Shaky Shores

Coastal impacts & responses to the 2016 Kaikōura earthquakes

Special Publication 3, 2018

Te Hunga Takutai o Aotearoa
NEW ZEALAND
COASTAL SOCIETY

The New Zealand Coastal Society was inaugurated in 1992 'to promote and advance sustainable management of the coastal environment'. The society provides a forum for those with a genuine interest in the coastal zone to communicate amongst themselves and with the public. The society currently has over 400 members, including representatives from a wide range of coastal science, engineering and planning disciplines, employed in the engineering industry; local, regional and central government; research centres; and universities.

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Foreword

Tom Shand, NZCS Chair

Just after midnight on 14 November 2016, the 'Shaky Isles' of New Zealand shook for two minutes. A series of faults unzipped in the north-eastern South Island from Culverden to Cape Campbell as tectonic pressures were released and shifted. While the event originated in that region, it was felt across the nation.

After a long night for many listening to the earth and the ocean settle and waiting for tsunami evacuation instructions to be issued and rescinded, the dawn brought the first glimpses of the event's scale – hillsides were disfigured with fault ruptures and landslip scars, a hundred kilometers of coastline was uplifted exposing subtidal reef and marine habitats, and communities were fractured and cut off as road and rail was twisted, torn and buried. Two lives were lost. This was the most significant seismic event to occur on the New Zealand mainland since the 1931 Napier Earthquake.

The Kaikōura coastal area, which was directly impacted, is an area that is of great cultural significance and is renowned for its scenery, ecosystems and tourism experiences. The impact of the Kaikōura-Hurunui Earthquake and the coastal uplift has etched this date on the minds of many New Zealanders. What followed was a huge response and recovery effort that still continues to this day.

Starting in the first hours after the earthquake New Zealand Coastal Society (NZCS) members, from emergency responders, to engineers, planners and scientists, have been involved in the response and recovery efforts. Whilst these endeavours continue, much of the work has now moved into 'business as usual'. The NZCS would very much like to acknowledge all of the tireless effort that has gone into supporting the communities impacted by the earthquake to respond and make the journey towards recovery.

As part of the NZCS focus on advancing knowledge about the coastal area, this publication offers an assessment of the many aspects of that response and recovery and shares some of the lessons learnt. The authors are some of New Zealand's leading scientists, engineers, coastal and emergency managers and they are thanked for their efforts in sharing their knowledge.

The first section of the publication focuses on the physical effects of the earthquake including the seismic event and deformation of the coastline, the generated tsunami, and the less evident, but large-scale, submarine landslides.

The second section focuses on the impacts on the ecological, social and built environment, including some of the challenges related to evacuation and the immediate post-event response.

The third section focuses on longer-term response and rehabilitation, including the massive construction efforts required to repair, reopen and strengthen road and rail, some of the legislative measures required to enable this, and some of the ongoing issues as we transition back into business as usual. North Canterbury was not the only region to experience the direct effects of the earthquake, with parts of Wellington – particularly around the waterfront and port – suffering damage; this and some of the repair challenges are also discussed.

This publication looks specifically at the coastal impacts and response to the Kaikōura earthquakes. But the NZCS also wants to acknowledge the impacts that the event has had on the people and communities throughout the region, and the disruption it has caused to many people's lives and livelihoods. It is hoped this publication helps to share some of the lessons learnt to support preparing for and responding to similar disasters in the future.

Post-quake Kaikōura Peninsula (Photo: Bare Kiwi)

Kaikōura – by the numbers

12.02 am

14 November 2016

~2
minutes – length of quake event (approx.)
[1]

3$^+$
g – peak ground acceleration
[2]

–2.5-6.5
m – coastal ground displacement (vertical)
[3]

7.8
earthquake magnitude (cumulative)
[1]

12
m – maximum ground displacement (horizontal)
[1]

~15
km – quake depth
[4]

21
number of faults involved
[5]

8000
kilotonnes – energy produced by the quake, TNT equivalent
[6]

20,200
number of aftershocks as of 22 November 2017
[7]

6.9
m – tsunami peak height (Goose Bay)
[1, 2]

~110
km – extent of coastal uplift and deformation
[1]

180
km – length of coastline affected
[1]

200$^+$
m – inland deposition of tsunami seaweed and debris
[2]

11,000$^+$
landslides (200 creating temporary dams)
[2]

9.4×10^8
m^3 – material eroded in the submarine canyon
[8]

16
days – Kaikōura without road access post-quake
[9]

306
days – to reinstate rail line from Picton to Christchurch
[10]

309
days – to reinstate CentrePort's container cranes
[11]

397
days – to reinstate SH1 from Picton to Christchurch
[12]

1200
buildings damaged/demolished in Wellington
[13]

1.84×10^9
$ – total cost of insurance claims
[14]

$2\text{-}3 \times 10^9$
$ – estimated cost to government of earthquake damage
[15]

Earthquake ⬢
Coastal ⬢
Infrastructure ⬢

Sources

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Section 1: The physical effects


Kaikōura coastal uplift (Photo: Don Neale)

The 2016 M_w 7.8 Kaikōura earthquake and tectonic deformation of the Kaikōura coastline

By Kate Clark

Introduction

Within hours of the 14 November 2016 Kaikōura earthquake photos and footage of uplifted seabed with stranded paua and limp, drying bull kelp were in the media and rapidly propagated around the world. Such images conveyed one of the most readily apparent and devastating impacts of the earthquake – many metres of coastal uplift affecting nearly 100 km of one of New Zealand's most scenic and ecologically rich coasts. From a geological perspective, the spatial detail of coastal deformation offered valuable information about the faults that ruptured during the Kaikōura earthquake, particularly shedding light on the role of offshore faults that were responsible for triggering the tsunami.

This article provides an overview of the Kaikōura earthquake, describes the coastal deformation and the methods used to measure it, and places this event in the context of New Zealand's rich historic record of coastal change caused by earthquakes and the geological record of past uplift along the Kaikōura coast.

The Kaikōura earthquake

The Kaikōura earthquake occurred just after midnight on the 14th November 2016. The M_w 7.8 earthquake initiated at ~15 km depth and ~4 km south of the north Canterbury rural township of Waiau, located 32 km inland from the coast and 60 km southwest of Kaikōura Peninsula[1]. The earthquake occurred in a complex tectonic regime at the transitional zone between the westward-dipping Hikurangi subduction zone to the northeast and the Alpine fault to the southwest (see Figure 1).

Historically, large earthquakes have occurred to the west (1888 M 7.0 North Canterbury earthquake) and north (1848 M 7.4 Awatere earthquake) and the earthquake occurred in an area of well-known high seismic hazard[2]. Nevertheless, the Kaikōura earthquake, which lasted for ~2 minutes, was unprecedented in its complexity, propagating 170 km towards the northeast along a sequence of connected and disconnected faults[3]. Many of the faults that ruptured were mapped prior to the earthquake but some, such as the Papatea fault, were not.

Rupture reached the ground surface on more than 20 faults and the varying amounts and senses of displacement across the faults produced a highly variable ground deformation pattern. Geodetic measurements of ground surface displacement using Interferometric Synthetic Aperture Radar (InSAR) and GPS (continuous and campaign) data showed metre-scale displacements over a very broad region[4]. Fault surface rupture field surveys revealed the largest horizontal displacements of up to 12 m along the Kekerengu fault and vertical movement of up to 9 m on the Papatea fault[5]. In addition to the rupture of multiple crustal (also called upper plate faults), the underlying Hikurangi subduction interface may have also ruptured. This currently remains an unresolved

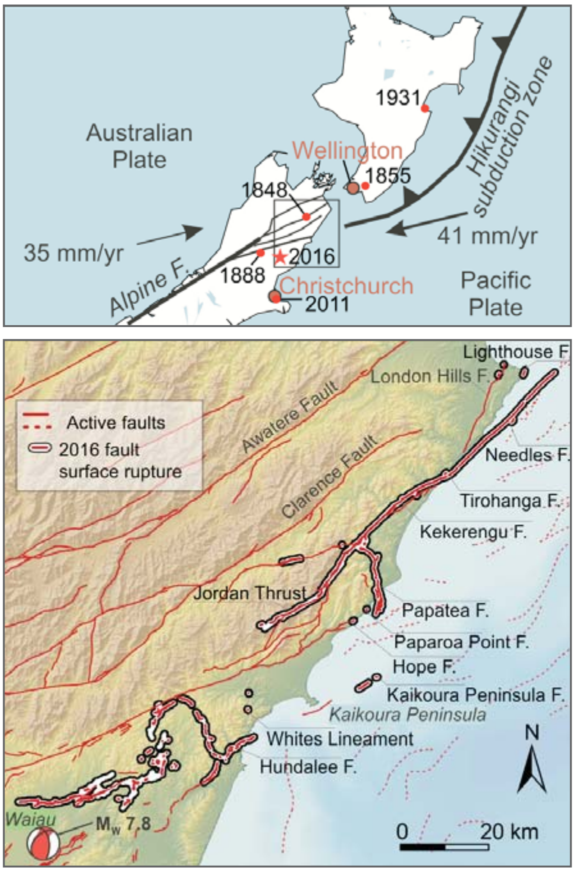

Figure 1: Upper panel shows the tectonic setting of the 2016 Kaikōura earthquake with significant historic earthquakes mentioned in the text shown by red dots. Lower panel shows the fault surface ruptures of the 2016 Kaikōura earthquake.

aspect of the Kaikōura earthquake. The Kaikōura earthquake also generated more than 10,000 landslides over an area of about 10,000 km^2, and several hundred of these occurred along the coastal slopes[6]. The coastal landslides blocked the road and main trunk railway in multiple locations and were also sources of a significant amount of sediment entering the marine environment.

Coastal deformation in the 2016 Kaikōura earthquake

The spatial pattern of coastal deformation that occurred in the Kaikōura earthquake is the most highly variable observed in any global earthquake in modern times. Along 110 km of coastline, the vertical displacement ranged from -2.5 to 6.5 m (see Figures 2 and 3). The high variability reflects the complexity of the earthquake – three major and multiple minor fault ruptures crossed the coastline and the coast was also deformed by the rupture of one or more entirely offshore faults. Another remarkable aspect of the Kaikōura earthquake coastal deformation is the high-precision and high-resolution record of deformation that was obtained due to the suite of observation methods used for measurement, namely a combination of airborne LIDAR differencing, field surveying, and satellite geodesy[7].

