Bellagamba, University of Canterbury

QuakeCoRE, GEER, and EERI

Earthquake Reconnaissance Report:

M7.8 Kaikoura, New Zealand Earthquake on November 14, 2016

QuakeCoRE NZ Centre for Earthquake Resilience

GEER

EERI

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1 INTRODUCTION

This joint reconnaissance report on the November 14, 2016 M7.8 Kaikoura, New Zealand Earthquake is a true Learning From Earthquakes (LFE) collaboration. It builds upon initial and ongoing collaborative efforts to establish the Kaikoura Clearinghouse that is a joint effort by the Earthquake Engineering Research Institute (EERI), New Zealand Society of Earthquake Engineering (NZSEE), GNS Science, and QuakeCoRE. The clearinghouse website was launched on November 15, 2016 (26 hours after the event) and contains links to preliminary reconnaissance field observations, links to articles from the news media, reconnaissance photos, aerial imagery, ground motion information, and more. This report supplements the valuable data and observations that have been posted to the Kaikoura Earthquake Virtual Clearinghouse website and data map shown in Figure 1.

This reports draws extensively from several sources of information, in particular the early report produced by QuakeCoRE and available in the QuakeCoRE December newsletter[1]. QuakeCoRE is a network of leading New Zealand earthquake resilience researchers from seven partner organizations including University of Canterbury, University of Auckland, GNS Science, and Resilient Organizations. Researchers from each of these organizations have contributed to this report. Additional information has been provided by: Chris Massey and Sally Dellow on landsliding, Laurie Johnson on emergency response and organizing for recovery, and Rick Wilson on tsunami warning and effects. A more in-depth report on the tsunami warning and effects was prepared by Wilson and Johnson for EERI and released in December 2016.[2] Several authors of this report contributed to the to the reconnaissance effort as members and collaborators with the NSF-supported Geotechnical Extreme Events Reconnaissance (GEER) Association team that will also produce a report summarizing their observations.

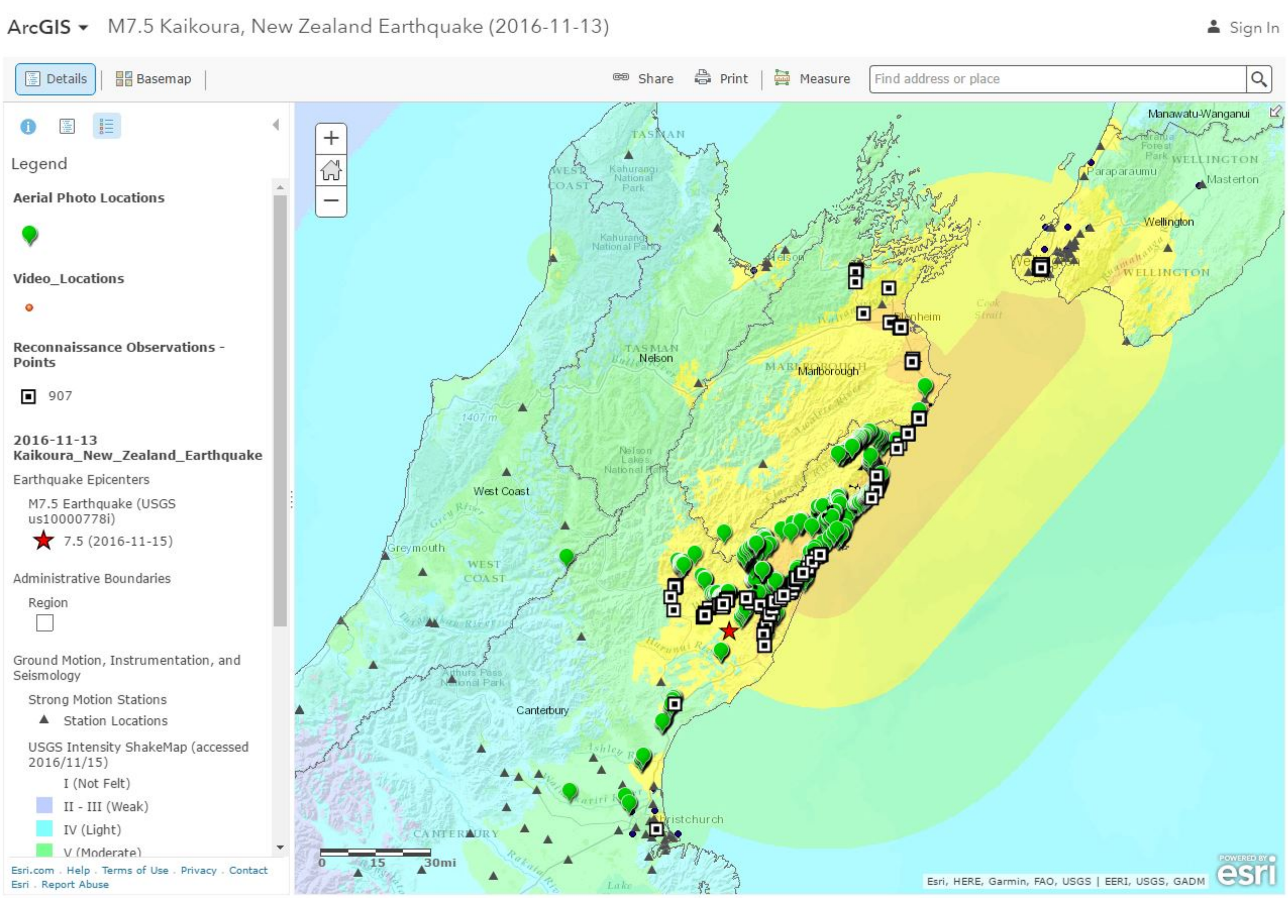


Figure 1. The online Kaikoura Field Observations map[3] contains over 400 observational data points overlaid on a USGS Shakemap[4] and other background data layers (source: EERI).

The report has been organized to provide an overview of the seismic setting ground motions, followed by broad observations on the several disciplinary topics including emergency response efforts, tsunami impacts and warning, ground failure and geotechnical impacts, and distributed infrastructure. The following sections have been designed to describe major impacts to the built environment as specific to several key impacted regions in New Zealand including the

Kaikoura township and surrounding areas, Northern Canterbury, the Marlborough wine region, and Wellington (Figure 2). The report concludes by describing how the recovery is being organized and providing an early view of the recovery trajectory.

In New Zealand, collaboration across the science and engineering sector after this earthquake has been exemplary. The collaboration extended internationally, through GEER and EERI. The full story of this event is clearly still unfolding and EERI will continue to work with our New Zealand partners and other researchers to carefully track the resilience of impacted communities as we learn from colleagues in the field.

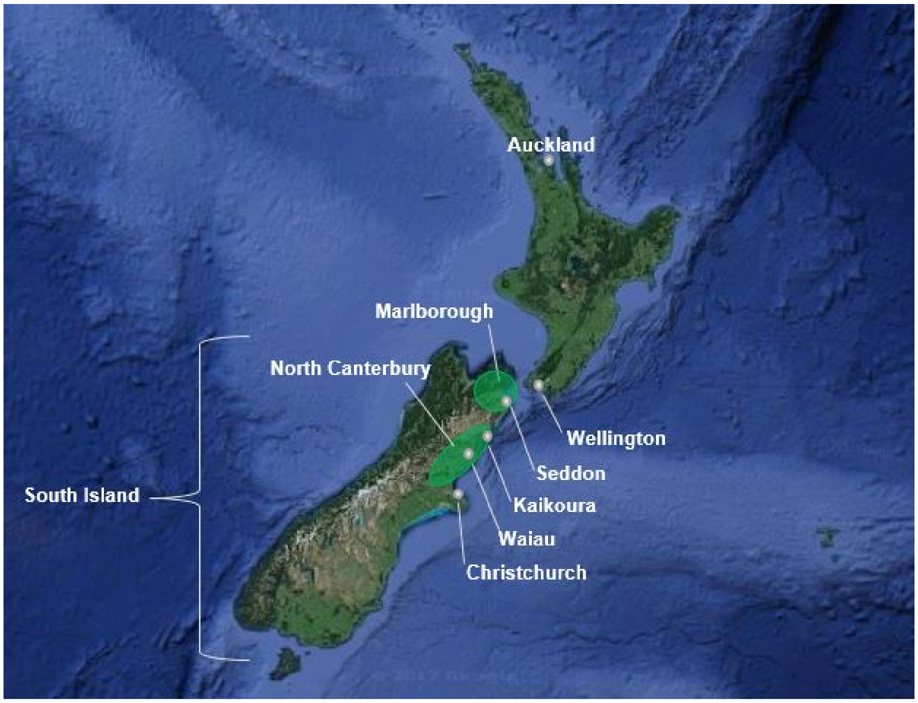


Figure 2. A map of New Zealand highlighting main areas of earthquake impact from the M7.8 Kaikoura, New Zealand Earthquake on November 14, 2016. The areas highlighted in green are regions, rather than cities or townships (source: EERI, Google Maps).

2 SEISMOLOGY AND GROUND MOTIONS

2.1 Event Description

On November 14, 2016 at 12:02am local time (November 13, 2016 New Zealand at 11:02:56 UTC), the moment magnitude M7.8 Kaikoura earthquake occurred along the east coast of the upper South Island. The earthquake initiated in the Waiau Plains in North Canterbury, and involved multiple fault segments (Figure 3) as the rupture generally propagated northward over 150km to Cape Campbell in Marlborough.

The Marlborough Fault Zone (MFZ) is one of the most active crustal regions of New Zealand with many mapped active faults. Several mapped fault segments participated in this earthquake, including The Humps, Hundelee, Hope, Jordan Thrust, Kekerengu, and Needles Faults. In addition, several significant rupture displacements occurred on previously unmapped fault segments, most notably the Papatea Fault near the Clarence River mouth. The most notable seismological aspect of the earthquake was the number of these fault segments which ruptured co-seismically in the same event. While previous surface mapping of these faults suggested they could be considered as separate fault segments for the purpose of earthquake rupture forecasting, clearly they are connected together at depth (or at least close to connected), and this event highlights the increased emphasis required to explicitly consider such complex multi-segment ruptures for future earthquake hazard and risk assessments as well as tsunami detection.

