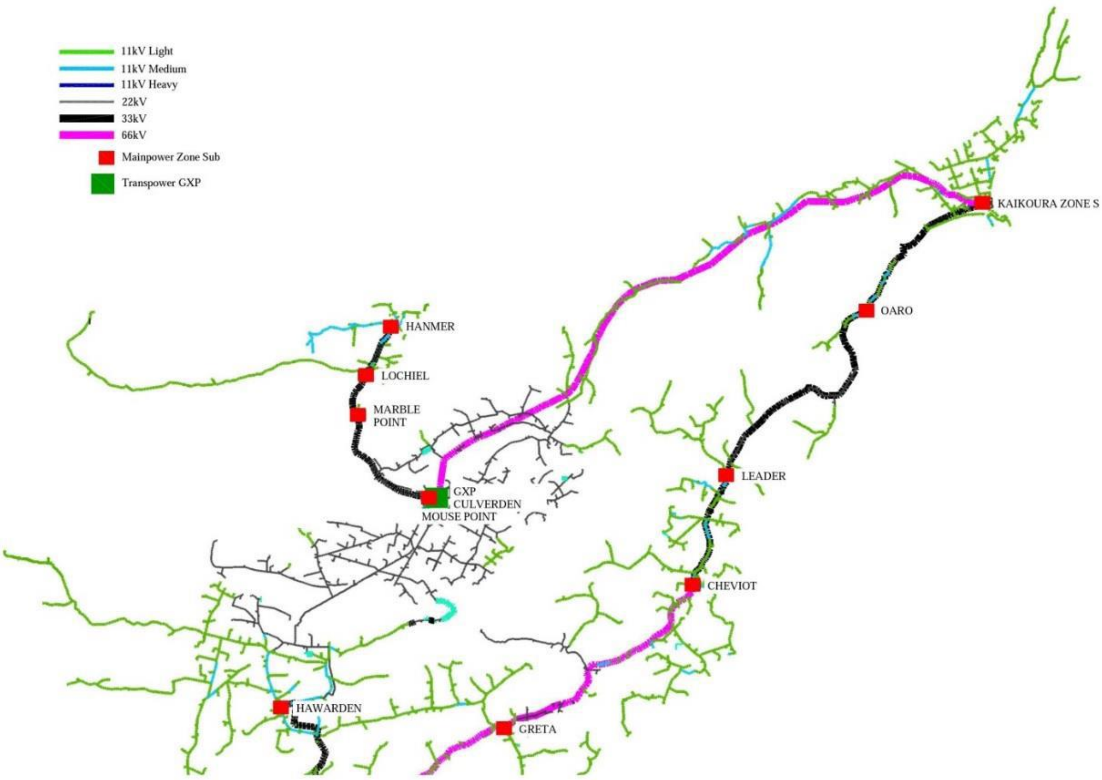

Figure 2: North Canterbury Network (North).

Figure 3: MainPower Subtransmission Network.