Within four days of the earthquake, a team of geologists undertook a field survey of the coastline in conjunction with marine ecologists[7]. Coastal uplift was measured in the field at 39 sites and the zonation of flora and fauna on rocky parts of the coastline was used to determine the amount of vertical deformation. Most commonly, the post-earthquake elevation of algae that, prior to the earthquake, lived up to and around mean low water (MLW) elevation was surveyed. The upper limit of bull kelp (*Durvillaea antarctica*) and the associated band of coralline algae was used at coastlines experiencing high wave energy, whereas the upper limit of *Carpophyllum maschalocarpum* and associated coralline algae was used in areas of lower wave energy.

The most extensive and detailed record of the Kaikōura earthquake coastal deformation was derived from the differencing of pre- and post-earthquake high-resolution topography. Airborne LIDAR surveys of the Kaikōura coastline had been conducted in July 2012 and then repeated within 5 - 7 days of the earthquake. The area of LIDAR overlap is a ~0.5 - 4 km-wide, ~90 km-long coastal strip from several kilometres south of the Haumuri Bluff to Tirohanga (see Figure 3). To calculate the coastal deformation caused by the 2016 earthquake, we (see reference 7) subtracted the 1 m-pixel 2012 LIDAR digital terrain model (DTM) from the equivalent 2016 LIDAR DTM. Slopes >5° were eliminated from the DTMs such that we only differenced the overlapping low-slope regions, and we also removed riverbeds, beaches and landslides from the analysis, as their change is not solely due to tectonic deformation. Highly precise measurements of coastal deformation were also obtained at a few points using the Kaikōura tide gauge and continuous and campaign GPS measurements.

The combination of multiple types of coastal deformation measurements shows the extensive and highly variable coseismic deformation along the Kaikōura coast (see Figure 3). If we define the coastal stretch impacted by the earthquake as the region from Haumuri Bluff to Cape Campbell (a straight line distance of 110 km), then 80 km (73%) of the coastline underwent uplift, with 48 km (44%) undergoing uplift of > 1 m. Around 28 km (25%) underwent a minor amount of subsidence (<0.5 m), with only a very localised area (2 km around the Kekerengu fault) undergoing > 1 m subsidence. Only a very minor stretch (3 km, 2%) of coastline around Peketa was not impacted by coastal deformation.

There are four peaks in coastal uplift along the coastline, centred around Oaro to Goose Bay, Kaikōura Peninsula, Half Moon Bay to Waipapa Bay, and Wharanui Beach to Cape Campbell (see Figure 3). The following describes aspects of the coastal deformation and the causative faults in each of these areas.

- At the north end of the Oaro embayment, the Hundalee fault ruptured across the coastline. At the fault scarp there was 1.2 m of vertical offset and the northern side of the fault scarp appeared visually to be the start of significant coastal uplift. Only minor coastal deformation occurred south of the Hundalee fault. Immediately north of the Hundalee fault coastal uplift peaked at ~2.2 m and north of Goose Bay the uplift gently tapered off to zero at Peketa, 11 km northeast of the Hundalee fault. The Hundalee fault is primarily responsible for uplift of this area; the fault rupture continued offshore from Oaro and projected into the head of the Kaikōura Canyon.
- The entire Kaikōura Peninsula and much of the coastline north and south of the Peninsula was uplifted by between 0.8 and 1 m. Uplift of the Peninsula and the surrounding area is attributed to an entirely offshore fault, variously named the Kaikōura Peninsula fault[8] or

Figure 2: Photos of coastline uplifted in the 2016 Kaikōura earthquake. Top photo shows the point at the north end of Waipapa Bay where the Papatea fault rupture caused 5-6 m of coastal uplift (Photo: Steve Lawson). Middle photo shows detail of the uplifted platform by the Papatea fault (Photo: Ursula Cochran). Bottom photo is from Long Point (10 km southwest of Cape Campbell) where 1.3 m of uplift occurred (Photo: Kate Clark).

the Point Kean fault[7]. It is likely that the Point Kean fault, mapped for the first time by a post-earthquake bathymetric survey[7], is a secondary strand of the Kaikōura Peninsula fault so here we simply relate Kaikōura Peninsula uplift to the Kaikōura Peninsula fault. The Kaikōura Peninsula fault lies ~1 km offshore and to the southeast of the Peninsula and trends southwest to northeast. It dips to the northwest and is most likely responsible for the broad swell of moderate coastal uplift from ~4 km south of the Peninsula up to ~16 km north of the Peninsula.

- From Mangamaunu to Waipapa Bay there was particularly high and variable coastal uplift; most of the coastline was raised >2 m and there are three faults that ruptured across the coastline. The Hope fault had minor surface rupture (<0.5 m) at Half Moon Bay. North of Half Moon Bay uplift increased from ~2 m up to 4.5 m at Paparoa Point. The peak in uplift at Paparoa Point is due to rupture of the Paparoa Point fault, which has three fault scarps running across the point with vertical offsets of 0.3 - 1 m.

  North of Paparoa Point, the coastal uplift decreased slightly before the very sharp and prominent uplift at the western strand of the Papatea fault at Waipapa Bay. Two strands of the Papatea fault cross the coastline at Waipapa Bay and between these faults the land was uplifted 5 - 6 m, creating a spectacular new rocky coastal platform extending 200 - 300 m offshore from the pre-earthquake coastline (see Figure 2). North of the Papatea fault, coastal uplift tapered off rapidly, and from the Clarence River mouth northwards there is a 25 km stretch of coastline that underwent negligible coastal deformation in the Kaikōura earthquake (<0.2 m subsidence).

- North of the Kekerengu fault, coastal uplift once again rises to 2 - 3 m. The uplift is related to rupture of the Needles fault, the offshore extension of the Kekerengu fault. Seafloor surveys immediately after the 2016 Kaikōura earthquake confirmed a fresh fault rupture across the seabed[7] and the scarp heights on the seabed were of comparable magnitude to the amount of coastal uplift seen from Wharanui Beach up to Cape Campbell. The field survey measurements showed a gradual tapering off of uplift from 2.4 m at Wharanui Beach to 0.4 m at Cape Campbell, with a sharp decrease in the amount of uplift of 0.5 m occurring near Cape Campbell across the Lighthouse fault.

Kaikōura 2016 earthquake coastal uplift in geological context

The coastal deformation that occurred in the 2016 Kaikōura earthquake is undoubtedly a startling event to have witnessed in our lifetimes, but within 'geological timescales' sudden, earthquake-driven, metre-scale uplift of the coast was not an unexpected occurrence for this area. The coastal landforms of the Kaikōura coast attest to periodic sudden uplift in earthquakes, and evidence of these events is preserved by uplifted beaches, also called marine terraces, that fringe many parts of the coastline from Oaro to Cape Campbell. Compared to more well-known uplifted beach sequences, such as Turakirae Head, near Wellington, the Kaikōura coast marine terraces have received comparatively little attention from the geological community.

Studies in the 1970s and 1980s identified marine terraces around Kaikōura Peninsula[9, 10] and a recent review of these studies concluded there was good evidence for at least three uplift events of between 1 and 3 m per event in the past ~3,000 years[8]. An unpublished study by Miyauchi et al. in the 1980s mapped marine terraces from Kaikōura Peninsula to Cape Campbell and obtained many radiocarbon ages from uplifted beach shells; these data have been

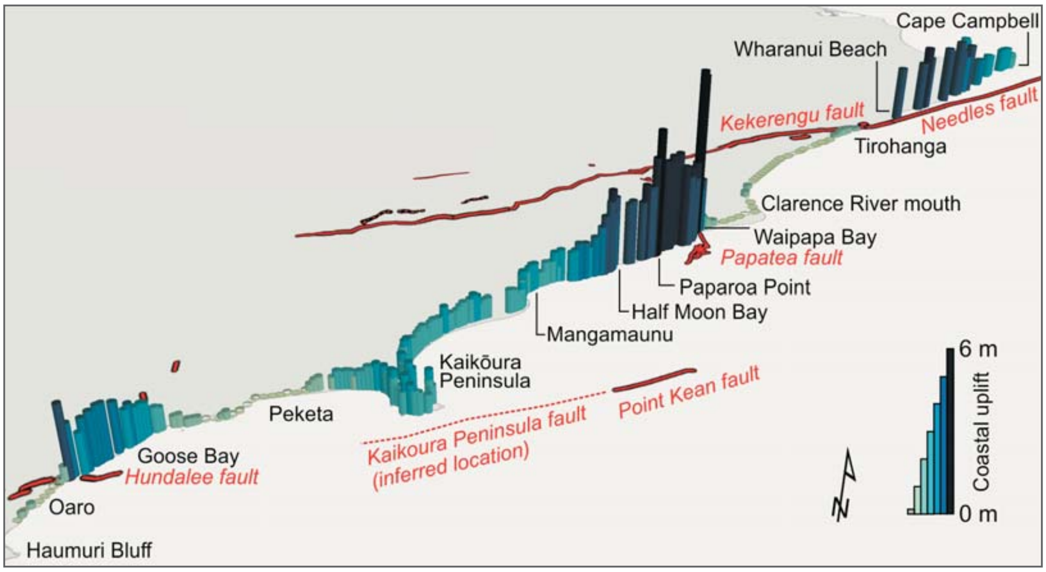

Figure 3: Coastal uplift caused by the 2016 Kaikōura earthquake. This oblique perspective map looking north along the Kaikōura coast shows a summary of uplift values obtained from field surveys and LIDAR differencing (see reference 7 for source data; negative values (subsidence) not shown).

recently compiled[11], but much of it is too poorly constrained and sparse to develop a high resolution record of the magnitude and frequency of past earthquakes that have uplifted the coastline. Improved mapping and measurement of marine terrace elevations using LIDAR topographic data, and dating of uplifted beaches using modern radiocarbon techniques, is currently the focus of a Natural Hazards Research Platform project by GNS Science and the University of Auckland.

The Kaikōura earthquake joins a number of earthquakes in New Zealand's historical period that have caused widespread sudden change to the coastline. The most notable historical events are the 1855 M 8.2 Wairarapa and 1931 M 7.8 Napier earthquakes. The Wairarapa earthquake caused coastal uplift of up to 6 m at Turakirae head, uplift of ~1m around Wellington Harbour, and <1 m subsidence in the lower Wairau Valley in Marlborough[12]. The Napier earthquake caused uplift of a ~90 km long dome from Hastings to the Mohaka River mouth; maximum uplift was 2.7 m and Ahuriri Lagoon was uplifted ~1 m leading to large-scale land reclamation of the formerly intertidal lagoon surface for the Hawkes Bay airport[13]. In more recent times, the 2003 M 7.3 Secretary Island earthquake, 2009 M 7.8 Dusky Sound earthquake, and 2011 M 6.2 Christchurch earthquake all caused minor coastal deformation of <1 m.