Surface rupture along the causative faults resulted in significant localized damage to transportation infrastructure near the coast and also fault rupture-induced landslides. The strong earthquake-induced ground motions in the near-source region also resulted in substantial landslides along State Highway 1. Ground motions with horizontal accelerations exceeding 1.0g were observed at four locations (two in the Waiau area, and also in Kekerengu and Ward). The ground motion

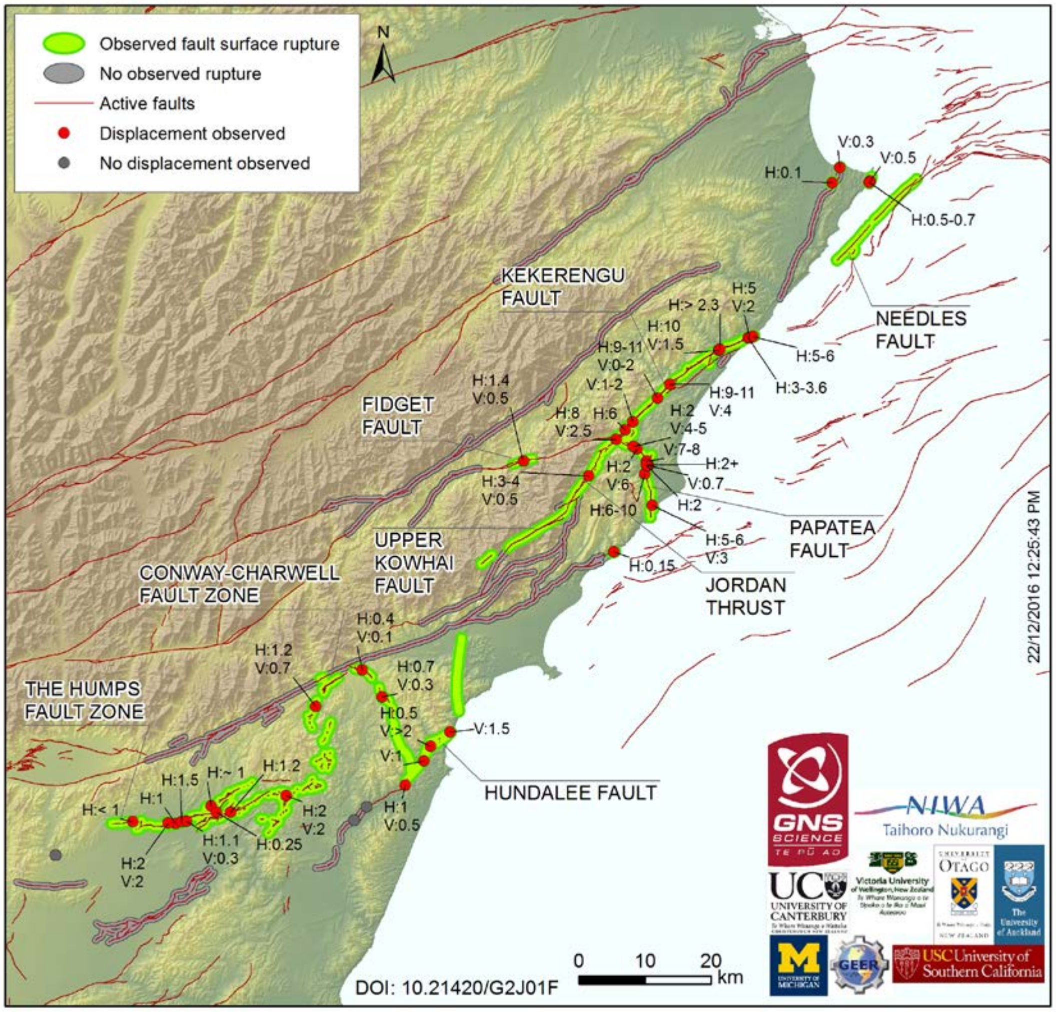


Figure 3. *A map highlighting the mapped fault ruptures with measured displacement as well as other previously mapped faults in the region (source: Nicola Litchfield, et al. GNS Science/EQC).*

recorded near the hypocentre in Waiau also exhibited 2.7g in the vertical direction, exhibiting the so-called 'slapdown effect' with asymmetric accelerations, very similar to that at Heathcote Valley in the 2010-2011 Canterbury earthquakes.

The ground motions from this earthquake were recorded at 224 GeoNet strong motion and broadband stations. Acceleration response spectra from four of these stations are shown in Figure 4. Significant efforts from several groups are currently making use of these observations to understand the overall ground motion intensity in the region. Figure 5 illustrates the inferred peak ground velocity (PGV) and Modified Mercalli intensities (MMI) based on broadband ground motion simulation (see: https://www.youtube.com/watch?v=P7t2u61daPg)[5].

The general northward rupture propagation in this event resulted in forward directivity effects in the Wellington region, with the closest rupture plane approximately 50 km from the Wellington Central Business District (CBD). The characteristics of the ground motion in the Wellington region resulted in both geotechnical and structural related damage (described in subsequent sections). Figure 6 illustrates the observed ground motions in the urban Wellington region. The summary statistics for typical mid and low-rise structures are also identified as a percentage of the ULS design response spectrum. In addition, the empirically-predicted response spectrum in Wellington CBD for the Kaikoura earthquake is also shown, which highlights the higher ground motion amplitudes in the 1-2 second period range. Figure 6, for context, also illustrates the empirically-predicted demands for a hypothetical Wellington Fault earthquake, indicating the significantly higher spectral demands expected across all period ranges for such an event.

Amplified spectral accelerations between periods of 1- 2 seconds were most significant in the soil deposits in the Wellington Basin and the Hutt Valley. As the soil depths increased, this amplification also increased, resulting in spectral accelerations that exceeded the design spectra in the 1-2 second period range in the deepest deposits along the edge of the Wellington waterfront. The significant duration of these records was approximately 25 seconds. The maps in Figure 7 present the spectral acceleration at different locations in Wellington region as a percentage of the ULS design spectra for 0.3 seconds and 1.5 seconds, indicating demands at or above ULS design spectra for many of the waterfront sites for T=1.5 seconds. Short period demands throughout the region were well below the design spectrum.

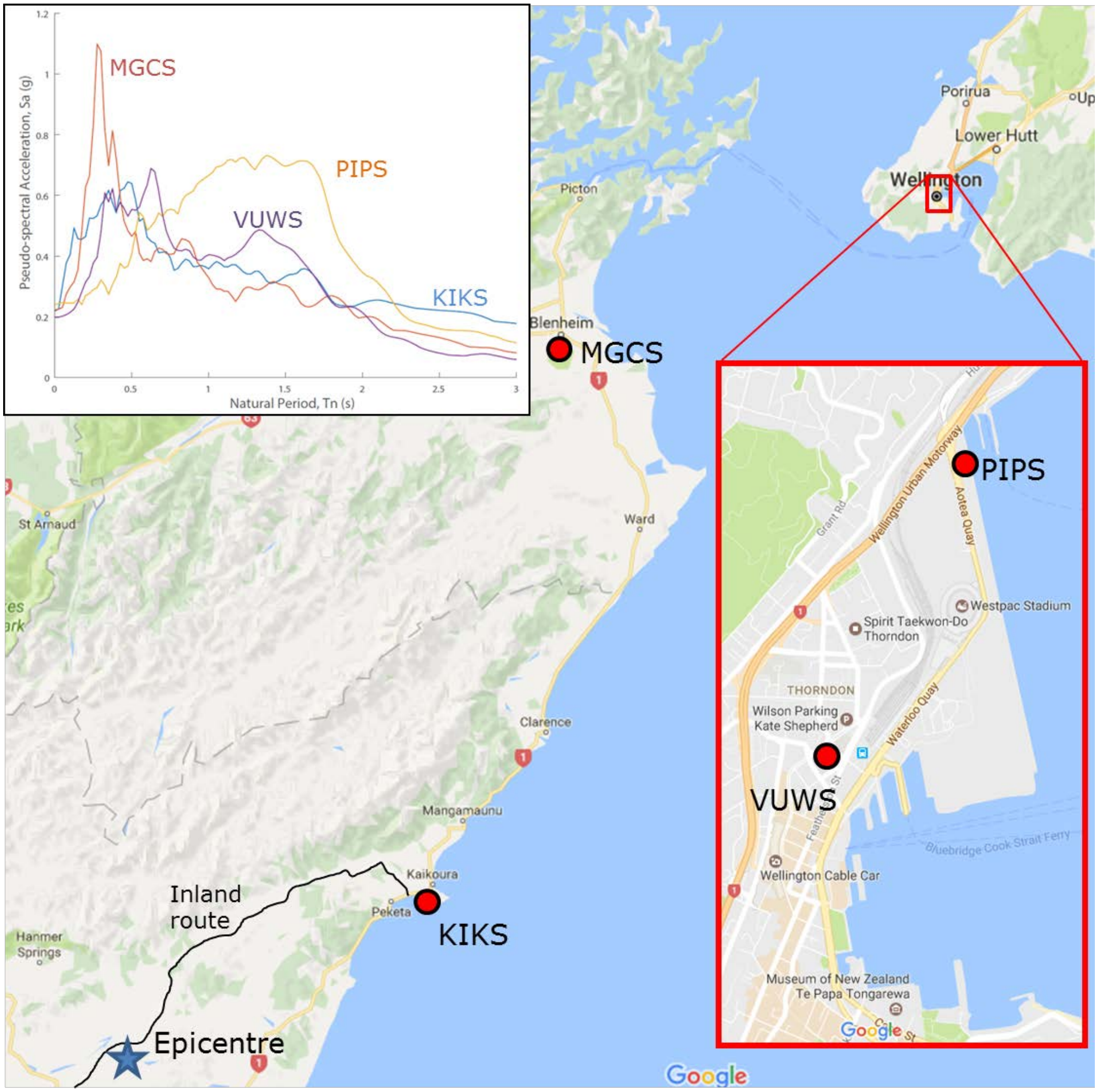
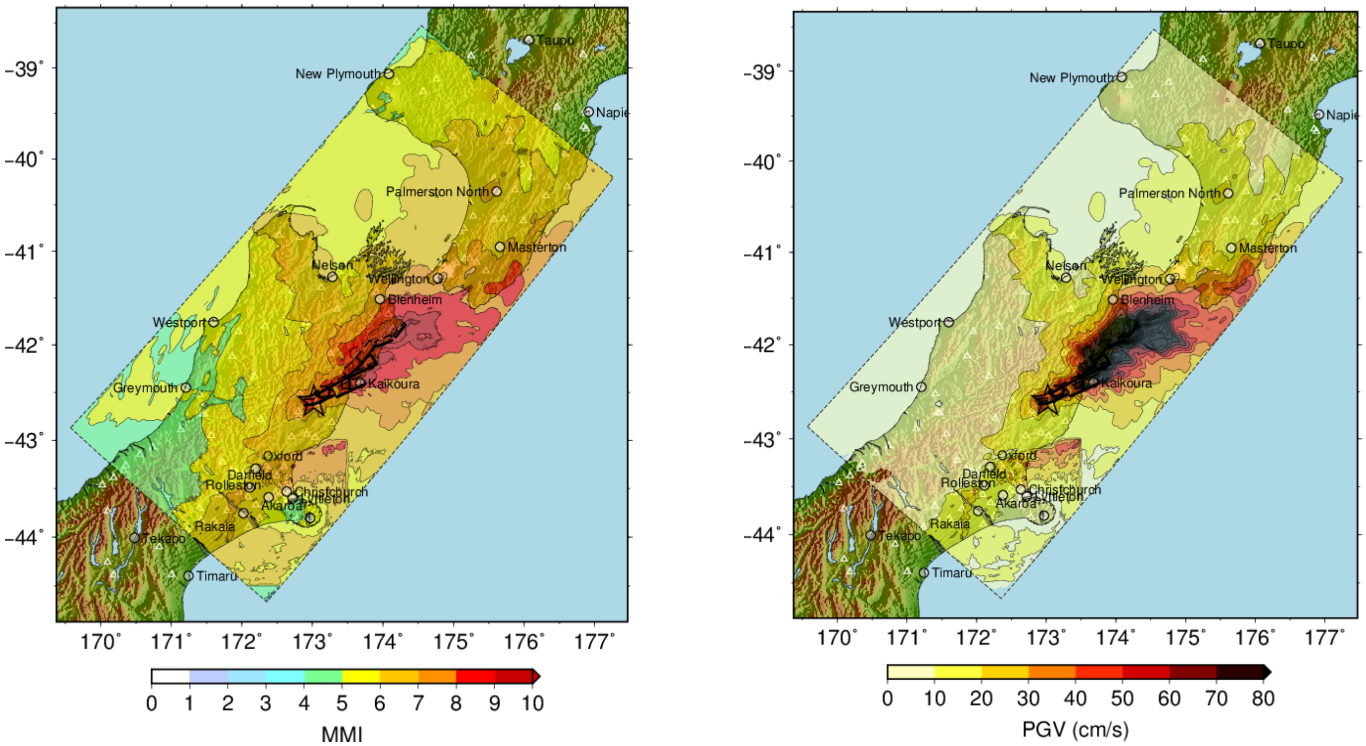