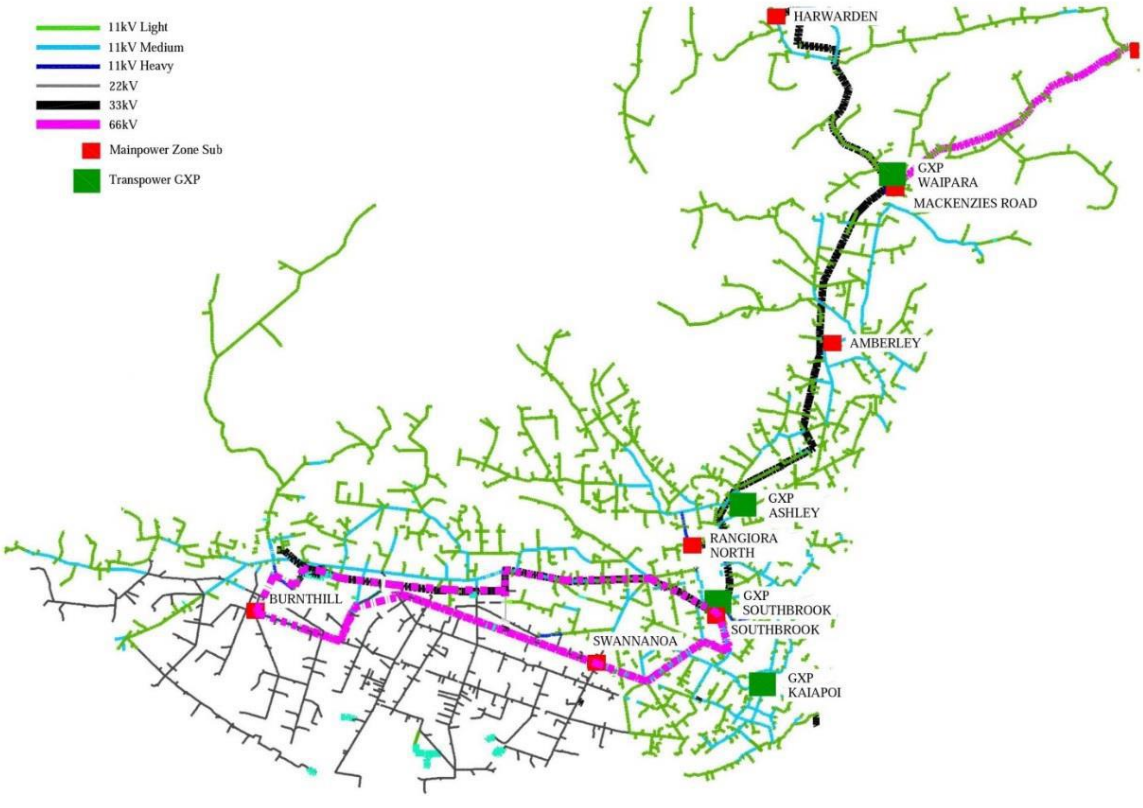

Figure 4: North Canterbury Network (South).

Within the region directly affected by the Kaikōura earthquakes the electricity distribution company MainPower takes supply from Transpower's Waipara and Culverden GXP substations at 66kV and 33kV. Transpower completed an extensive program of seismic damage mitigation to the GXP stations which, during the September 2010 Darfield Earthquake, proved to withstand ground motions of the intensity experienced in the Kaiapoi region [1]. From Transpower's Culverden GXP, MainPower's network consists of 33kV lines that feed the local Culverden and Hamner Springs townships at 33kV and a single circuit 66kV line that feeds Kaikōura, as shown in Figure 2.

MainPower also takes supply at 66kV and 33kV from Transpower's Waipara substation as shown in Figure 4. The 33kV supplies feed south and west, while the single circuit 66kV line takes supply north to the settlements of Greta Valley and Cheviot, before stepping down to 33kV to supply to the Parnassus area and provide a backup for Oaro and Kaikōura.

MainPower's point of interconnection for the supplies from Waipara and Culverden is on the 33kV between Parnassus and Oaro. Kaikōura's normal peak load is 6MW which can be reduced to 5MW by the use of water heating demand control. The 33kV coastal supply from Waipara can supply the reduced peak.

KAIKŌURA 2016 EARTHQUAKE

At 12:02 a.m. on the 14th of November, an earthquake of magnitude 7.8 struck the South Island. The epicentre of the initial rupture was about 15 kilometres north-east of Culverden and 60 kilometres' south-west of the tourist town of Kaikōura and at a depth of approximately 15 kilometres. This earthquake consisted of the initial epicentre at Culverden and over an almost instantaneous sequential triggering and rupture of a further 22 faults over a 2 min period. These faults progressed in a north easterly direction from Culverden toward Kaikōura a township located on the coast and north along the east coast of the South Island [2]. Effects of the earthquake were also felt in the cities of Wellington and Christchurch. Two deaths and 57 injuries were reported as a result of the earthquake. Many major roads were closed in the South Island because of slips and damage to bridges, including State Highway 1 between Picton and Waipara, and State Highway 7 between Waipara and Springs Junction (SH 65 turnoff). The closure of SH1, the Inland Kaikōura Road and the Main North railway line effectively cut off all land routes into Kaikōura [3].

NATIONAL GRID IMPACT

Generally, the influence of the Kaikōura earthquake on the National grid was minor, apart from leg damage of an HVDC tower in Marlborough and a bus conductor fall-off at the Culverden substation.