The landforms and geological records around the New Zealand coastline show that a large proportion of our coast is tectonically active and prone to periodic sudden shifts due to earthquakes. With intensifying development along our coastlines, the impact of coastal earthquakes and landslides will only increase unless we plan for resiliency.

The 2016 Kaikōura earthquake is a vivid demonstration of how society relies on infrastructure based on the coastal corridor and the natural process of earthquake-driven landsliding and land level change can have enormous and unanticipated impacts. Abrupt changes in land level due to earthquakes should be considered in land use planning, particularly along the east coast of the North Island where future large earthquakes on the Hikurangi subduction zone could cause widespread sudden coastal change.

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Tsunami generated by the 2016 Kaikōura earthquake

By Jose Borrero and Emily Lane

Introduction

The November 2016 M_W 7.8 Kaikōura earthquake was one of the largest earthquakes in New Zealand's recorded history, and it generated the most significant local source tsunami to affect New Zealand since the Gisborne earthquakes and tsunamis of 1947[1]. This was an unusual tsunami event in many regards.

Firstly, the epicentre of the earthquake was on land, not offshore as is generally expected for a tsunamigenic earthquake. The earthquake rupture propagated more than 150 km in approximately two minutes along numerous loosely connected faults running parallel to the north-easterly trending Kaikōura coastline (see Kate Clark's article on page 3 for more information). The resulting deformation occurred mostly on land with only the relatively small, offshore extensions of these faults causing the coastal and seafloor uplift that caused the tsunami waves.

Secondly, the tsunami generated by the earthquake was relatively benign in the immediate earthquake source area and the only damaging tsunami effects were observed at Little Pigeon Bay some 160 km away on the north coast of Banks Peninsula. This is in direct contrast to most tsunami events where the worst effects generally occur relatively close to the earthquake epicentre or area of largest sea floor deformation. This tsunami also highlighted several issues related to tsunami preparedness and hazard planning in New Zealand, particularly with regards to rapid onset, local source events and included confusion and inconsistent messaging related to evacuation (the local civil defence experience and perspective is discussed in detail in Marion Schoenfeld's article on page 15).

The tsunami source

The earthquake rupture initiated on land and generally propagated north-eastward along the Kaikōura Coast. Uplift ranging from 2 to 6 m was observed along the coastline from Oaro in the south to Cape Campbell in the north (see Figure 1). Several faults crossed the shoreline, rupturing both onshore and off, notably the Hundalee Fault, the Papatea Fault and the Needles Fault. The offshore portions of these faults are relatively small, but the uplift they experienced was comparatively large because the faults extend so far inland. Uplift also occurred on a previously unidentified off-shore fault northeast of Kaikōura. This uplift of the shoreline and seabed is what caused the tsunami. However, in contrast to 'typical' tsunamis, the patterns of uplift were relatively disjointed and complex giving rise to a complex initial tsunami wave shape containing multiple crests and troughs.

Most of the tsunami energy radiated away perpendicular to the faults with only a small amount of tsunami energy propagating in the direction of the fault lines (see Figure 2). Because the fault rupture area was so close to shore, the bulk of the tsunami energy was directed offshore with less energy propagating north and south along the coastline.

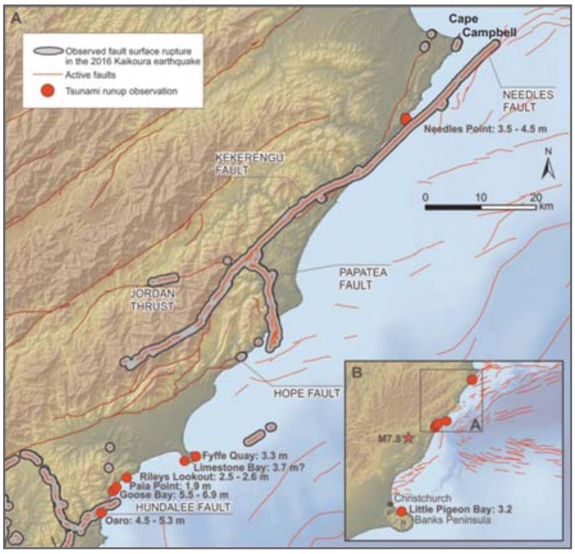

Figure 1: Summary of tsunami runup measurements from the 2016 Kaikōura earthquake. Also shown are onshore active faults, offshore faults, and fault ruptures of the 2016 Kaikōura earthquake. The 'B' inset shows the earthquake epicentre and location of Little Pigeon Bay. Figure reproduced from Power et al.[4]

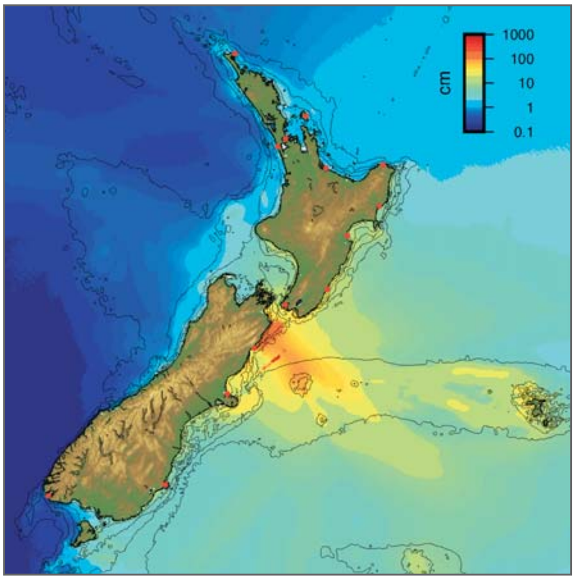

Figure 2: Regional propagation pattern of the tsunami generated by the 2016 Kaikōura earthquake. Warmer colours indicate higher maximum tsunami amplitudes. Note that the bulk of the tsunami energy is radiated offshore. Red dots indicate locations of GeoNet tsunami gauges.

Furthermore, the coastal uplift also helped protect the immediate source area from the effects of the tsunami. Because the coastline was pushed upwards, the initial motion of the water was directed offshore. Then, as the water surged back onshore, the now-uplifted coastline was not as severely inundated. A similar effect was seen in Indonesia's Mentawai Islands after the M_W 8.4 earthquake of September 2007[2].

It is interesting to note the relative speed of the two factors that govern tsunami generation – the seafloor displacement and the response of the water to that displacement. The earthquake rupture occurred over approximately two minutes. However, the majority of the energy release occurred between 60 and 80 seconds into the earthquake. It was during these 20 seconds that the coastal and seafloor deformation occurred that caused the tsunami. However, the Kaikōura sea level gauge record (see Figure 3) shows that the first part of the tsunami wave – the negative drawdown of the water level – took approximately 25 minutes to reach its lowest point before rebounding and reaching its highest point some 17 minutes after that with the first full wave cycle taking just over 40 minutes. Indeed, just after the earthquake, in the dark of night, residents in and around the uplifted coastal areas of Kaikōura reported hearing rushing water for several minutes after the earthquake. This was the sound of the tsunami forming as the ocean returned to gravitational equilibrium by flowing off the uplifted nearshore regions.

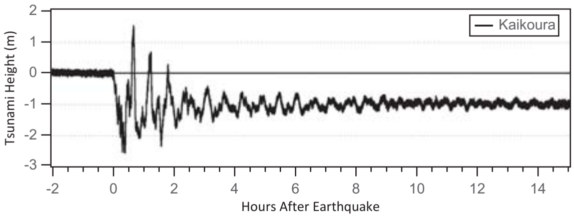

Figure 3: The Kaikōura sea level gauge data with tide removed showing the static offset produced by co-seismic uplift.

Although many are familiar with the oft-repeated mantra that 'tsunami waves travel at the speed of a jet airliner', the propagation speed of a tsunami wave is governed solely by the water depth and the jet plane analogy only holds true for the deepest part of the ocean*. In the case of the Kaikōura event, the tsunami was generated in water depths ranging from zero to a few hundred meters where the water wave propagation speeds are much slower. Because the fault rupture time (a matter of tens of seconds) is very short compared to the wave propagation time (minutes to hours) tsunami modellers can initialise their simulations with instantaneous uplift (if faults ruptured more slowly this process would need to be included in the modelling).

Analysis of sea level gauge records

The Kaikōura tsunami was recorded on sea level gauges along the east coast of New Zealand from Castlepoint to Lyttelton Port, and on Chatham Island to the east. Individual peak-to-trough tsunami wave heights exceeded 2 m on the Kaikōura tsunami gauge located in the earthquake source region. Elsewhere, the peak-to-trough heights reached maxima of 1 m at Sumner Head in Christchurch, 0.5 to 0.7 m in Lyttelton and Wellington Harbours, and less than 0.5 m elsewhere (see Figure 4).

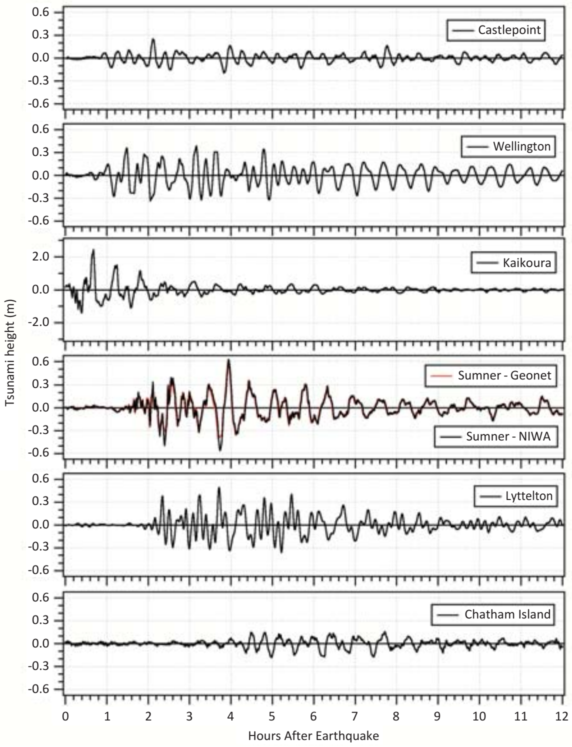

Figure 4: Tsunami as measured at various sea level gauges around New Zealand. The Kaikōura record has been filtered to remove the effect of the co-seismic uplift.

The tsunami signal persisted on the gauges for many hours after the earthquake. At Kaikōura the largest waves occurred immediately after the earthquake and decayed steadily afterwards. This contrasts with Sumner and Lyttelton where the largest wave occurred some 2.5 hours after the tsunami arrival and multiple waves of a similar size occurred over several hours.