Figure 4. *Representative acceleration response spectra for the Kaikoura earthquake at strong motion station locations across the affected region: Kaikoura (KIKS), Blenheim (MGCS) and Wellington (PIPS and VUWS) (source: Brendon Bradley, Liam Wotherspoon).*



(a) (b)

Figure 5. Simulated values of (a) Modified Mercalli Intensity (MMI) and (b) peak ground velocity (PGV) (source: Brendon Bradley, Liam Wotherspoon)[5].

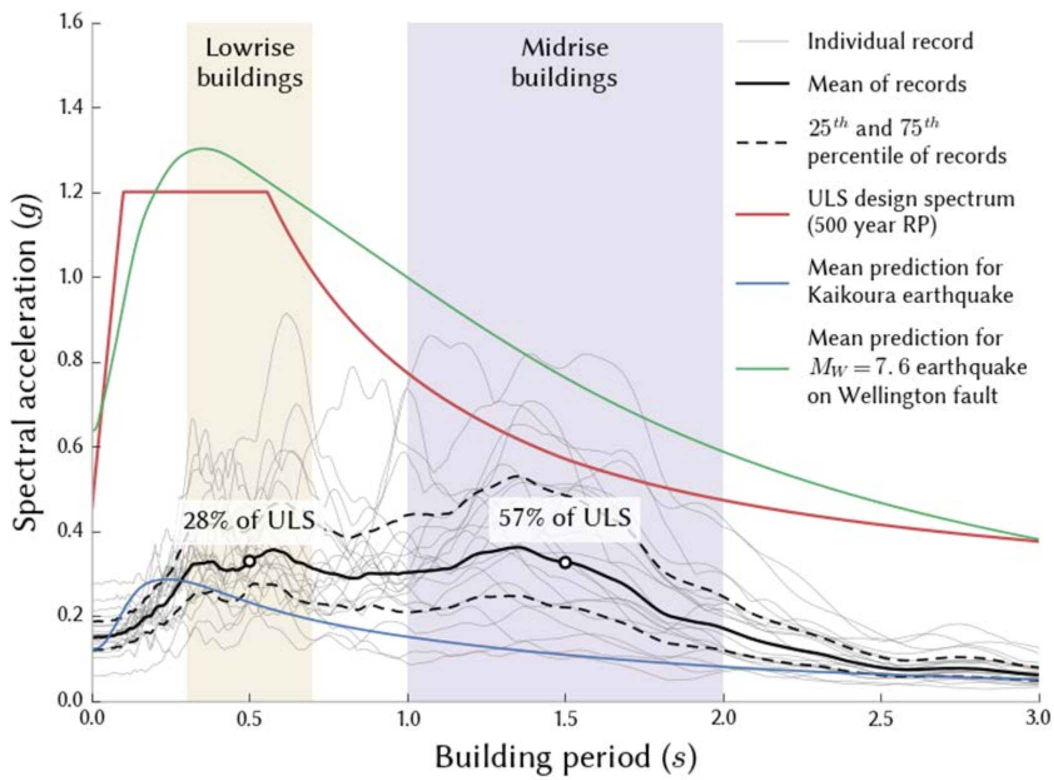
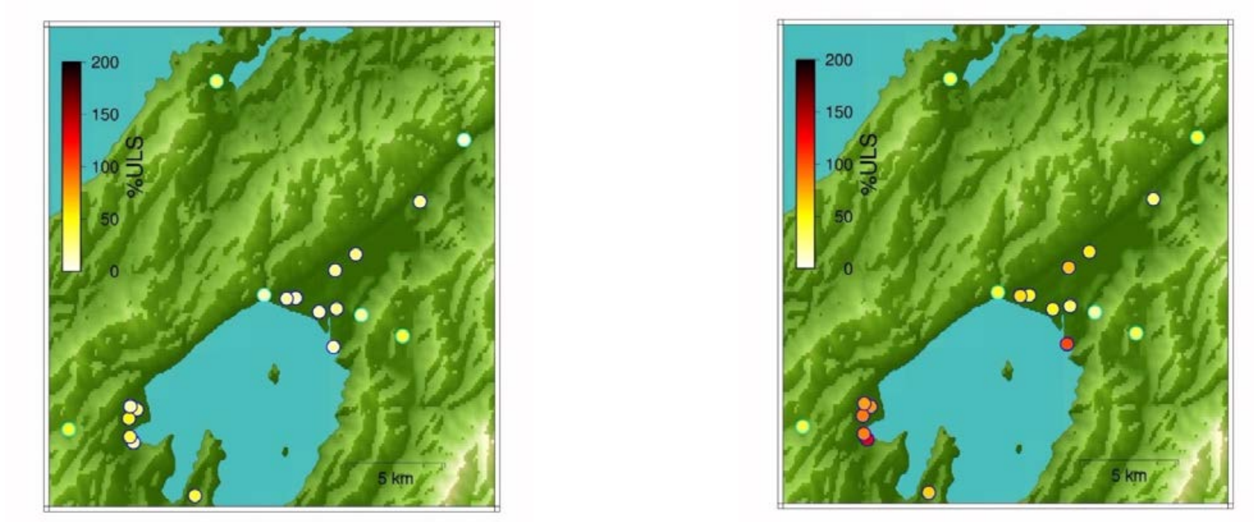


Figure 6. Observed ground motion response spectra in the urban Wellington region and the 500yr return period design spectra, compared with the empirically-predicted response spectrum for the Kaikoura earthquake; and the empirically-predicted spectra for a hypothetical Wellington fault earthquake (source: Brendon Bradley, Liam Wotherspoon).



(a) (b)

Figure 7. Map of Wellington and the Hutt Valley region showing the spectral acceleration as a percentage of the ultimate limit state design (500 year return period) for a) 0.3 second period; b) 1.5 second period (source: Kaiser GNS, Liam Wotherspoon).

3 AFTERSHOCK HAZARD

Aftershocks following the Kaikoura earthquake are concentrated in a broad region from North Canterbury to north of Wellington. With an earthquake of this size aftershocks can be quite large (e.g. M>6) which themselves pose a risk and can lead to further ground failure (e.g. landslides) and damage to buildings. The current aftershock sequence has resulted in at least three M>6 earthquakes mostly concentrated just north of the epicenter. However, there is a high concentration of aftershocks located near Cape Campbell at the NE tip of the South Island which marks the northern end of the fault rupture. This area is less than 50 km from Wellington which means that many of these aftershocks have been widely felt in Wellington. GeoNet has been routinely issuing aftershock forecasts and currently estimates there is a ~5% probability of a M7.8 or greater earthquake in this region in the next year.

Given the proximity of the aftershock region to Wellington there is a significant hazard and risk to buildings in Wellington from aftershocks. QuakeCoRE, in collaboration with GNS Science, has estimated the increased risk to Unreinforced Masonry (URM) buildings in Wellington using a combination of GeoNet aftershock forecast, fragility models from QuakeCoRE researchers and the RiskScape risk modelling tool. URM buildings pose a significant life safety risk due to failure of parapets and unsecured facades which often fail outwards into the street. Although URM buildings were not damaged in the mainshock (see Section 9 on Building Impacts in Wellington), these buildings are at risk from aftershocks occurring closer to Wellington which would likely be dominated by short period energy. Aftershock risk forecasts for URM buildings developed by GNS Science and QuakeCoRE have estimated that the risk to URM buildings is 15 times higher for the next month than before the earthquake. By this time next year, the risk is approximately 2 times higher than before the Kaikoura earthquake. QuakeCoRE held a Charrette style workshop on December 19, 2016 that brought together multi-disciplinary researchers and practitioners to develop a short list of options to address this issue.