The earthquake caused a bus fault at Culverden when the 66kV bus reached limit of its seismic movement and the sliding end dropped as designed. The loss of the 66kV bus resulted in loss of supply to approximately 3600 MainPower customers in Culverden, Hanmer Springs and Kaikōura. The bus was fixed by mid-day and MainPower were restoring since then. There was minor cracking in buildings but seismic strengthening prevented structural and operational damage.

Transpower identified a tower on the HVDC line in Marlborough region north of Kaikōura that had earthquake damaged and needed replacement following the Kaikōura earthquake. One of the damaged legs of the HVDC line tower is shown in Figure 5. Figure 6 illustrate the face damage between two legs and Figure 7 shows multiple ground cracks between the HVDC tower legs.

Figure 5: Leg damage of the HVDC Tower.

Figure 6: Damaged face of the HVDC Tower.

Figure 7: Ground crack between legs of the HVDC tower.

Considering the location and the impact on the HVDC link, Transpower decided to use temporary tower poles and currently has plans for the construction of a new tower. Despite the need for replacement, the HVDC tower was not at immediate risk during normal conditions and it was decided that the tower should be kept under regular observation until replacement works were completed. As a consequence of this earthquake damage, the tower is more prone to further damage from larger aftershocks or extreme storms/winds. To accommodate this risk, Transpower changed the risk classification of the HVDC when unusually high winds are forecast. The two risk types associated with operating HVDC flows in Transpower's reserve management system are:

- DC contingent event (CE): Losing a single HVDC pole when both HVDC poles are in service under which circumstance more power can normally be put on the remaining HVDC pole to help compensate for the loss.
- DC extended event (ECE): It accounts for the situation when losing the total power received over the HVDC link.

Both types of risk pose serious threat to national grid security especially under heavy north transfer scenario. Therefore weather forecasts for the Marlborough region were continually monitored before repairs started. If forecast wind speeds in the Marlborough region exceeded 80 km/h (safety speed) from certain directions, the HVDC bi-pole was classified as a CE risk otherwise ECE risk.

The tower repair was completed on 21 January 2017 and the requirement to change the risk reclassification of the HVDC when unusually high winds are forecast was cancelled.

DISTRIBUTION GRID PERFORMANCE

Immediately after the Kaikōura earthquake, MainPower lost about 6MW of load which is low due to the timing of the earthquake. MainPower experienced 33kV line tripping in Hanmer Springs with approximately 1500 customers affected by losing capacity of 1.3MVA load at the time of the earthquake. The line was patrolled by helicopter and was restored by 5 a.m. of the first day. Multiple minor feeder faults were reported at Cheviot. There were approximately 1000 customers affected and the power was restored by midday.

During the 2010 Darfield earthquake, Transpower reported that some of their transformers experienced tripping due to operations of protective devices called a Buchholz relay. This type of relay is a pressure operated switch that generally triggers due to transformer oil surges experienced during electrical faults [4]. Because of the ground motion associated with the earthquakes some of these devices inadvertently operated, temporarily taking out the supply. These had to be reset or overridden to provide supply back. Similar incidents have been reported at Mouse Pt substation in Culverden. Buchholz relays tripped despite the fact that they were seismically restrained. The Buchholz relay tripping and multiple feeder faults affected 1900 customers and caused loss of 1.2 MVA capacity during the earthquake.

The earthquake damage to the lines south of the Waiau River was minor and most customers there had power restored by late afternoon of the 14th November. On the contrary, there was extensive damage to HV and LV lines in the vicinity of the Waiau town and Inland Rd to Kaikōura. As a result, 400 Waiau area customers were without power at the end of first day. Figure 8 shows a damaged 33kV pole in Oaro.

The extent of customer installation and low voltage damage was such that it was unsafe to bring the distribution system alive without inspecting all customer installations. There were practical difficulties around access and customer contact that slowed the recovery process. The remaining distribution system was livened as it was proven safe and repairs carried out or customer LV connections isolated.

Figure 8: Oaro 33kV pole damage.

Figure 9: Cracked 66 kV pole.