A particularly persistent signal is seen on the Wellington sea level gauge where the tsunami excited at least two resonant modes of the harbour[3]. This can be seen clearly on the sea level gauge record as the slowly decaying, nearly sinusoidal oscillations from 6-12 hours after the earthquake. The resonance is also evident in the wavelet spectrogram shown in Figure 5, where the colour scale depicts the amount of energy present at a particular wave period (y-axis) over time (x-axis). In this plot, we see that during the first five hours of tsunami activity, the harbour resonated strongly at wave periods of approximately 15 and 30 minutes. After six hours post-earthquake, the harbour settled in to a more regular pattern of ~30-minute oscillations as seen on the sea level gauge record.

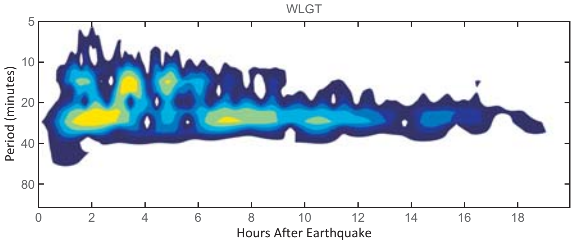

Figure 5: Wavelet spectrogram of the de-tided sea level gauge record from Wellington. The colour scale depicts the amount of energy present at a particular wave period (y-axis) over time (x-axis). Between 1 and 3 hours after the earthquake, there is more energy resonating at a wave period of ~30 minutes. From 3 to 6 hours, this resonance transitions to periods of ~15-17 minutes. Finally, from 6 hours onward, Wellington Harbour settled in to a steadily decaying resonance at ~30 minute period.

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[*] Tsunami propagation speed (celerity) is expressed as: $c = \sqrt{gd}$ where g is gravitational acceleration (9.8 m/s^2) and d is the water depth. Thus, in the middle of the Pacific Ocean, where the water depth is roughly 5000 m, the propagation speed would be 221 m/s or 797 km/hr, comparable to a jet airplane. But when the water is only 10 m deep, that same tsunami is only going 36 km/hr.

Also evident on the sea level gauge record (see Figure 3) is the co-seismic uplift at Kaikōura. Because the gauge is attached to the sea floor, this uplift appears as the baseline sea level after the event being 1 m lower than it was before the event (time t = 0). After the earthquake the water level drops approximately 2.5 m (which includes the 1 m uplift). This was followed in turn by a positive surge reaching ~1.5 m above the pre-earthquake mean sea level resulting in a total water level fluctuation (the total tsunami trough-to-peak wave height) of more than 4 m and a positive surge of 2.5 m above the mean sea level. Indeed, if a tsunami wave of this magnitude had occurred on a coastline not uplifted by the earthquake itself, and coinciding with high tide (Mean high water spring is 0.9 m above mean sea level in Kaikōura), the inundation effects would have been much worse, especially in Kaikōura township.

Tsunami coastal effects

Following the earthquake, several teams of researchers conducted reconnaissance surveys to measure and map the tsunami effects.

The first of these surveys examined the tsunami effects in Little Pigeon Bay, located east of Lyttelton Harbour on the north coast of Banks Peninsula. While post-tsunami ground surveys of the Kaikōura coastline were planned, field investigations were delayed since the region was in a State of Emergency and Civil Defence Emergency Management (CDEM) was focussed on the immediate aftermath. Furthermore, numerous landslides had blocked State Highway 1 limiting access to the affected areas.

Early reconnaissance flights along the coast did not reveal notable evidence of tsunami inundation, although considerable coastal uplift was evident. Likewise, there were no initial reports from coastal communities of tsunami inundation and indeed the coastal uplift provided some amount of protection. However, later ground surveys revealed evidence of inundation of several beaches and river valleys in Oaro and Goose Bay[4] (see Figure 1 for a summary of runup heights).

Little Pigeon Bay

On Monday afternoon (14 November 2016) a report was received through the *Christchurch Press* newspaper that an historic cottage in Little Pigeon Bay, a small, funnel-shaped bay on the northern side of Banks Peninsula (see Figure 1), had been severely damaged by the tsunami. Since this was the only confirmed report of tsunami inundation, research efforts were focussed in that area. Multiple teams of researchers visited the site on several occasions after the event and determined that the primary causes of damage were uplift forces, debris impacts, and sediment deposition.

Uplift forces completely removed the veranda along the western side of the cottage, and part of the northern veranda (this was never recovered). The western end of the cottage was also lifted approximately 5 cm from its foundations. Debris impacts destroyed veranda posts on the seaward side of the cottage, removed the front door, and displaced several of the walls inwards. The maximum wall displacement due to debris impact was approximately 70 cm adjacent to the front door. The tsunami deposited sediment on the floor of every room of the cottage, with finer material plastered on the walls providing a clear indication of internal inundation (and/or splash) levels. The tsunami surge penetrated inland some 150 m from the shoreline (>100 m past the cottage itself) and reached a maximum elevation of 3.7 m above NZVD2016 (see Figure 6) and estimated as 3.2 m above the sea level at the time of wave arrival (see Figure 1). Fortunately, no one was staying at the cottage at the time of the tsunami as the level of damage occurring there could very well have caused serious injuries or deaths.

Oaro, Kaikōura and northward

In the weeks following the earthquake, teams conducting surveys of coastal uplift along the northern Kaikōura coast were also able to observe and measure tsunami inundation effects. To the north of Needles Point, tsunami runup was measured at 3.5 to 4.5 m above sea level at the time of the tsunami. On the Kaikōura Peninsula itself, researchers found evidence of tsunami runup of 3.3 m. On the south side of the peninsula, local residents observed 'the sea rushing off the shore platforms immediately after the earthquake', which was followed sometime later by the sea 'pushing back into the marina and rising to a level equivalent to the top of the boat ramp'.

Further to the south at Riley's Lookout and Paia Point, evidence suggested tsunami runup of 1.9 to 2.6 m relative to the tide at the time of the tsunami. At Goose Bay, the effects of tsunami inundation were evident weeks after the earthquake with marine debris scattered well above the high tide and storm berm levels with maximum tsunami runup heights measured at 5.5 to 6.9 m above the sea level at the time of the tsunami arrival.

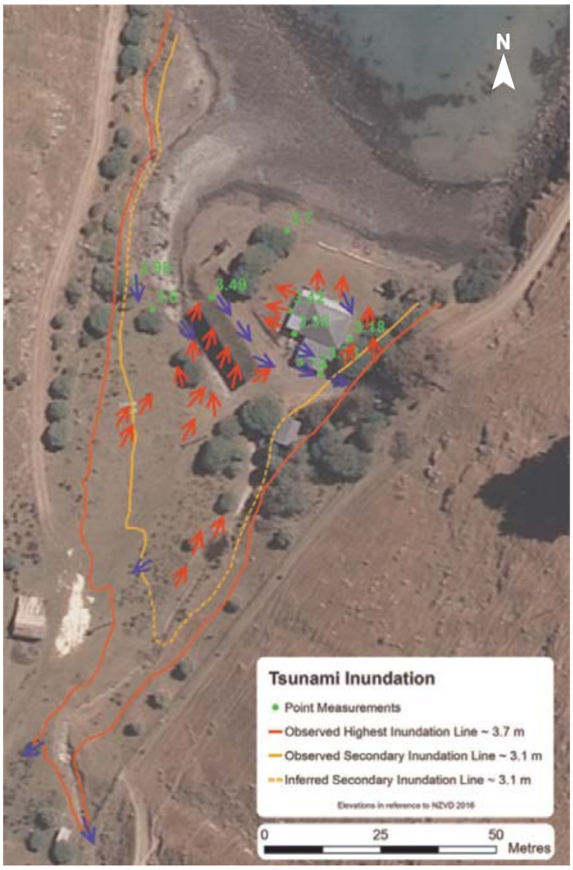

Figure 6: Map of tsunami inundation lines; point measurements of minimum tsunami inundation heights, relative to NZVD2016 and flow indicator directions (blue as inferred uprush and red inferred backwash). Figure reproduced from Lane et al.[7]

Continuing south to Oaro, local residents noted tsunami effects such as marine debris scattered along the railway embankment, and sub-tidal flora and fauna scattered inland up the river valley. Research teams measured the inland extent of the tsunami at over 250 m and the maximum runup height at the beach of 4.5 to 5.3 m above sea level at the time of the tsunami arrival.

Modelling the tsunami

The complex rupture pattern and subsequent coastal and seafloor deformation caused by the Kaikōura earthquake present challenges for accurate detailed modelling of this event. Indeed, the initial published attempts to use detailed fault rupture models as the input to tsunami propagation models yielded poor results with regards to tsunami amplitudes[5]. Later studies, such as Bai et al.[6], produced much better fits between measured and modelled mareograms (sea level time series). However, that study relied on the inclusion of significant coseismic slip on the subduction zone interface to achieve those results; yet there remains considerable debate as to how much energy was released through slip deep on the subduction zone as opposed to shallower crustal fault.

Details of the tsunami source mechanism notwithstanding, it is clear the tsunami was generated by multiple areas of localised uplift occurring primarily on steeply dipping, relatively shallow faults running along the coastline to the north of Kaikōura. As discussed above and shown in Figure 2, this results in tsunami energy being radiated primarily offshore from the source region with edge wave propagating laterally north and south along the coast. This laterally propagating wave front (see Figure 7) directly impacted the north-facing shores of Banks Peninsula contributing to the relatively large tsunami heights observed there.

Detailed hydrodynamic modelling of the tsunami inundation at Little Pigeon Bay was presented in Lane et al.[7] Rather than modelling the tsunami from the source, their approach used the measured sea level gauge record from Sumner Head as the forcing time series to their model. This approach accurately reproduced the observed inundation and suggested that the inundating and damaging surges at Little Pigeon Bay likely occurred during the initial tsunami waves and were amplified by the selective resonance of the bay itself – a further reminder of the effect of local topography on tsunami runup heights.

The bigger picture

The maximum recorded tsunami amplitude at Kaikōura was 2.5 m (4 m trough-to-peak) and it caused runup heights up to 6.9 m. Runup heights varied greatly along the coast due to the complex nature of the fault rupture and the details of the coastal topography. Inundation reached 100-250 m inland up some river flats. Waves from the tsunami were observed at sea level gauges from Banks Peninsula in the south to East Cape in the north and sea level disturbances lasted over 12 hours after the earthquake.

This event highlighted many issues and shortcomings in New Zealand's tsunami preparedness for local source events. Due to the unusual nature of this earthquake and the fact that that epicentre was located on land and some 150 km from the tsunami source area, it was not immediately evident that a tsunami would be generated. This led to uncertainty amongst tsunami experts and civil defence officials.

Ultimately, confirmation that a tsunami had been generated came some 40 minutes after the earthquake when data from the Kaikōura sea level gauge was viewed on an international website.