For more information on aftershock forecasts, visit: Geonet Future Scenarios and Aftershock Forecasts[6] and GNS Science Aftershock Rate and Hazard Modelling[7].

4 TSUNAMI WARNING AND EFFECTS

The following section on tsunami warning and effects is abridged from Wilson and Johnson (2017), "EERI Preliminary Notes on Tsunami Damage and Response: Tsunami Generated by M7.8 Kaikoura, New Zealand, Earthquake on November 14, 2016." This reference provides more detailed information about tsunami generation, the timeline of notifications and response, and an extensive list of recommendations and best practices for tsunami science, engineering, and warning notifications in both New Zealand and distant areas.[8]

4.1 Tsunami Description and Effects

A small to moderate-sized local tsunami was generated by the vertical displacements along the offshore faults during this earthquake. The tsunami was recorded at four tide gauges in New Zealand (Table 1). The peak recorded tsunami amplitude was 2.31m at the tide gauge on the North Wharf at Kaikoura, which also experienced approximately 1m of uplift as observed on the marigram at the tide gauge (Figure 8).

Table 1. Tsunami information from tide gauges in the region (adapted from the U.S. National Tsunami Warning Center website).

Tide Gauge Measurement Location	Observed Arrival Time (UTC)	Peak Amplitude (above sea level in meters)	Time of Peak Amplitude (UTC)
Castlepoint, NZ	1200	0.25	1312
Kaikoura North Wharf, NZ	1113	2.31	1144
Chatham Islands, NZ	1425	0.16	1729
Queens Wharf, NZ	1113	0.46	1300

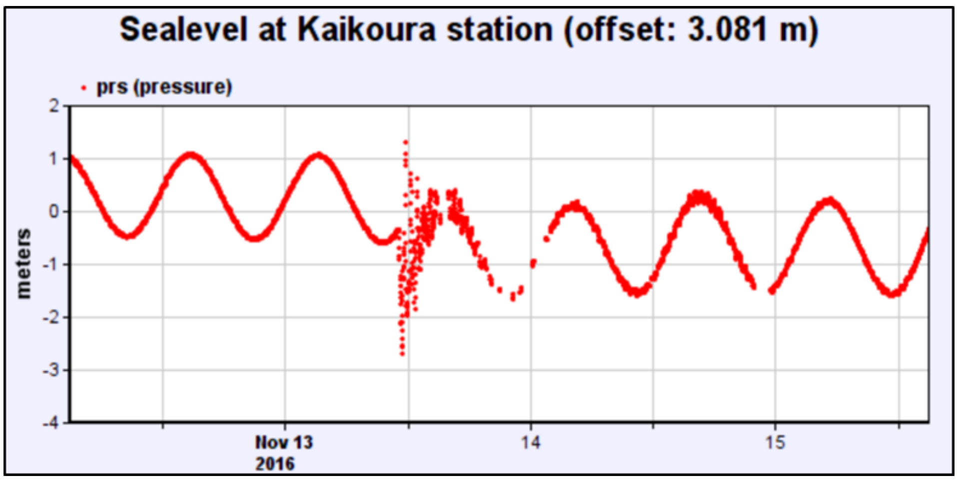


Figure 8. Marigram from Kaikoura North Wharf tide gauge from November 12-15, 2016. The sudden, apparent 1m drop of the water level represents a 1m tectonic uplift at the tide gauge site. Shortly after this, the tsunami signal is noted by the water level fluctuations of 4m peak to trough (source: IOC Sea Level Station Monitoring Facility website).

Tsunami run-up elevation was measured at approximately 4-5m at the southern end of Little Pigeon Bay, according to the GeoNet Tsunami website.[9] Because the bay faces north towards the tsunami source region and it narrows from north to south, it appears that the tsunami surge became focused as it reached the back-end of the bay. This focusing produced amplification of the tsunami surge as it came onshore, producing the 4-5m run-up. Additional reports have described even higher maximum run-up heights of 6.9m +/- 0.3m at Goose Bay, and 5.3m +/- 0.3m Oaro Bay[10].

Based on field accounts within the source region itself, the tsunami may have been 2-3m in amplitude, however, the coastline experienced 1-2m of co-seismic uplift and another meter drop because of low-tide conditions during the main activity of the tsunami. Co-seismic uplift and low-tide conditions appeared to offset the potential for significant inundation in this region. Although the effect was beneficial during this small to moderate tsunami event, it should be noted that large earthquakes within the subduction zone will likely cause tsunami run-up significantly larger than the coastal uplift from co-seismic deformation, increasing the potential for inundation along the coast.

4.2 Tsunami Impacts on Infrastructure

The one report of tsunami damage comes from the area that experienced high tsunami run-up (4-5m) in Little Pigeon Bay, east of Christchurch. Figure 9 shows photos of the structure that was damaged; Figure 9a is a picture of the structure before the tsunami, and Figure 9b shows the structure after the tsunami. According to the GeoNet website, the structure was pushed off its foundation, partly caving in the external walls. The maximum water level inside the structure was measured to be approximately 1-1.5m. Damage to the structure may have been caused by a combination of the force of the water and debris; tree trunks and other large debris were found approximately 140 meters inland from the shoreline.

As previously mentioned, the tsunami surge appears to have been amplified because of directionality of the incoming tsunami from the source region and narrowing of the bay. In past events, narrow bays and/or harbors have also shown they are prone to this type of amplification. Examples include Aneyoshi Bay in Japan during the 2011 Tohoku-Oki event[11] and Santa Cruz Harbor in California during the same 2011 event[12].

(a)

(b)

Figure 9. Before (a) and after (b) pictures of a cottage damaged by the tsunami at the north end of Little Pigeon Bay (photos: Stuff website[13]). The deck of the house was detached and deposited on the beach.

4.3 Tsunami Notifications and Response

In New Zealand, the Ministry of Civil Defence and Emergency Management (MCDEM) is responsible for the dissemination of national official tsunami notifications. With technical support from GNS Science, MCDEM assesses all messages received from the Pacific Tsunami Warning Center (PTWC, based in Honolulu, Hawaii) to determine the threat for New Zealand. Table 2 summarizes the three tsunami information statements from the PTWC during the first two hours after the earthquake.

Official tsunami notifications for New Zealand are disseminated by MCDEM via the National Warning System. According to local newspaper accounts, the coastal population away from the epicentral region was confused by the change in message from the original “no tsunami threat” to the change approximately 40-50 minutes after the earthquake to there being a tsunami threat and being ordered to move away from the coast. However, after a large, sudden drop in the water level at the tide gauge at Kaikoura occurred (Figure 8), the PTWC and decision makers at MCDEM recognized that a tsunami had been generated. Despite the confusion in the messaging, most coastal residents who felt the earthquake immediately evacuated to high ground. The tsunami warning remained in effect for various parts of the coast until about 3PM local time, 15 hours after the earthquake.

Table 2. Summary of tsunami information statements for New Zealand and other areas within PTWC’s responsibility (source: PTWC).

Tsunami Information from PTWC	Time Message Sent by PTWC (Local New Zealand time)	Information about Earthquake	Message about Tsunami
Statement #1	1212AM	event time 1203AM….M7.4	There is NO tsunami threat from this earthquake.
Statement #2	1243AM	event time 1203AM….M7.9	Drawdown of 2.5m observed at Kaikoura tide station; Damaging local tsunami might have occurred.
Statement #3	1259AM	event time 1203AM….M7.9	New Zealand Civil Defense has issued tsunami threat message for east coast of south island; Tsunami threat beyond New Zealand not expected.

In addition to the mixed tsunami-warning messages sent in the hour following the earthquake, there have been a number of issues raised about the notification and emergency response efforts. After the earthquake, according to the November 19, 2016 *Associated Press* article[14], the national emergency call center staff based in Christchurch evacuated their building, and tried but failed to engage the backup system. According to an article on the Stuff website (dated November 14, 2016), there was public criticism by Christchurch residents about a delay in sirens and evacuation notifications.

In response to this criticism, according to the Otago Daily Times[15] on December 3, 2016, Prime Minister John Key indicated that plans for a new national alerting system will be accelerated. These plans include providing 24-hour monitoring by a duty officer and improved decision-making regarding tsunami generation.

In other regions across the Pacific Ocean, the U.S. Pacific and National Tsunami Warning Centers (PTWC and NTWC) provided tsunami notification information. For example, the NTWC provided a number of “Tsunami Information Bulletins” about the tsunami threat to the west coast of the U.S. which includes the State of California. The California Governor’s Office of Emergency Services and the California Geological Survey are responsible for communicating the tsunami threat to coastal communities in the state and providing informational support to communities during a tsunami. For the west coast of the U.S., this earthquake occurred at 3:03AM on November 13, 2016. Table 3 summarizes the content of the messages sent by the NTWC:

Table 3. Summary of tsunami information statements for the U.S. west coast states; notable changes bolded and italicized (source: NTWC).

Tsunami Information from NTWC	Time Message Sent by NTWC (Pacific time)	Information about Earthquake	Message about Tsunami
Statement #1	3:15AM	event time 3:03AM….M7.4	Tsunami NOT expected for U.S. west coast
Statement #1(?)	3:57AM	***event time 3:32AM***….M7.9	Event being reviewed for U.S. west coast
Statement #2	4:27AM	event time 3:32AM….M7.9	Event being reviewed for U.S. west coast
Statement #3	5:07AM	***event time 3:03AM***….M7.9	Event being reviewed for U.S. west coast
Statement #4	5:50AM	event time 3:03AM….M7.9	Tsunami NOT expected for U.S. west coast

For some emergency managers in California at the state and county level, there was initial confusion about the message sent at 3:57AM because it identified a different start time for the earthquake, a larger earthquake magnitude, and a different message about the tsunami threat that went from no threat to gathering more information about the threat.