As a consequence of losing 66kV supply at Ludstone Rd substation (Kaikōura) from Transpower GXP and extensive distribution system damage, approximately 2700 customers were affected. Figure 9 shows a cracked 66kV pole. The 33kV coastal link was patrolled by helicopter and power restored to the substation via 33kV from Waipara by 1 pm on the 14th November. The Inland Rd 66kV line was also patrolled with many poles with a substantial lean found.

As with the Waiau area, most of the Kaikōura restoration was hampered by access issues and the need for inspections of installations before livening. Because of the soil conditions on the Kaikōura Plains the pole foundations were often unstable causing many failures. Tablet based field data capture forms (including photos) were developed to manage the customer installation safety inspection process and to record system defects to prioritize repairs. By the end of 14th of November 2016, MainPower reduced the number of affected customers to around 2,000 and much of the Kaikōura township had their power restored. The majority of the Waiau township had power restored by the end of the following day. There was no significant zone substation damage and all were returned to service within a few hours. This can be largely attributed to the earthquake strengthening measures put in place in the 1990's following awareness of the Edgecumbe earthquake damage.

Most of the faults were foundation failures. The number of replacement poles required was relatively low and stocks were not a problem. A small number of transformers fell off structures, some due to cross-arm failure. A few others were not adequately restrained by bolts under the cross-arm and the hangers lifted up over the arms. There were also quite a few conductor failures of small low strength conductors following substantial movement of support structures. The most common problem was loss of conductor clearances to ground or each other due to pole movement. As experienced in the Christchurch earthquake's concrete poles, especially transformer poles were particularly likely to sink into the ground compromising safety clearances. Prevention of pole foundation failure is difficult and remediation is still seen as the most viable strategy.

MainPower has been running a significant network reinforcement programme in conjunction with a focus on network maintenance and renewal activity. The increasing frequency of natural hazards and increased dependency on power supply has also demanded a focus on strengthening the security of supply and, improving the resilience of the network to reduce the impact of outages. The Kaikōura earthquake reinforces this need. This is consistent with the consumers' need for secure power supplies following the Christchurch earthquakes [5]. It also recognises the inherent improvements in reliability that will occur as network capacity and security upgrade programs are completed in response to new demand. MainPower expects to focus more on reliability during the next 10 years. In the case of extreme natural hazards, MainPower is committed to apply best endeavours to restore electricity delivery as soon as practicable. The Kaikōura earthquake has provided an opportunity to assess response times and practices.

MainPower had conducted qualitative natural hazards related risk analysis and an earthquake was identified as the greatest threat, which is consistent with the current incident. MainPower installed seismic restraints at zone substations in the 1990's except for Marble Quarry zone substation, which supplies less than 10 ICPs and deemed unnecessary to restrain. Restraints are designed to the specification for Seismic Resistance of Engineering Systems in Buildings NZS 4219 and its related Code of Practice for General Structured Design and Design Loadings for Buildings NZS 4203 1992. [1]

The majority of damage caused by the Kaikōura earthquake was superficial (broken cross arms, leaning poles). However, considering the scale of the event, further assessment is required to determine the long term impact on the network.

At the time of pubication, MainPower had been engaged with after quake straightening of poles and restoring of full ground clearances. Less critical system repairs are still ongoing. Much of the work will be incorporated into the normal line inspection and maintenance cycle which is being brought forward in the worst affected areas.

ELECTRICITY INTERDEPENDENCY IMPACT WITH COMMUNICATION INFRASTRUCTURE

Communication with field staff was vital to the distribution network restoration and MainPower was fortunate to have its own voice and data radio network coverage over the affected areas throughout the recovery process.

Telecommunication services were also affected by the loss of power supply to the Kaikōura region. The Kaikōura telephone exchange lost main supply immediately after the event. Fortunately, equipment functionality was maintained by switching to back-up generators. The generator on site had fuel for approximately five days and there were arrangements in place for refuelling. Fortunately, power was restored for much of the Kaikōura township including the exchange by the end of the first day (14th of November 2016).