That the New Zealand tsunami research and emergency response community does not have immediate and easy access to real-time sea level gauge data remains a major shortcoming in our tsunami response capacity and one which could easily be remedied. While tsunami water level data is available in real-time through the GeoNet website (https://www.geonet.org.nz/tsunami), the visualisation of this data is of poor quality and unsuitable for quantitative assessments of tsunami activity. (An example of the graphical output of the tsunami gauge network as it exists now is presented in Figure 1 of Marion Schoenfeld's article in this publication.)

This event also highlights the regional source tsunami hazard for the Chatham Islands from tsunamis generated along the

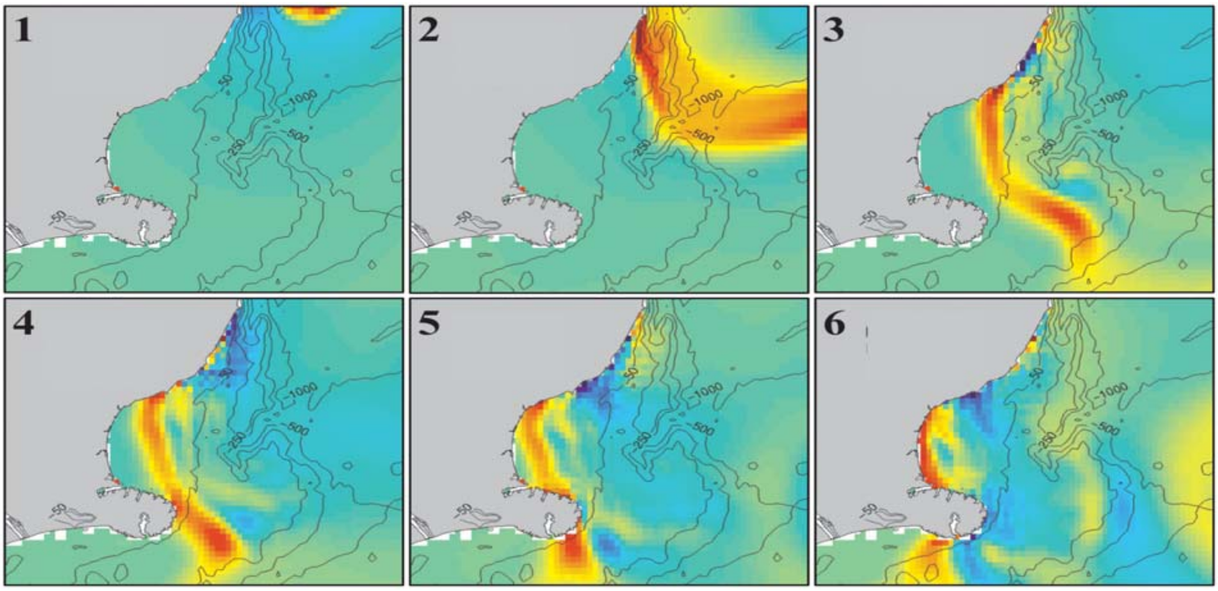

Figure 7: Snapshots of tsunami wave propagation showing the wave front propagating south towards the north-facing coast of the Banks Peninsula. Warmer colours indicate higher tsunami amplitudes.

Hikurangi subduction zone. As shown in Figure 2, the bulk of the tsunami energy is radiated perpendicular to the coastline out in to the Pacific Ocean. Although the main beam of tsunami energy was directed to the south of the Chatham Islands, wave energy was trapped on the Chatham Rise and contributed to the tsunami effects observed there. Furthermore, future ruptures to the north, particularly along the Wairarapa or Hawke's Bay coasts, would have their tsunami energy aimed directly at the islands.

This unfortunate phenomenon occurred on Robinson Crusoe Island located offshore of central Chile during the tsunami of 2010[8]. In that event, the earthquake along the Chilean mainland coast disrupted communication to the offshore islands preventing tsunami warnings from reaching the people there. The tsunami arrived less than one hour after the earthquake with maximum runup of more than 18 m causing 18 fatalities on the island.

New Zealand was lucky this time as the Kaikōura tsunami caused minimal damage, in part because the coastal uplift due to the earthquake protected Kaikōura township and the surrounding region and also because, in most places, the largest waves arrived at low- to mid-tide.

Nevertheless, this event serves as a reminder of the power that tsunamis can have and the need for improved understanding and preparedness.

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Submarine landslides and turbidity currents

By Emily Lane, Joshu Mountjoy, Alan Orpin and Ashley Rowden

The 14 November 2016 Kaikōura Earthquake triggered submarine slope failures that became a massive turbidity current, flowing from the Kaikōura Canyon more than 680 km along the seafloor. This exceptional event has allowed scientists to gain the first comprehensive insights into the impact of canyon flushing on the seafloor geomorphology and the rich canyon ecosystems.

Background

The Kaikōura Canyon lies seaward of the south shores of Kaikōura Peninsula (see Figure 1). Like an underwater Grand Canyon, its steep sides cut deep into the continental shelf. From its head, less than 1,000 m off-shore from Goose Bay (see Figure 2), its sheer walls drop from the shallow 30 m deep continental shelf to over 600 m deep over the space of a kilometre. The flanks of the canyon show a complex underwater seascape of sharp ridges, meandering valleys and landslide scars that are the result of numerous slope failures and erosion that has occurred over many thousands of years. This active canyon acts as a conduit carrying material from the coast to nourish the southernmost reaches of the Hikurangi Channel system at over 2,000 m depth at the base of the continental slope. At 1,500 km in length, the Hikurangi Channel is one of the longest continental margin dispersal systems on earth (see Figure 1). The Kaikōura Canyon also lies in the boundary zone between the Pacific and Indo-Australia tectonic plates in a seismically active area, sliced by numerous faults.

Past evidence of submarine landslides

Submarine landslides are well known here from past research. Studies of the canyon in the 1990s using side scan sonar, multibeam sonar and seismic profiling identified head scarps, turbidite deposits and gravels, boulders and megarippled-sand covering the canyon floor – signs of slope failures most likely triggered by earthquakes. The last slope failure event was estimated at around 1830, and the one prior at around 1700, suggesting that large submarine landslides could occur relatively frequently, geologically speaking, perhaps every 150 years or so[1]. Based on those estimates, a 2003 study on tsunamis in the Kaikōura region highlighted the potential for catastrophic local tsunamis caused by these landslides[2].

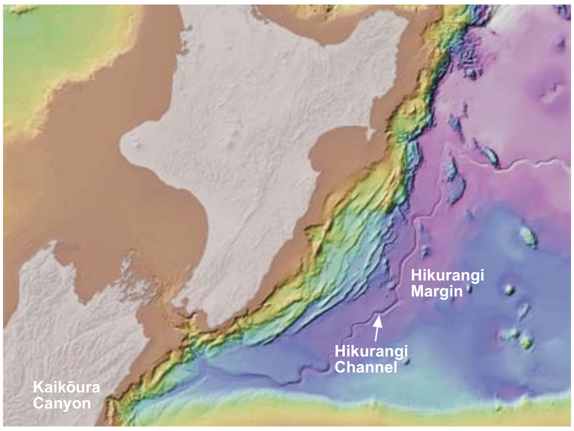


Figure 1: Kaikōura Canyon (bottom left) incises into the narrow continental shelf (coloured red-brown) and feeds into the Hikurangi Channel, which wends its way northeast for over 1500 km. Depth is shown by colour, with red-brown ~100 m through to pink ~3,000 m.

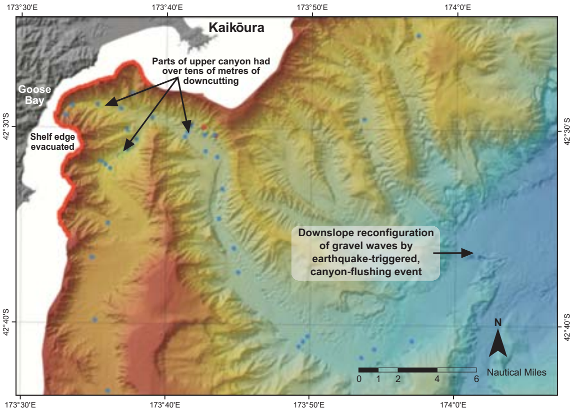


Figure 2: High-resolution bathymetry collected by NIWA in July 2017. Depth is shown by colour: red ~200 m to blue ~2000 m. The coloured symbols within the canyon show the location of sample sites for NIWA's September 2017 voyage to assess the benthic impact of the Kaikōura Earthquake. The red line shows the swath where the shelf edge was cut back. Pre- and post-earthquake bathymetry comparison shows massive volume loss, particularly in the head of the canyon, and some deposition elsewhere.

Because of this hazard, Environment Canterbury wanted to understand more about the tsunami threat posed by the Kaikōura Canyon. In 2013, NIWA led a scientific voyage to the canyon head to take a closer look. Using a multibeam sonar, they collected very accurate bathymetry (underwater topography) of the canyon. This bathymetry showed no large accumulation of unstable modern sediment, somewhat contrary to what had been speculated by Lewis and Barnes[1] – good news for Kaikōura though, as this meant there was less chance of large, shallow-water slope failures of the kind that could cause catastrophic local tsunamis. Although large shallow failures are less likely than originally proposed, slope failures deeper in the canyon, or smaller ones on the sides and head wall, are still possible and could still cause tsunamis.

Biology of the Canyon

In part because of its physical characteristics and location, Kaikōura Canyon has an abundant supply of organic matter from the land and nearshore environments as well as from surface water supplied by nutrients from ocean currents and upwelling events. This abundance of organic matter means that the canyon is a biological hot spot, teeming with life. In 2006, scientists aboard the *RV Tangaroa* took an inventory of the seafloor life in the canyon using grab and core sampling, photographic sea floor surveys, and bottom-fish trawls. This study showed that Kaikōura Canyon is one of the most productive deep-sea regions in the world[3]. High productivity levels, combined with deep water close to shore, are also why the region is a favourite feeding spot for many species of whales, which provide Kaikōura with one of its major tourist activities – whale watching.

Kaikōura earthquake and turbidity currents

On 14 November 2016, the Kaikōura Earthquake occurred and suddenly what we knew about the canyon became more than academic. As luck would have it, the *RV Tangaroa* was not far away, searching for evidence of past large earthquakes off the east coast of the North Island. The science team aboard realised that the earthquake had provided a rare opportunity to answer some fundamental science questions. The voyage was diverted south towards Kaikōura to study the effects the earthquake had on the seafloor and take cores of any newly deposited sediment.