With regard to the magnitude change, the initial tsunami alert message was sent minutes after the earthquake and it included only a preliminary magnitude. Initial preliminary magnitudes in the mid M7 range and above can increase in magnitude as the earthquake fault continues to rupture. This occurred as the magnitude was upgraded from M7.4 to M7.9.

With regard to the change in the message from “no tsunami threat” to “evaluation of the tsunami threat,” M7.9 is the threshold for the NTWC to evaluate the tsunami threat further. The NTWC indicated that it needed more time to evaluate the tsunami threat because the tsunami had not reached the first deep-ocean tsunami detection buoy, which took several hours after the earthquake. Once the tsunami reached the buoy and the measurement was evaluated, the NTWC indicated that there would be no tsunami threat to the west coast of the U.S. and CalOES called off its response activities.

Refer to Wilson and Johnson (2017) for additional details about lessons learned from this event.[8]

5 GROUND FAILURE AND GEOTECHINICAL IMPACTS

5.1 Landslides

The November 14, 2016 M7.8 Kaikoura earthquake generated tens of thousands of landslides. Landslides affected a total area of about 10,000 square kilometers, with the majority concentrated in a smaller area of about 3,500 square kilometers. The mapped landslide distribution reflects the complexity of the evolution of the earthquake rupture, as shown in Figure 10. The largest landslides occurred either on or adjacent to the faults that ruptured to the surface. These landslides are distributed across a broad area of intense ground shaking and not clustered around the earthquake epicentre. The majority of landslides occurred in two geological and geotechnically distinct materials: Neogene sedimentary rocks (limestones, sandstones and siltstones), and Carboniferous to Cretaceous Torlesse “basement” rocks (sandstones and argillite)[16]. The most frequently occurring landslide types, adopting the scheme of Hungr et al., correlate to these materials, where first-time and reactivated planar and rotational rock-slides are the dominant landslide type in the Neogene sedimentary rocks, and first-time rock and debris avalanches are the dominant landslide type in the basement materials[17].

A noteworthy feature of this earthquake is the number of valley blocking landslides it generated, which was partly due to the steep and confined slopes in the area and the widely distributed strong ground shaking. More than 190 significant valley blocking landslides have been mapped. The largest has an approximate volume of 12(±2) M m^3, and its debris travelled about 2.7 km downslope, where it formed a dam blocking the Hapuku River. There are at least three other mapped valley-blocking landslides with volumes ranging from 2M to 8M m^3.

Another noteworthy aspect of this event is the large number of landslides that occurred on the steep coastal cliffs south of Ward and extending to Oaro, north of Christchurch.

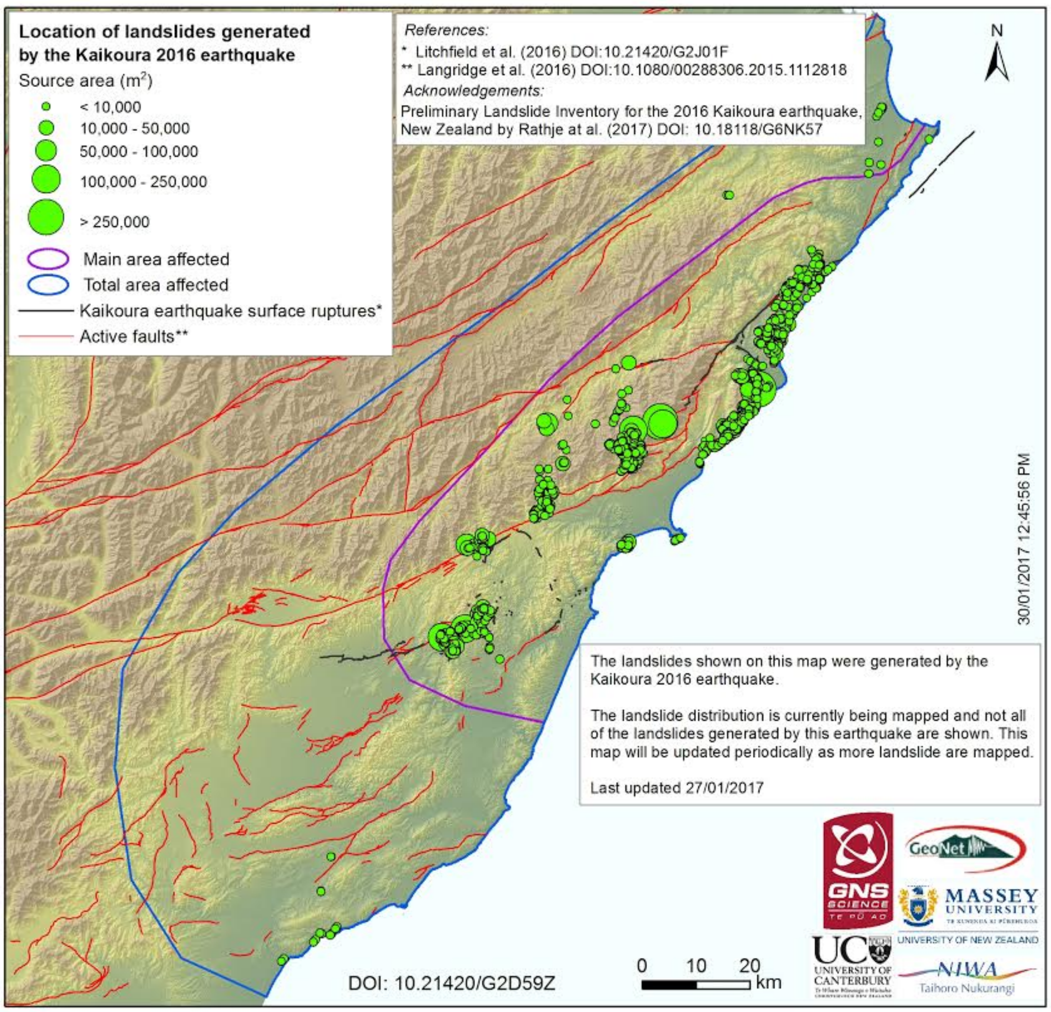


Figure 10. Map showing a non-comprehensive distribution and volume of landslides caused by the November 14, 2016 earthquake in Kaikoura (source: Chris Massey, et al. GNS Science).

The area affected by landslides is relatively remote with few people living there, and so only a few homes were impacted by landslides and there were no recorded deaths due to landslides. Landslides along the coast, however, caused the closure of State Highway (SH) 1 and the North Line of the South Island Main Trunk Railway, preventing people and goods from entering or leaving the town of Kaikoura, which had a permanent population of about 3,550 people (and seasonally expands due to tourists). Figure 11 shows examples of common damage observed along this route. These closures led the responsible government agencies to focus on opening the Inland route, State Highway 70, to Kaikoura to allow the passage of people, food and fuel. At the time of writing the northern section of SH1 from Kaikoura and the North Line of the South Island Main Trunk Railway are both still closed, two months after the earthquake.

(a) (b)

Figure 11. (a) Landslide crossing State Highway 1 north of Kaikoura at Okiwi Bay (photo: Dmytro Dizhur, Marta G*iaretton), (b) Papatea fault rupture crossing State Highway 1 and the main north rail line north of Kaikoura (photos: Bellagamba).*

The long-term stability of the cracked slopes, remobilisation of landslide debris in rain events and the performance of the valley blocking landslide “dams” in future strong earthquakes and significant rain events are an ongoing concern to the central and local government agencies responsible for rebuilding homes and infrastructure. Of particular concern are the debris flood hazards that might occur, should some of the landslide dams breach catastrophically. Several of these dams are located upstream from people and critical infrastructure such as road bridges, which might be at risk if the hazard were to occur. The longer-term effects of sediment aggradation as the debris moves downstream from the steeper inland slopes to the sea is another “cascading” hazard that could pose a risk to agriculture, aquaculture and infrastructure.

5.2 Liquefaction

Soil liquefaction and associated impacts on land and infrastructure were relatively insignificant compared to the landslides and faulting induced ground failures. The lack of pervasive effects of liquefaction, despite the large 7.8 magnitude of the Kaikoura Earthquake, was in stark contrast to the widespread and severe liquefaction caused by the 2010-2011 Canterbury earthquakes, which were of much smaller magnitudes. The relatively low liquefaction impacts reflect the characteristics of the Kaikoura earthquake in relation to the seismic demand specific to liquefaction triggering, and general ground conditions in areas affected by the strong ground shaking. In other words, there were no large areas over which both a high seismic demand and poor ground conditions with high liquefaction potential were encountered.

During this event, large areas over the South Island (North Canterbury, Marlborough and Wellington regions) were exposed to a moderate to high seismic demand, which tested the soils in these regions, and caused liquefaction in soils of relatively low liquefaction resistance. This resulted in a relatively infrequent evidence of liquefaction, though there were a number of sites where liquefaction did occur. The most severe manifestations of liquefaction and related effects occurred to the north and east of Blenheim along the Wairau River, particularly in abandoned channels and meander bends of the Wairau River (as illustrated in Figure 12). The stopbanks and vineyards constructed on abandoned channels suffered significant damage, while adjacent land was relatively undamaged. While there were several instances of localised effects of liquefaction in urban areas, in most of the cases liquefaction affected predominantly land in rural areas. There was clear evidence that liquefaction and lateral spreading affected bridges in the areas of North Canterbury and Marlborough, and such effects were contributing to the overall damage and performance of the bridges, together with the inertial loads and soil-structure interaction.

Liquefaction occurred in the reclaimed land along the Wellington Waterfront, with the most significant impacts occurring at the CentrePort. Characteristic effects of liquefaction and associated ground movements including soil ejecta, ground cracks, differential ground settlement and lateral displacements affected some of the wharves and buildings. Minor cracking and settlement was identified at other locations along the Wellington waterfront, adjacent to wharves and buildings, and minor ejecta was identified around the stadium.

(a)

(b)

Figure 12. Liquefaction-induced lateral spreading along the Wairau River (Blenheim area): (a) large ground fissures and cracks in the zone adjacent to the river (spreading displacements in the area were in the range between 2m and 5m); (b) massive sand boils indicating severe liquefaction in the soils inland behind the river banks (approximately 20m to 50m distance from the river) (photos: Misko Cubrinovski).