Chorus network service to remote customers relies on roadside cabinets, which are equipped with backup batteries typically lasting up to eight hours (with some up to 24 hours). The service is lost if there is no power source supplied before the battery is depleted. After the Kaikōura event, generators were deployed to cabinets and in most cases the service was restored even to remote areas. However, houses in those remote areas did not have power to enable the residents to use their normally AC-powered devices such as modems, cordless phones etc. A detailed summary of the impact of the Kaikōura earthquake on telecommunication infrastructure and its performance is summarised in Giovinazzi et al. [6].

CONCLUSIONS

The benefit of seismic strengthening seems to be revealed as there was no significant damage to major distribution zone substation or transmission Grid Exit Points in the Kaikōura earthquake. More concrete details and quantitative investigation into the performance of the electrical infrastructure following this earthquake response will be useful to better prepare and provide validation information for future events in the region.

This paper is an early account of the immediate impacts on electrical infrastructure following the Kaikōura earthquakes. A more detailed analysis and quantification of asset damage, repair times, key learnings from interdependencies, and incorporating earthquake damages to the recently released asset management plan will be part of future work. From a research development viewpoint this data and restoration time information will also be useful for fine tuning the modelling of an electrical distribution resilience toolbox that the power system resilience group at University of Auckland is currently developing.

ACKNOWLEDGMENTS

Thanks to the New Zealand Lifelines Committee and Transpower, for providing public information released through their various communication outlets that has informed this paper. The Asset Management Plan of MainPower also provided contextual information to better analyse the earthquake prior-state of the existing electrical assets that feeds the impacted area of the Kaikōura earthquake. The authors would also like to express gratitude to Nicola Cull from MainPower for providing additional information about the earthquake impact and Dr. Andrew Austin for his time in proof reading the earlier version of this manuscript. This project was partially supported by the Resilience to Nature's Challenges National Science Challenge.

REFERENCES

1 MainPower Asset Management Plan 2016-2026.

2 Stirling MW, Litchfield NJ, Villamor P, Van Dissen RJ, Nicol A, Pettinga J, Barnes P, Langridge RM, Little T, Barrell DJA, Mountjoy J, Ries WF, Rowland J, Fenton C, Hamling I, Asher C, Barrier A, Benson A, Bischoff A, Borella , Carne R, Cochran UA, Cockroft M, Cox SC, Duke G, Fenton F, Gasston C, GrimshawC, Hale D, Hall B, Hao KX, Hatem A, Hemphill-Haley M, Heron DW, Howarth J, Juniper Z, Kane T, Kearse J, Khajavi N, Lamarche G, Lawson S, Lukovic B, Madugo C, Manousakis I, McColl S, Noble D, Pedley K, Sauer K, Stahl T, Strong DT, Townsend DB, Toy V, Villeneuve M, Wandres A, Williams J, Woelz S, and R. Zinke (2017)."The Mw7.8 2016 Kaikōura earthquake: Surface fault rupture and seismic hazard context". *Bulletin of the New Zealand Society for Earthquake Engineering*, **50**(2): (In press).

3 Davies AJ, Sadashiva V, Aghababaei M, Barnhill D, Costello SB, Fanslow B, Headifen D, Hughes M, Kotze R, Mackie J, Ranjitkar P, Thompson J, Troitino DR, Wilson T, Woods S and Wotherspoon LM (2017). "Transport infrastructures performance and management in the South

Island of New Zealand during the first 100 days following the 2016 Mw7.8 Kaikōura earthquake". *Bulletin of the New Zealand Society for Earthquake Engineering*, **50**(2): (In press).

4 Watson NR (2010). "Impact of the Darfield Earthquake on the Electrical Power System Infrastructure". *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. **43**(4): 421-424.

5 Massie A and Watson NR (2011). "Impact of the Christchurch earthquakes on the electrical power system infrastructure". *Bulletin of the New Zealand Society for Earthquake Engineering*, **44**(4): 425-430.

6 Giovinazzi S, Austin A, Ruiter R, Foster C, Nayyerloo M, Nair N and Wotherspoon LM (2017). "Resilience and fragility of the telecommunication network to seismic events: evidence after the Kaikōura (New Zealand) earthquake sequence". *Bulletin of the New Zealand Society for Earthquake Engineering*, **50**(2): (In press).