Within four days of the earthquake, the scientists had evidence of new deposits from turbidity currents triggered by slope failures caused by the earthquake. This observation was a world first. Never before had a turbidity current of this size been sampled so soon after the event that caused it. In fact, the turbidity current in the Hikurangi Channel off the Wairarapa coast (300 km from Kaikōura) was still a highly fluidised mixture of water and sediment slowly settling out of the water column (see Figure 3). Later measurements underlined the range of the turbidity current. For example, off the coast of Hawke's Bay, the sediment deposit from the turbidity current was still 65 cm thick on the canyon floor – suggesting the turbidity current travelled at least 680 km along the Hikurangi Channel[4]. Even more astounding, this far downstream, the current had overtopped the 180 m high wall of the channel and left a 7 cm thick deposit on the levee (see Figure 3). All the evidence confirmed that this was a new deposit. Cores revealed that there was a brown oxic 'surface' layer below the deposit – but not one on top. There was no evidence of biological mixing of the top layer although there were clear signs of such disturbance by animals living in the layers below. Furthermore, the deposit contained high levels of radioisotope $^{234}Th_{ex}$ which has a half-life of 24 days, again indicating that this material had been recently deposited.

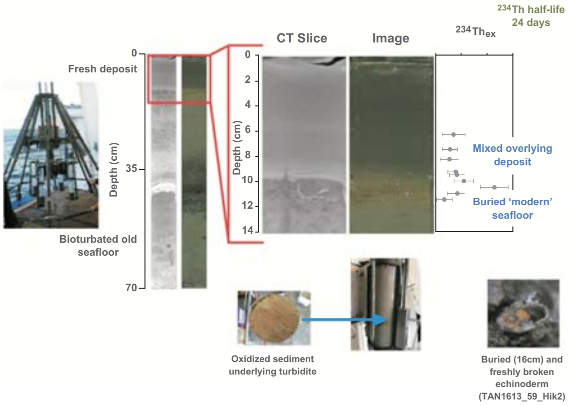


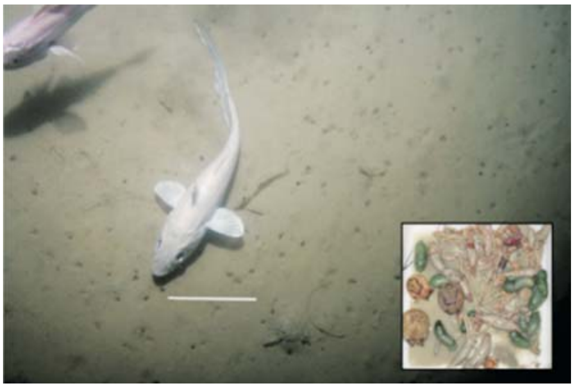
Figure 3: 19 November 2016 – evidence for fresh co-seismic deposit in the Hikurangi trough east of the Wairarapa coast (2733 m). This deposit is evidence for a thick turbidity current, over 180 m high, that flowed along the Hikurangi Channel, overtopping its banks to leave a blanket of fluidised mud days after the Kaikōura Earthquake. (Core imagery and chronology modified after Mountjoy et al.[4], 2018.)

Surveying the impacts – physical and biological

To address the clear need for a better understanding of the wider effects of the earthquake on the seafloor near the coast, a dedicated NIWA survey using *RV Ikatere* was undertaken in January 2017, less than three months after the earthquake. Over the rest of the year NIWA's vessel fleet returned to the Kaikōura Canyon and the surrounding region several times. These voyages had multiple objectives – surveying the impact of the earthquake on the physical seabed due to fault movement; understanding the physical processes that had occurred in the canyon during and following the earthquake; and documenting the effect those processes had on the abundant seafloor life known to be living in the canyon prior to the earthquake.

In January 2017 the *RV Ikatere* voyage was funded by the Natural Hazard Research Platform. Its aim was to map offshore faults using multibeam survey techniques and then to survey the head of the Kaikōura Canyon to compare it with the earlier 2013 surveys. The canyon head survey revealed that mudslides had occurred over almost the entire upper end of the canyon, and a swath of about 30 km had failed (see Figure 2). Areas that in 2013 had been draped with mud were now scraped clean.

One of the first opportunities to gauge the impact of the earthquake in the deeper sections of the canyon, well beyond the shelf edge, came later in January 2017 during a MPI-funded *RV Tangaroa* voyage as it returned from a seabed survey of Chatham Rise. The motivation was to take even this limited 24-hr opportunity to survey marine life in Kaikōura Canyon and compare it with the survey done in 2006. The difference between the two surveys was extraordinary. While fish were still present, there was no evidence of a single invertebrate organism living on or in



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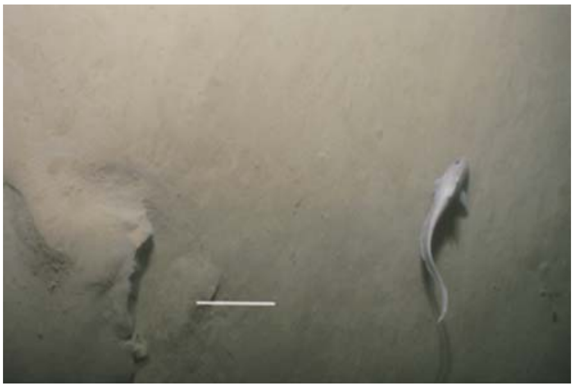

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Figure 4: A comparison of seafloor images taken at the same site in Kaikōura Canyon in 2006 and 2017. Note the holes and other surface features indicative of large animals living beneath the seafloor (known as bioturbatory features or Lebensspuren) seen in 2006, and their absence in early February 2017.

the seabed over a stretch of nearly six kilometres. Previously, the seafloor had been covered with evidence of marine life – burrows, tracks, pits and mounds – but now it was smooth and apparently lifeless (see Figure 4). In some locations were small bacterial mats (individually less than 1 m^2), which presumably developed in response to the elevated levels of organic matter and potentially methane resulting from the freshly deposited sediments and decaying remains of the previous animals.

Another day whilst on transit in April 2017, and then again for a full two weeks in July 2017, the *RV Tangaroa* returned to survey the full length of the Kaikōura Canyon. By comparing the bathymetry data from the January and July 2017 voyages with that taken in 2013, it was possible to estimate the volumes of sediment stripped from the canyon walls and floor by the slope failures and turbidity current (see Figure 2). The total erosion in the canyon caused by the Kaikōura Earthquake was estimated to be around 9.4 x 10^8 m^3 (Mountjoy, et al.[4]). By comparing failure regions with shake-maps of ground acceleration, it was also possible to estimate that the slope failure threshold lies around 0.38-0.44 g, meaning that once the acceleration is more than about 40% of gravity, things begin to slide. At the canyon floor, up to 50 m depth of sediment was mobilised and flowed down canyon. Further down canyon huge sediment waves were reworked and moved downstream up to 560 m. Erosion of the seabed also means that the biomass of organisms once living in the sediment is exported, with around 39 x 10^6 kg of biomass (equivalent to 2.67 x 10^6 kg of carbon) estimated to have been swept downstream.

Although the volume of the submarine landslides in the Kaikōura Canyon from the 14th November 2016 earthquake seems large – and indeed it was a significant event for the undersea life – compared with the volume of slope failure needed to cause a sizeable tsunami it was still small. The submarine landslides may have added a small amount to the tsunami heights around Goose Bay, but almost all the observed wave heights and inundation caused by the 14th November Kaikōura tsunami can be adequately explained by the co-seismic undersea uplift. Preliminary modelling of the slope failures suggests that they have added up to 1 m to the tsunami height at the coast around Goose Bay.

Other opportunistic voyages through 2017 looked further afield offshore of the eastern North Island for evidence of turbidity currents triggered by the Kaikōura Earthquake. More sediment deposits from the turbidity currents were seen in sediment cores collected in local slope basins along the Hikurangi Margin, hundreds of metres above the Hikurangi Channel floor. Researchers are interested to study the 'locally felt' intensities of ground-shaking far from the earthquake epicentre. In addition, the question arises of how these deposits continue to evolve and whether any evidence of them will remain in the long-term sedimentary record.

In September 2017 *RV Tangaroa* returned yet again, with the mission to investigate the extent of seafloor impact and if organisms were recolonising the canyon seafloor (see Figure 2 for survey locations). Amazingly, the recovery was already well underway. In some areas juvenile urchins and other animals that lived in the sediments before the earthquake were found once again. But in other areas, scientists were seeing that different species were moving into the areas, thereby opportunistically filling niches created by the impact of the earthquake. In yet other areas of the canyon, the earthquake seemed to have not caused any sediment deposition or erosion and the animal communities were apparently unaffected.

The bigger picture

The 14th November 2016 earthquake and subsequent submarine landslides and turbidity currents that flushed through Kaikōura Canyon are not a unique occurrence. They are just another event in a regular, geologic-scaled routine of the Earth. These co-seismic flushing events cut down into the canyon substrate and in doing so drive morphological development of the seafloor. In addition, the evacuated and deposited material provides nutrients for the deep-sea communities. In one hit, between 1.7 to 4 times the total annual terrestrial sediment flux in New Zealand was flushed out of the canyon during the Kaikōura Earthquake. Ecologists believe that earthquakes are thus likely to regulate the structure and function of seafloor communities in the canyon and beyond by regularly 'resetting the clock' every one to two hundred years.

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Section 2: Impacts on the ecological, social & built environment

Kaikōura town shoreline post-quake (Photo: Bare Kiwi)

Civil Defence response to the Kaikōura-Hurunui earthquake and tsunami

By Marion Schoenfeld

This article describes the Canterbury Civil Defence response to the Kaikōura-Hurunui earthquake. As always, there are lessons to be learnt and some of these are outlined below, along with the actions taken to improve future responses. The initial stages of the response focused on the tsunami generated by the earthquake. This was followed by efforts to deal with the thousands of landslides caused by the earthquake, some of which blocked roads and railways isolating Kaikōura and other smaller settlements. Other landslides dammed rivers creating a significantly hazardous situation if the dams were to fail.

Tsunami response

At approximately 12:35 am, some 30 minutes after the earthquake, tsunami waves were evident on the Kaikōura tide gauge, despite the fact that the earthquake epicentre was located on land, tens of kilometres to the south. Because all communication into Kaikōura had been disrupted, it was not possible to issue a tsunami warning there. In any case, such a warning would have been futile as the tsunami had already arrived by then[1]. From that point on, the focus was on whether evacuations were necessary for the rest of the Canterbury coast, including Christchurch.

Canterbury CDEM hazard scientists initially assessed the tsunami threat based on three things:

- the measured tsunami height at Kaikōura (2.0 m),
- the pre-existing modelling of a Hikurangi-sourced tsunami showing significant tsunami height attenuation towards the south[2], and
- the stage of the tide at the expected tsunami arrival time.