6 DISTRIBUTED INFRASTRUCTURE

With high intensity shaking experienced over a wide area of the upper North and lower South Island, a number of infrastructure networks were impacted by the Kaikoura earthquake.

6.1 Utility and Telecommunication Disruption

Widespread power outages occurred across upper North and lower South Island but power was reinstated in most areas the day of the earthquake. Two days after the earthquake, Kaikoura and other small rural settlements in North Canterbury and Marlborough were the only locations still without some utilities. In North Canterbury approximately 7,000 homes and businesses were initially without power, reducing down to approximately 1,200 two days after the event. By 8:00 P.M. on November 14, 2016, only 800 houses were still without power in Marlborough, mainly in settlements to the south east of Blenheim.

Fixed line telecommunications were impacted in North Canterbury, with over 10 breaks in the fibre optic cable along SH1, however cell services in most areas were restored within 24 hours of the event. Telecommunications companies worked together to share infrastructure and provide back-ups for their systems.

6.2 Transportation Infrastructure

Damage to the transportation infrastructure resulted in major disruptions following this earthquake. In Wellington, CentrePort suffered liquefaction induced damage (see Section 5.2 on Liquefaction).

The most severe damage was experienced by the road and rail networks along the east coast of the South Island. Landsliding, fault rupture, bridge damage (shaking- and liquefaction-induced) and road/rail platform instability closed a large section of State Highway 1 north and south out of Kaikoura and the main north rail line from Ward south to Cheviot. Figure 11 shows examples of common damage observed along this route. Closure of the inland road route south from Kaikoura isolated the town. There was widespread slumping of bridge approaches, with main bridges north and south of Kaikoura experiencing vertical offsets between approaches and the deck, and lateral displacement of deck sections and piers. The timeline for full reinstatement of routes is at this stage not clear, with current estimates of months for road and over a year for rail. All rail transportation was halted, with freight shifted onto new coastal shipping services and additional road services. Kaikoura was inaccessible by land for three days, with an inland access road partially cleared initially for emergency vehicles and then opened for scheduled convoys 11 days after the event. Full access to Kaikoura for two way traffic via the inland route was opened on December 19, 2016, 35 days after the event. State Highway 1 south of Kaikoura reopened to traffic during daylight hours on December 21, 2016. There is currently little redundancy in the land transport network, with one 45 km stretch of highway serving as the only paved land transportation link between the northern and southern parts of the South Island, with all freight and normal traffic using this route. The significant increase in the level of traffic on this route will require accelerated maintenance and improvements of the surface.

7 BUILT ENVIRONMENT AND LANDSCAPE IMPACTS IN KAIKOURA, NORTH CANTERBURY, AND MARLBOROUGH

7.1 Kaikoura Township Impacts

Coastal uplift had extensive impact on the local marine ecology in Kaikoura (Figure 13), and has compromised the use of port facilities used by local tourism operators except at high tide. One interesting co-seismic phenomenon has been the appearance of submarine outgassing at Kaikoura Peninsula, now named Hope Springs.

As described in the tsunami section of this report, there was evidence of tsunami run-up on the northern side of Kaikoura Peninsula, however a combination of the low tide at the time and significant co-seismic coastal uplift meant that tsunami in fact had little impact on the town itself.

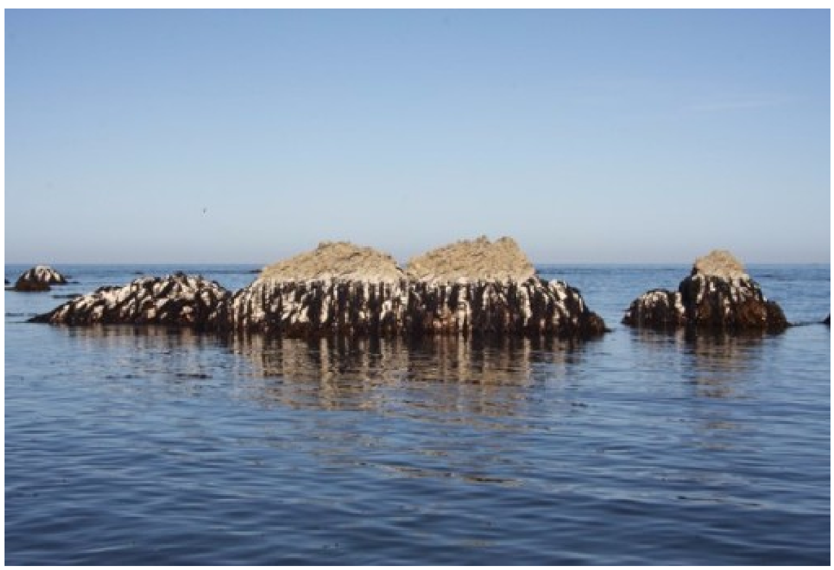


Figure 13. Uplifted rocks just offshore from Kaikoura township. The uppermost extent of the dark-coloured seaweed was formerly the low tide level (photo: Matthew Hughes).

In Kaikoura, some minor rock fall occurred along its limestone cliffs, with small soil collapses on road cuts.

The Kaikoura District Council indicated that as of February 21, 2017, there were 36 red-tagged buildings (34 residential and 2 commercial) within the Kaikoura community as well as surrounding rural areas within the Council's district boundaries. There were an additional 269 structures yellow-tagged (235 residential and 34 commercial), and nearly 1,900 white-tagged structures. The Kaikoura District Council had moved into its new administration building, designed with post-tensioned rocking walls with dissipative fuses (PRES-LAM technology), just prior to the earthquakes and the structure remained fully functional and able to house the emergency operations centre and considerable mutual aid that came from the national government, regional and local councils, the NZ Red Cross and other aid organizations.

Other damage included street lights and power poles snapping at their bases or being tilted, cracking and displacement of road surfaces and footpaths, spalling of concrete street curbs and channels, and toppling of unreinforced masonry fences. Examples of damage are shown in Figure 14.

(a) (b)

Figure 14. Damage in Kaikoura, including: (a) toppled entrance to the local hardware store, and (b) toppled and broken headstones at Kaikoura Cemetery (photos: Matthew Hughes).

Kaikoura's potable water and waste water systems were disrupted. The sanitary sewer system sustained significant damage due to ground uplift and deformation in the northern reaches of the Kaikoura community. The New Zealand Defence Force and other agencies provided emergency supplies through tankers, bottled water and desalination units, and portaloos and chemical toilets were distributed around the community. The potable water system has been largely restored through emergency repairs, although a boil water notice remains in place at the time of publication. The waste water system has also been restored, with people again being able to use their residential toilets.

As described in the Distributed Infrastructure section, ground failures and shaking induced damage blocked all land access to Kaikoura in the days following the earthquake, with limited public access from two southern routes resumed more than one month after the earthquake. Despite efforts made to provide access to the town from the south (see Section 6 on Distributed Infrastructure), as a tourist town dependent on its summer trade for the bulk of its annual income, Kaikoura has suffered a major economic blow with its sudden isolation.

7.2 Building performance in other communities in North Canterbury and Marlborough

Severe horizontal (1.12g) and vertical (3.21g) peak ground accelerations were recorded in Waiau, resulting in the out-of-plane loss of veneer from residential housing, significant damage to historic stone and concrete churches and to cob cottages, as well as widespread damage and in some cases collapse of domestic chimneys. A number of significantly damaged registered historic buildings include: All Saints Church (1924, Waiau) shown in Figure 15, Waiau Lodge Hotel (1910, Waiau), Cob Cottage museum (1860, Waiau), Watters Cob Cottage (1880ca., Rotherham) and St Oswald's Church (1927, Wharenui).

Similar damage was observed in the Marlborough region. Extensive damage to masonry veneers and chimneys, as shown in Figure 16 and Figure 17, was observed in communities as far north as Seddon. Damage to chimneys in the Marlborough area was less than expected however, because many unreinforced masonry chimneys had previously been removed or replaced with lightweight flues following the Canterbury Earthquake Sequence, the 2013 Seddon earthquake, and other recent earthquakes.

In general, lightweight timber buildings with lightweight roof and wall cladding sustained little to no structural damage. However, extensive and widespread superficial damage was observed in such lightweight structures.

(a)

(b)

Figure 15. Damage to All Saints Church in Waiau showing tilting of the bell tower and significant settlement of tower foundation (photos: Dmytro Dizhur and Marta Giaretton).

(a)

(b)

Figure 16. Widespread disintegration and detachment of chimneys, with examples from (a) Hamner Springs and (b) Waiau (photos: Dmytro Dizhur and Marta Giaretton).

(a)

(b)

Figure 17. Damage to single family homes in Waiau including (a) partial collapse of modern brick veneer system, and (b) collapse of external house cladding (photos: Dmytro Dizhur and Marta Giaretton).

8 PERFORMANCE OF THE MARLBOROUGH WINE INDUSTRY

The Marlborough region forms 66% of New Zealand's total wine producing area and the M7.8 Kaikoura earthquake has again affected the industry, following earlier damage in the 2013 Seddon earthquake. Initial estimates indicate that approximately 80% of the wine storage tank capacity in the Marlborough area is undamaged, with the rest being impaired. Wine loss as a result of the earthquakes amounted to just over 2% of Marlborough's total annual production. The following damage was commonly observed and is shown in Figure 18 and Figure 19:

- Damage to tank anchoring systems
- Shear and pull-out failures of some storage tank anchoring connections
- Damage to the walking platforms atop of tanks due to tank movement
- Buckling and overturning of storage tanks
- Collapse of stacking systems - particularly wooden barrel storage.

Figure 18. Damage to the walking platforms atop of tanks and anchoring connections due to tank movement (photos and annotations: Dmytro Dizhur).

(a) (b)

Figure 19. (a) Diamond buckling of tanks and shear failure of connections. (b) Collapse of stacking systems - wooden barrel storage (photos: Dmytro Dizhur).

A reconnaissance effort in the region has been initiated in collaboration with several interested parties, including New Zealand Wine, Wine Marlborough, Ministry of Primary Industries (MPI), Ministry of Business, Innovation, and Employment (MBIE), Tourism New Zealand, engineering consultants, and researchers from the University of Auckland, Lincoln University, LandCare Research, Massey University, and University of Canterbury. The aim is to develop a collaborative industry view adding value to the wine industry by documenting the extent of damage that has been experienced, correlate these observations against damage sustained to the wine industry in past earthquakes in New Zealand and overseas, and assist with interactions and recommendations for future design improvements to add earthquake resilience to the industry. Researchers have installed a number of accelerometers throughout one winery in order to measure the short term dynamic response of these structural systems during aftershock activity, to assist in better understanding how improvements could be made in future designs.

9 BUILDING IMPACTS IN WELLINGTON

As noted previously, the Kaikoura earthquake exhibited low spectral demands in the short period range throughout Wellington which meant that most short stiff buildings experienced well below code-level shaking demands during the earthquake. As a result the URM and other low strength but stiff buildings were un-tested and suffered little to no damage. This includes numerous existing earthquake-prone buildings throughout the city.

The earthquake did, however, test the modern engineered structures with a fundamental period near 1.5 sec, especially those on reclaimed sites around the port area or affected by basin effects. Seismic demands for such buildings often exceeded the code-level spectrum and structural components were subjected to repeated cycles of inelastic deformation.

One 5-story ductile concrete frame building (plus lightweight penthouse) located on reclaimed land for the port lost support for precast double tee floor units during the earthquake. The frame parallel to the floor unit span showed clear evidence of beam elongation. The performance of this building is the subject of a NZ Government investigation.

Through early observations of the performance of buildings by engineers conducting post-earthquake assessments, it is apparent that damage has been concentrated in 5-15 story concrete moment frames with precast flooring systems. Highest concentration of damaged buildings has been on sites where basin effects and/or soft soils have amplified the demands in the 1-2 second period range. The duration of the earthquake has also meant that these structures were likely subjected to multiple cycles of inelastic action. The following critical damage states have been observed:

- Reduced seating for precast floor units due to beam elongation in supporting frames and unit support damage. The most vulnerable buildings to loss of support for precast units are those where there are multiple frame bays in parallel with a single span of flooring, leading to larger beam elongation demands over the length of the floor unit.
- Cracking of precast floor units. Specific concern is focused on cases of cracks transverse to the span of the unit near the support, indicating reduced capacity to support gravity loads.
- Fracture of mesh in precast diaphragm topping. This is specifically a concern for pre-1995 buildings where additional ties in the diaphragm are not typically provided for lateral support of columns.
- Damage to corner columns of concrete moment frames due to frame elongation and shear demands.

The above described building and damage profile has become the focus of a targeted damage assessment program developed by Wellington City Council for 72 buildings throughout the CBD.

Extensive non-structural damage was observed to some commercial office buildings throughout the Wellington area including to hung ceiling and building services systems (Figure 20), external and internal wall cladding systems and architectural finishes at seismic joints within building complexes. The damage was similar to that observed in other recent earthquakes in New Zealand causing buildings to be closed for repairs and economic losses. Excellent performance of ceilings, building services and fire sprinklers was observed where these had been adequately braced for seismic impacts illustrating the benefits of bracing. Damage to exterior cladding systems was observed in multiple buildings including loss of connections for precast cladding panels and damage to curtain wall systems. In some cases, where damaged exterior cladding posed a potential threat to public spaces, affected roadways and sidewalks were closed.

Figure 20. Typical ceiling damage observed in commercial buildings (photo: Helen Ferner).

10 EMERGENCY RESPONSE AND MANAGEMENT

New Zealand has a tiered emergency governance system defined by the Civil Defence and Emergency Management Act (CDEM) of 2002. Within this system, the central government leads in policy and direction setting and local authorities (i.e. district, city and regional councils) are responsible for implementation as well as coordination. At the national level, the Ministry of Civil Defence and Emergency Management housed in the Department of Prime Minister and Cabinet (DPMC) staffs the National Crisis Management Centre and supports the national Minister of Civil Defence during emergencies. At the local-level, Civil Defence Emergency Management Groups (CDEM Groups) are the key coordination bodies for local authorities to work in partnership with emergency services (e.g. fire and ambulance services), central government (e.g. police and armed forces) and non-government agencies (e.g., infrastructure services, social agencies, and non-governmental organizations (NGOs)) on local-level response and recovery.

In the hours following the November 14 earthquake, three CDEM groups activated their emergency coordination centres. Two CDEM groups—the Canterbury and Marlborough CDEM groups—activated on the South Island and one CDEM group—the Wellington Region CDEM group—activated on the North Island.

- **The Canterbury CDEM group** involves eight district councils, the Christchurch City Council, and Environment Canterbury—the Canterbury Regional Council. While over 600,000 people reside in the Canterbury region, only about 15,000 people live in the Hurunui and Kaikoura district council areas—the two most heavily impacted councils in the Canterbury CDEM group and located in the northern reaches of the region.

- **The Marlborough CDEM group** represents the Marlborough District Council which is home to about 43,500 people.

- **The Wellington Region CDEM group** involves four district councils, four city councils, and the Greater Wellington Regional Council. Over 470,000 people resident in the Wellington region but the earthquake mainly affected three city councils in the more densely developed southern reaches of the island—the Wellington City Council with 191,000 residents, Hutt City Council with 40,100 residents, and Porirua City Council with 51,700 residents.

New Zealand emergency management operates with a form of the Incident Command System (ICS) called the Coordinated Incident Management Systems, or CIMS. Under CIMS, each response organization is led by a controller who leads the incident control function and oversees the other functional areas of intelligence, planning, operations, logistics, public information management, and welfare. In responding to the Kaikoura earthquake, a national controller led CIMS-based operations at the National Crisis Management Centre and interfacing with the Acting Minister for Civil Defence, Gerry Brownlee. Mr. Brownlee has also served, for the last six years, as the key ministerial contact for response and recovery following the Canterbury Earthquake Sequence. In addition, three Group Controllers have overseen the CDEM Group Emergency Coordination Centres, providing resources and support to the Local Controllers leading activated local emergency operation centres.

In the first days to weeks following the earthquake, the multi-level governmental response to the Kaikoura earthquake focused first on tsunami-related evacuations, life safety, building and infrastructure damage assessment, access provision and control, and social welfare services including the provision of food, water and temporary accommodation to those in need. Given the relatively focused pattern of damage, there was additional resource capacity within each of the CDEM groups to support the most heavily impacted local district and city councils. For example, personnel from the southern part of the Canterbury region provided additional support to local emergency operations in the Hurunui and Kaikoura districts. The Marlborough CDEM group also took on emergency responsibilities for the northern part of Kaikoura District after coastal landsliding severed access from the south and the Kaikoura District offices. Furthermore, CDEM groups received resources via the national controller from central government as well as unaffected parts of the country.

Under the CDEM Act of 2002, the national Minister of Civil Defence has power to declare a state of national emergency and local authorities and CDEM Groups may declare a state of local emergency. The emergency powers include: the publishing of public information relating to an emergency; the conferment of various powers on incident controllers and police to, for example, order the evacuation of buildings, enter buildings to protect life, close roads, remove aircraft and other means of transport, requisition property, give directions, and carry out inspections. A state of emergency declaration generally lasts seven days but can be repeatedly extended.

Following the November 14th earthquake, states of emergency were declared by the Hurunui and Kaikoura District Councils. Both of these councils faced substantial building and infrastructure damage and massive landslides blocked railroad and highway routes within the districts. The emergency declarations helped districts to gain additional staff and resources necessary to carry out response operations. Other local authorities that did not declare states of emergency instead relied upon normal government authorities and the mutual aid system that New Zealand's multi-level emergency management structure provides to fulfill their emergency response obligations.

11 RECOVERY ORGANIZATIONAL EFFORTS

Following the 2010-2011 Canterbury Earthquake Sequence, the Ministry of Civil Defence and Emergency Management led a comprehensive review of the country's legislative framework for recovery which resulted in the introduction of a Civil Defence Emergency Management (CDEM) Amendment Bill to Parliament in 2015. The CDEM Amendment Bill had progressed through its third reading and was awaiting final approval when the November 14, 2016 earthquake struck. The bill became a formal Act of Parliament on November 15, and then, on November 29, Parliament acted with urgency to allow provisions of the CDEM Amendment Act to be used to support recovery from the Kaikoura earthquakes. A key feature of the CDEM Amendment Act is the introduction of a transitional recovery period as a mechanism to help facilitate a smooth and coordinated transition of arrangements and powers from the country's CIMS-based emergency management structure to a recovery management structure. The transition period powers include the ability to enter, examine and mark buildings; restrict public access and close roads; require assessments of buildings or types of buildings; and carry out emergency-related projects. The transition period notice can be given at either the national or local level, and it generally lasts for 90 days but can be extended.

National officials have elected to use the transitional recovery management structure provided in the CDEM Amendment Act rather than to establish a central government department to lead recovery, as they did with the Canterbury Earthquake Recovery Authority following the Canterbury Earthquake Sequence. On December 9, 2016, the Acting Civil Defence Minister gave notice of a National Transition Period to apply to the Kaikoura, Hurunui and Marlborough district councils and officially ended the states of emergency declaration in place in local councils on that same day. The Director of Civil Defence Emergency Management Minister also appointed a National Recovery Manager to oversee use of the national-level use of transition period powers and coordinate recovery activity across the district councils and central government agencies.

Wellington City Council also received transition period approval from the Acting Minister of Civil Defence, and is using the transition period powers to require building owners to share the results of earthquake-related building inspections with the Council. The Wellington City Council has appointed its Chief Resilience Officer to serve as Recovery Manager and also established a one-stop shop called ERIC (Earthquake Recovery Information Centre) to help people and businesses in earthquake recovery. The Kaikoura District Council has appointed a former mayor to serve as Recovery Manager and entered into short-term employment contracts and memoranda of understanding with other councils on the South Island to augment staff to support recovery.

New Zealand's Parliament has approved a suite of legislation, including the Hurunui/Kaikōura Earthquakes Emergency Relief Act 2016 and the Hurunui/Kaikōura Earthquakes Recovery Act 2016, intended to exempt, modify, or extend provisions in certain laws and plans to assist with earthquake recovery. This includes modifying environmental review requirements, under the Resource Management Act 1991 (RMA,) for earthquake-related public works projects, such as restoration of the Kaikoura harbor, and the coastal highway and rail corridor, and it has committed funds for their repair. A government-contractor alliance, known as the North Canterbury Transport Infrastructure Recovery (NCTIR) and modeled after the Stronger Christchurch Infrastructure Rebuild Team (SCIRT), has been established to led the design and construction of the repair to the coastal highway and rail corridor around Kaikoura which is estimated to cost up to NZ$2 billion.