Although the scenario modelling was for a much bigger event, it showed that between Kaikōura and Christchurch a tsunami would lose ~75% of its height and be further attenuated as it propagated in to the South Canterbury Bight. However, the modelling also showed that the bays along the northern coast of Banks Peninsula could experience relatively large tsunami waves (see the tsunami modelling figures in the Borrero and Lane article in this publication for an illustration of this effect).

Based on this information, it was surmised that the largest possible tsunami height in the Christchurch area would be no more than 2 m (assuming no attenuation from the source) and would not cause significant inundation in Christchurch or any of the coastal settlements of Canterbury apart from possibly the Banks Peninsula bays (especially since it was due to arrive on a relatively low, but rising, tide). Assuming a level of attenuation consistent with the model scenario suggested tsunami heights of ~0.5 m, similar to seiches that regularly occur in Pegasus Bay without causing inundation.

At 12:50 am, based on this assessment, Canterbury hazard scientists advised that activating the tsunami evacuation sirens was unnecessary in Christchurch (there are no sirens in the Banks Peninsula bays, which were the only places deemed to be under some threat). Local Civil Defence and Emergency Management (CDEM) did not deem it appropriate to tell people it was unnecessary to evacuate, as the national level messaging of 'long or strong get gone' would be undermined and people following that message were actually making a wise decision.

At 1:00 am the Ministry of Civil Defence and Emergency Management (MCDEM) sent an advisory that a tsunami had been generated[3]. At this time the tide gauge in Christchurch began to show tsunami activity with an amplitude of ~0.5 m, while the Kaikōura tsunami gauge showed that subsequent waves were smaller than the first wave. Local hazards analysts expected that the wave in Christchurch would not build any higher.

At 1:29 am, MCDEM issued a National Warning advising people to move inland or to higher ground immediately, stating that the warning would remain in place until it was cancelled. At 2:01 am, a further National Warning from MCDEM stated explicitly that a tsunami had been generated. They noted that tsunami activity had been seen on GeoNet tsunami gauges in Kaikōura and Wellington (Christchurch was not mentioned) and that the threat must be regarded as real until the warning was cancelled. This was confirmed as a directive that local CDEM should evacuate tsunami zones[3]. At this time Christchurch wave heights remained at around 0.5 m.

This resulted in confusion in coastal communities due to differences in messaging from MCDEM (evacuate) and local CDEM (no message to evacuate/no sirens sounding). In order to create unified messaging and alleviate confusion, local Christchurch CDEM decided to follow the directive of MCDEM and activate the sirens. The Waimakariri District also chose to activate their sirens, this despite the fact that two clear 0.5 m wave signatures were showing on the Christchurch tsunami gauge, indicating that the first wave had arrived and the initial assessment of low threat was correct. The ensuing evacuation further clogged the already congested roads out of coastal Christchurch. By 8:00 am, MCDEM changed the warning status to 'Beach and Marine Threat' (i.e. no threat of flooding on land) for the Canterbury coast, and allowed people to return home. A timeline of the response is overlain on the GeoNet tsunami gauge plot from that evening in Figure 1.

Evaluation of the tsunami response

In spite of numerous public meetings on tsunami risk given by local CDEM and direct work with the coastal communities over some years, most Christchurch residents did not know the extent of the evacuation zones and generally had no idea whether to evacuate or where to go: the messaging had not been effectively disseminated. There were numerous examples of people living many kilometres outside the evacuation zones getting in their cars and driving tens of kilometres inland, when the tsunami evacuation zones in most places only reached around 1 km inland or less. One of the biggest lessons learnt was the need to communicate with people who are outside the evacuation zone that they do not need to evacuate, as well as targeting those who are within the zone. The Hurunui and Waimakariri Districts saw that the strong earthquake shaking led to significant self-evacuation that conformed with established community response plans. This was followed by a relatively easy evacuation of coastal communities once official warnings were issued (W Dalley, pers. comm.).

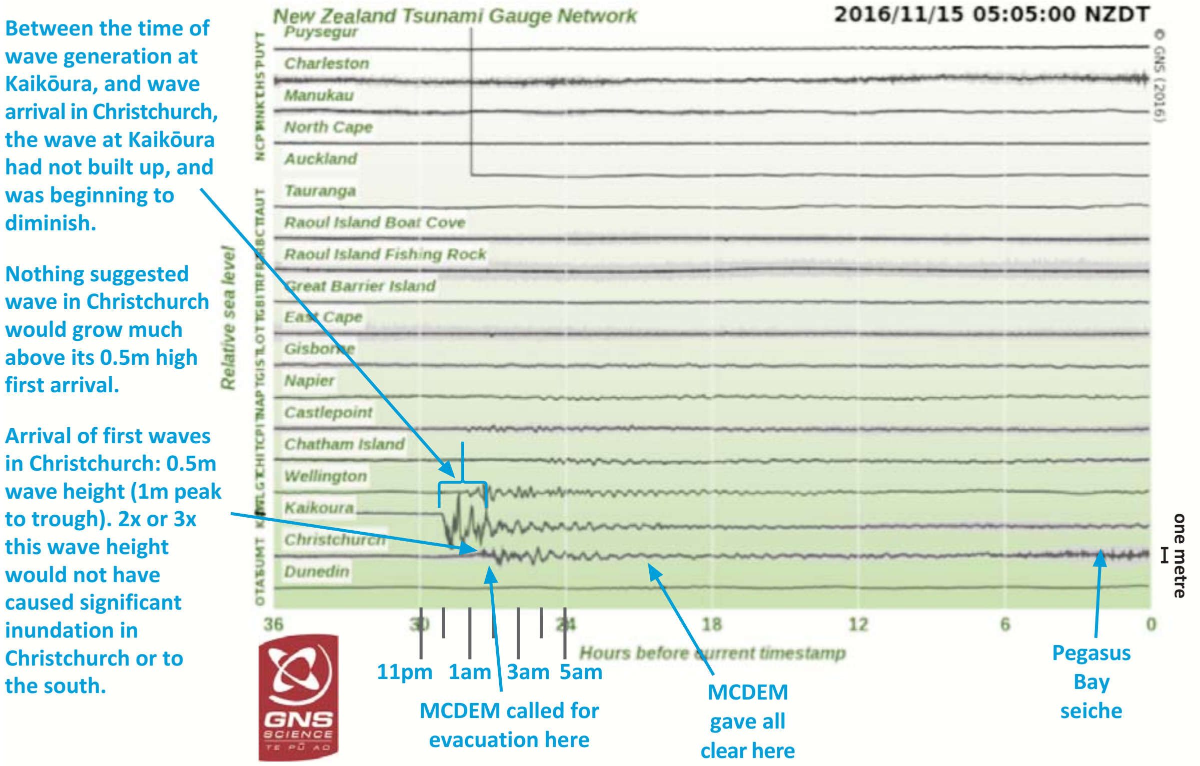


Figure 1: Annotated timeline overlain on tsunami gauge data. As predicted by local experts, tsunami heights in Christchurch did not exceed that of the first arrival. The feature annotated to the far right on the Christchurch timeline is an example of the tsunami gauge recording long waves associated with the Pegasus Bay Seiche – a very common occurrence. Notice that the amplitude of the waves is similar to that of the tsunami itself. This phenomenon is well known by local experts and gives some context to the scale of the tsunami on 14th November.

Substantial confusion occurred amongst Waimakariri residents who lived just outside the evacuation zones, many of whom evacuated unnecessarily (B Wiremu, pers. comm.) as these people had not been targeted in tsunami education efforts. On MCDEM's directive, the Selwyn District Council (SDC) called for the evacuation of communities on the coast (i.e. Rakaia Huts and Fisherman's Point/Taumutu). The SDC civil defence team indicated that they did this despite the sense that it was unnecessary and therefore they evacuated 'the bare minimum to comply with the MCDEM'. SDC do not have sirens, but the voluntary evacuation went fairly well (R O'Rourke, pers. comm.).

Because there are relatively few residents within the evacuation zones in communities such as Ashburton, Timaru and Waimate along the southern Canterbury coast, these areas chose not to call for official evacuations or to activate the sirens installed in Timaru. However, Community Response Plans were activated with varying success with some residents experiencing confusion similar to that which occurred in Christchurch, Hurunui and Waimakariri districts. An independent enquiry into Timaru District's response recognised the conflict between local knowledge that the risk was low and the direction from the National Controller calling for an evacuation. The report however stopped short of criticising the Timaru District Council CDEM controller for deciding not to activate the sirens[4].

While communities along the northern coast of Banks Peninsula do not have sirens, some do have phone trees that were activated during the event. Although the house that was damaged in Little Pigeon Bay was empty at the time of the tsunami (see the Borrero and Lane article in this publication and reference 2), the owners had been telephoned to make sure no one was there (Emily Lane, pers. comm.). Local response arrangements worked in that area, which was one of the few areas at significant risk.

Although direct communication into Kaikōura was cut off, residents had access to Radio New Zealand (RNZ) throughout the event (K Scattergood, pers. comm.). Initially, RNZ reported that there was no tsunami threat and anecdotal evidence suggests that while many people heeded the natural warning of the earthquake, some went back to the coast after hearing that there was no danger. Others, trying to get to the Emergency Operations Centre (EOC) to be part of the response, turned back after hearing the updated 'tsunami is possible' warning, because the routes to the EOC were along the coast.

Self-evacuation rates in Kaikōura were good, although there were situations where some people were caught between the coast and steep cliffs with falling rocks and landslides coming down towards them (Kevin Heays, pers. comm.).

Landslide reconnaissance

Aerial reconnaissance began on the morning following the earthquake and quickly revealed extensive landsliding throughout the quake-affected area. Initial estimates suggested 80,000 to 100,000 landslides with areas >10 m^2 and volumes >10 m^3. Landslides had blocked roads and the railway, cutting off access to Kaikōura from both the north and the south. Further reconnaissance confirmed that an area of 3,600 km^2 in northern Hurunui and Kaikōura had suffered severe damage and the total area of landsliding was in the order of 10,000 km^2 (see Figure 2). Later estimates concluded there were ~20,000 landslides with areas > 100 m^2. While there were many more landslides along the coast than further inland, they were generally smaller than the huge landslides seen inland. To date there have been 18,000 landslides mapped with areas of 10 m^2 or larger[5].