According to the Aon Benfield 2016 Annual Global Climate and Catastrophe Report, total economic losses for the Kaikoura earthquakes are expected to be US$3.5 billion (NZ$4.9 billion) losses with 60% of the losses covered by insurance. As of January 24, 2017, the Earthquake Commission (EQC)—New Zealand's government-backed residential earthquake insurance—has logged over 21,000 claims for damage to residential structures, contents, and/or land. The EQC provides coverage up to NZ$100,000 for structures and up to NZ$20,000 for contents, and many policyholders also purchase supplemental cover beyond these limits from private insurers. The EQC and private insurers have struck a claims handling agreement, whereby the EQC will manage the claims settlement process for all policyholders with a land damage claim and private insurers will handle claims settlement for all their policyholders with only structural and/or contents related claims even if the claims value is under the EQC caps. This is a markedly different approach from the residential claims settlement practices following the Canterbury Earthquake Sequence and aimed at improving the speed and efficiency of the settlement process.

New Zealand's central government has also implemented a few recovery programs to assist small businesses, rural farmers and other rural industries with uninsured losses. One noteworthy program is a wage subsidy package targeting small businesses in the hardest-hit parts of the Hurunui, Kaikoura and Marlborough districts announced on November 17, 2016; it was later expanded to include impacted small businesses in the Wellington region. The package was modeled on the popular wage subsidy package for small businesses provided after the September 2010 and February 2011 Canterbury earthquakes. The wage subsidy program for the Kaikoura earthquakes targets impacted businesses with fewer than 20 employees and it covers up to eight weeks of wages at a rate of NZ$500 gross pay per week for a full time employee and NZ$300 gross pay per week for a part time employee. The subsidy program has been extended for an additional eight weeks in the Kaikoura and Hurunui districts and the Wellington region.

12 ISSUES FOR RECOVERY

Recovery is always complex, but recovery from the Kaikoura earthquakes is likely to be particularly so. The effects of the earthquake are geographically widespread, with each region experiencing effects in different ways. The recovery is institutionally complex. Each territorial authority has its own recovery arrangements, and distinct differences in terms of size, and therefore, financial and resource bases to draw from.

Kaikoura, the worst effected district in the Canterbury region, experienced all the usual earthquake impacts associated with direct damage and infrastructure disruption. Its recovery trajectory will likely be dominated by three key effects: the restoration time and eventual reliability of, transportation routes into and out of the area; the restoration time for key tourism infrastructure (drawcard attractions such as whale watching tours are currently not operational); and the degree and nature of impacts the earthquake and land-uplift have had on the local fisheries.

Further south, and also close to the epicentre of the earthquake, the Hurunui district is a largely rural based economy. The region suffered direct damage from the earthquakes, with building and infrastructure damage, as well as substantial amounts of land damage. This land damage will likely create ongoing issues for farmers as well as infrastructure providers in the region as landslips, associated aggregate dams, and other geomorphological changes to rivers and land will continue for many years to come. The district is also experiencing indirect effects from the re-routing of major transport routes within the region. The town of Cheviot has found itself currently at the end of the road, rather than being situated as a stopping point on a busy thoroughfare. The Kaikoura earthquakes have come on the back of three years of drought for the region, and so the compounding impacts of the earthquake on top of already strained financial resources may create challenging dynamics during the recovery. In other parts of the region, small towns and the roading infrastructure are having to cater for far more traffic than they would ever normally expect.

The Marlborough region was still recovering from significant shaking in 2013 from the Seddon earthquakes, which caused damage throughout the region. As noted in Section 8, the region's economically important wine industry experienced significant losses in both the 2013 and 2016 earthquakes, including damaged storage tanks and production infrastructures. The damage caused by the latest events was mitigated in part by the time of year and the fact that many wineries had invested in retrofit solutions following the 2013 earthquakes.

Key issues for the region during the recovery will likely be pressure points from shifts in transport patterns following the earthquakes. Available road infrastructure is facing increased congestion and deteriorating condition from increased use. Other key parts of infrastructure, such as the port at Picton, may see reduced demand as some freight shifts towards coastal shipping.

The Wellington region was also significantly affected by the earthquakes, with the long duration earthquake proving damaging for tall buildings and those located on poor soils. As of December 7, 2016 approximately 11% of Wellington office space had been closed due to damage assessments, creating business continuity issues for organizations around the city and making it very difficult for businesses to find alternative available premises. Two building demolitions in Wellington and one in Lower Hutt have also led to local cordons with impacts on neighboring businesses. Restoration of Wellington's container crane services are underway and expected to be complete as early as June 2017. In the meantime, container traffic has been diverted to other ports in New Zealand and then transferred to rail or truck for distribution. The short- and long-term effects on supply chains and goods delivery, as well as the local and regional economy, are still unknown. They are nonetheless important areas of recovery research following this earthquake. Perhaps one of the biggest concerns for the Wellington's recovery, however, is uncertainty about future earthquakes affecting the region and elevated concerns about the readiness of the city and its infrastructure to cope with such an event, particularly given the current heightened seismic risk during the aftershock sequence.

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15 END NOTES AND REFERENCES

[1] QuakeCoRE, 2016. Special Edition QuakeCoRE Newsletter– Kaikoura Earthquake, available at http://us10.campaign-archive1.com/?u=c65a2a0813835c484fde76107&id=764a87e2fc, December 2016.

[2] Wilson, R., and Johnson, L., 2017, EERI Preliminary Notes on Tsunami Damage and Response: Tsunami Generated by M7.8 Kaikoura, New Zealand, Earthquake on November 14, 2016: EERI. http://www.eqclearinghouse.org/2016-11-13-kaikoura/files/2017/01/EERI-Recon-Rpt-111316-NZ-tsunami_final.pdf

[3] Earthquake Engineering Research Institute (EERI), 2016c. Kaikoura, New Zealand Earthquake Field Observation Map, available at: http://arcg.is/2f1kXJK (accessed January 2017).

[4] United States Geological Survey (USGS), 2016a. M7.8 – South Island of New Zealand: ShakeMap GIS file, available at http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/1000778i/download/shape.zip (accessed January 2017).

[5] Bradley, B. A., H. N. T. Razafindrakoto, and V. Polak (2017). Ground motion observations from the 14 November 2016 Mw7.8 Kaikoura, New Zealand earthquake and insights from broadband simulations, Seismological Research Letters (DOI: 10.1785/0220160225).

[6] GeoNet website, "M7.8 Kaikoura Quake: Future Scenarios and Aftershock Forecasts," available at http://info.geonet.org.nz/display/quake/2016/11/14/M7.8+Kaikoura+Quake%3A+Future+Scenarios+and+Aftershock+Forecasts (accessed January 2017).

[7] GNS Science / Te Pū Ao website, "Aftershock rate and hazard modelling for the Mw7.8 14/11/2016 Kaikoura Earthquake" webpage, available at https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards/Earthquakes/Earthquake-hazard-modelling/M7.8-Kaikoura-Earthquake-2016 (accessed January 2017).

[8] Wilson, R., Johnson, L., 2017. EERI Preliminary Notes on Tsunami Damage and Response: Tsunami Generated by M7.8 Kaikoura, New Zealand, Eathquake on November 14, 2016., available at:

http://www.eqclearinghouse.org/2016-11-13-kaikoura/files/2017/01/EERI-Recon-Rpt-111316-NZ-tsunami_final.pdf

[9] GeoNet website, “Nov. 14, 2016 Kaikoura earthquake and tsunami,” available at http://info.geonet.org.nz/display/home/2016/11/14/M7.8+Kaikoura+Earthquake%3A+Latest+updates (accessed January 2017).

[10] Daly, M. (2017). Kaikoura Earthquake tsunami was as high as 7 metres at one spot, *Stuff*, 28 March 2017, available at: http://www.stuff.co.nz/national/90773348/kaikoura-earthquake-tsunami-was-as-high-as-7-metres-at-one-spot

[11] Wilson, R., 2011, Field work and observations from Japan, five months after the M9.0 Tohoku Earthquake and Tsunami of March 11, 2011: travel blog submitted Sept. 29, 2011; 23 p. http://www.eqclearinghouse.org/2011-03-11-sendai/files/2011/09/RWilson-Japan-tsunami-blog.pdf

[12] Wilson, R.I., Admire, A.R., Borrero, J.C., Dengler, L.A., Legg, M.R., Lynett, P., Miller, K.M., Ritchie, A., Sterling, K., McCrink, T.P., and Whitmore, P.M., 2012. Observations and impacts from the 2010 Chilean and 2011 Japanese tsunami in California (USA), *Pure and Applied Geophysics*, available at: http://dx.doi.org/10.1007/s00024-012-0527-z.

[13] McDonald, L. (2016). Little Pigeon Bay cottage smashed by tsunami waves, *Stuff*, 14 November 2016, available at: http://www.stuff.co.nz/national/nz-earthquake/86443298/Little-Pigeon-Bay-cottage-smashed-by-tsunami-waves

[14] Perry, N., 2016. : Huge quake exposes problems in how New Zealand prepares, *Associated Press*, 19 November 2016, available at: http://bigstory.ap.org/article/94e978d49afd459fb33b31c1c2320d88/huge-quake-exposes-problems-how-new-zealand-prepares

[15] Morris, C., 2016. Tsunami threat: A question of timing, *Otago Daily Times,* 3 December 2016, available at: https://www.odt.co.nz/news/dunedin/insight/tsunami-threat-question-timing

[16] Rattenbury, M.S.; Townsend, D.; Johnston, M.R. (compilers), 2006. Geology of the Kaikoura area: scale 1:250,000 geological map. Lower Hutt: GNS Science. Institute of Geological & Nuclear Sciences 1:250,000 geological map 13. 70 p. + 1 folded map

[17] Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an update. Review article. Landslides. April 2014. Volume 11. Issue 2, pp 167-194.