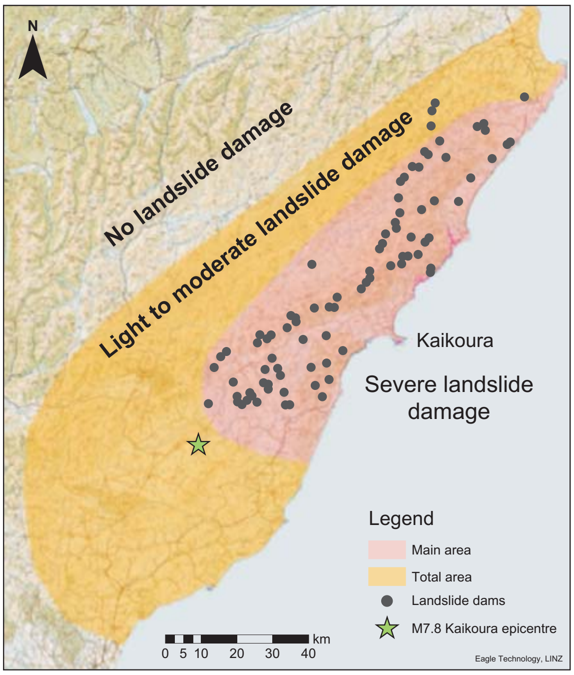


Figure 2: Map showing areas of landslide damage (figure courtesy GNS Science).

Landslides and road access

The New Zealand Transport Agency (NZTA) employed geotechnical experts to determine the extent of landslides affecting or threatening the state highway network and assess the easiest way of re-establishing a route into Kaikōura. Aerial reconnaissance confirmed that due to the location, number and size of landslides, the best option for accessing Kaikōura was to open up State Highway (SH) 70 (the inland road) rather than trying to clear SH1 along the coast. Work began on clearing the inland route and by 16 November, the road was passable, although tenuous, with slips above and below the road and damage to culverts and bridges. On 18 November, a caravan of New Zealand Army vehicles carrying essential supplies reached Kaikōura. On 21 November two escorted convoys allowed residents and service vehicles through to Mt Lyford and nearby isolated farms and houses. Access by Hurunui residents to their homes and by the army to Kaikōura remained subject to ongoing risk assessment by geotechnical experts, as stability could change considerably due to weather and/or significant aftershocks. The first private vehicles drove out of Kaikōura on 25 November. This was carefully controlled with the road open for only a two hour window and 'no stopping, no turning back' rules in place. On 28 November the inland road was handed back by CDEM to NZTA, and on 19th December it reopened to the public.

Reopening SH1 was more troublesome as the highway was affected by more than 40 significant landslides blocking it along two coastal stretches, a 21 km stretch north of Kaikōura and an 8 km stretch to the south. The North Canterbury Transport Infrastructure Recovery (NCTIR) team, a consortium of NZTA, Kiwirail, contractors and consultants, was established to work on stabilising the landslides, eliminating rock fall risk, and realigning the road. It was not until mid-June 2017 that a regular weekly schedule of open and closed days for State Highway 1 south of Kaikōura took effect with the road open from Friday through Monday and closed Tuesday to Thursday allowing work crews to continue repairing the road and rail corridor. Although the road north of Kaikōura finally reopened on 15 December, 2017, work continues and it is periodically closed due to slips, usually associated with bad weather. Additionally, the whole of SH1 was closed daily during non-daylight hours until 30 April, 2018, when NZTA removed the restriction.

Inspection of local roads, and ensuring safety on them, was the responsibility of district councils. The extent to which this was systematically addressed has not been documented. In Kaikōura District, where resourcing was an issue, this was somewhat ad hoc, particularly in the early days, and there were examples of local residents engaging in potentially dangerous work clearing landslides off roads.

Landslide dams

Landslide dams occur when debris falls into a river blocking the flow and causing a build-up of water upstream. Landslide dams present a significant flooding risk for areas downstream if they fail in an uncontrolled manner. The first of these was spotted in the afternoon 14 November, but by the end of the next day, this dam had breached and appeared stable.

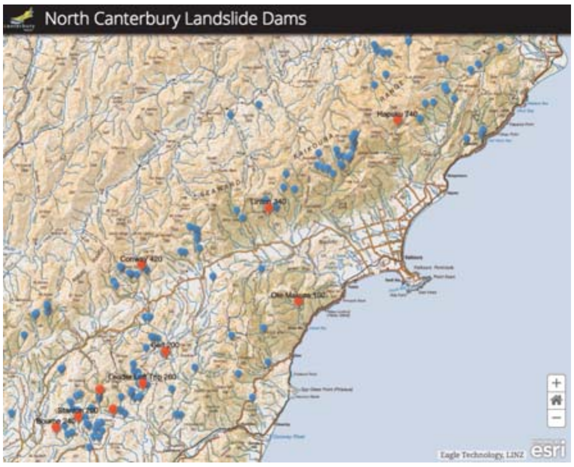
GNS Science and Environment Canterbury (ECan) staff then began the task of finding and assessing any other landslide dams. ECan staff targeted their search on rivers where population or assets such as bridges would be affected by an uncontrolled breach, thereby allowing exposure to potential hazards to be quickly addressed, while GNS Science started a more systematic catchment-by-catchment process. Within the first ten days, nearly 160 landslide dams had been identified and initial assessments had been carried out to determine the size, shape and stability of the dams, as well as the volume of water trapped by each dam and whether there were people or roads downstream.

Initially each landslide dam was named by river catchment and a number, but it quickly became apparent there were too many landslide dams and this started to cause confusion about which dam was being reported on or discussed. A new approach was adopted whereby each landslide dam was photographed, located by GPS, and recorded in a GIS, then assigned a unique identifier name (based on river catchment) and altitude (in m) above sea level (e.g. Leader 320). This removed the significant confusion that had arisen between the reconnaissance teams and MCDEM. Once a name and altitude had been assigned to a dam it became widely used and easily recognisable[5].

Several landslide dams were identified as potentially troublesome, particularly those on the Ote Makura, Towy, Linton and Hapuku Rivers, and these became part of regular aerial monitoring as several showed signs of erosion on the downstream sides of the embankments and piping of water through the dam[5]. Messaging put up on the ECan website advised people to stay out of riverbeds and to recognise that rumbling noises from upstream or the sudden appearance of turbid water in the river could signal a dam breach. Uptake of these messages was variable as some farmers continued to extract gravel from the riverbeds to repair farm tracks. Tourist ventures such as river kayaking companies also occasionally chose to ignore such warnings. An interactive website was also developed to provide information on dam status (see Figure 3).

Communication with Kaikōura and between agencies was difficult, and with so many geotechnical experts in the area, there were occasions where conflicting messages from different sources were made public regarding the danger posed by particular landslide dams. One such example related to a dam on the Ote Makura River above Goose Bay (south of Kaikōura township). Initially, this dam was assessed as a 'moderate hazard' by GNS Science because it was smaller than other dams, the lake volume was small compared to the embankment, and a breach was not imminent. Geotechnical staff at Kaikōura District Council (KDC), not fully aware of the GNS assessment, then received reports of changes to the dam. KDC were unable to fully assess this information since the reports came in late in the day and just as 200 people were set to move into a flood-prone campground to assist with shellfish relocation. Subsequently the dam was reclassified as high hazard, people were prohibited from entering the area, and 35 homes were evacuated while work began to assess potential dam break flood inundation areas.

The effect of an uncontrolled breach of the Ote Makura dam was investigated by GNS Science using the three-dimensional RAMMS debris flow software. A range of hazard scenarios from the 'Worst Credible' to 'Most Probable' were



Dam Name	Last Check	Dam Status
Hapuku 740	07/04/2017	Dam has overtopped and scoured a significant channel that has reduced the risk of major dam failure. A large lake still remains and the outflow channel is expected to continue to degrade in a relatively controlled fashion.
Leader 220	07/04/2017	Main dam crest has eroded and the lake level dropped approx. 3 m from peak. Water overtopping new outlet which has been stabilised by landowners. Moderate chance of further failure, but no out of river flooding anticipated.
Ote Makura 100	07/04/2017	Dam has overtopped and scoured a significant channel through the toe of the landslide. Hazard is significantly minimised.

Figure 3: A screen shot and sample data from the website http://ecan.govt.nz/landslide. Details of each dam can be accessed by clicking on the marker, with red markers for key landslide dams and blue markers for other dams.

developed based on estimates of lake water volumes derived from surveys and outflow discharges estimated based on local dam and catchment geometries and published empirical relationships from natural dam breaches.

Since the Worst Credible Hazard scenario indicated that dwellings located on the upper terrace were unaffected by debris inundation, KDC allowed some of the evacuated residents to return home after being evacuated for seven days. Because the results from the Most Probable Hazard scenario indicated that all dwellings were unaffected by debris, but that the campground could still be inundated, the remaining evacuees were allowed to return home after 16 days, though the campground remained closed for a while longer.

Due to uncertainty in the dam breach modeling, a plan was developed with the community to manage the residual risk to Goose Bay. Monitoring equipment was installed on the dam, signs warning of the risk were installed in Goose Bay, and residents agreed to evacuate if the alarm went off and also to evacuate ahead of a forecasted large weather event.

The dam on the Ote Makura eventually failed in April 2017 during Cyclone Debbie. A heavy rainfall warning was in place for North Canterbury and Goose Bay was pre-emptively evacuated while the key message of ‘stay out of riverbeds’ was reissued. Following the breach, debris lines indicating the height of the flood in the river channel were surveyed by GNS. These debris line elevations were in good agreement with those predicted by the Most Probable Hazard scenario. These data, along with similar data from other dams that breached in the area during the same storm, have been used by GNS to better train their dam breach simulations for future use[6].

Geotechnical assessment of building safety

Very few buildings were affected by liquefaction and/or lateral spread. Most that were lay on the banks of the Lyall Creek in Kaikōura township. There was no life safety risk associated with this hazard and EQC deployed geotechnical consultants to assess these properties. Other geotechnical engineers were deployed by the Canterbury CDEM group on behalf of local district CDEM to assess life safety risk in buildings due to geotechnical issues. These could be buildings under threat from rock fall, cliff collapse, debris flow, or landslide from above or below the building.

Staff in the Emergency Coordination Centre (ECC) identified locations of all buildings that could possibly be susceptible to these hazards, and deployed experienced geotechnical professionals to inspect the properties. Although scores of buildings were inspected over the first five weeks of response, relatively few were red tagged for geotechnical reasons – most were at Mount Lyford in the Hurunui District and along coastal stretches in the Kaikōura District.

Conclusion

This article describes a few aspects of what was a highly complex response operation. The issues described here are among those experienced by the Canterbury CDEM group and the ECC science team.

As with many emergency response situations, the main lessons to come out of the experience are the importance of relationships before and during the response and how effective communication – within the ECC, between the different levels of government, between different agencies and to the public – is utterly crucial to an effective response. Maintaining public confidence is a very important factor in this.

With regard to landslides and geotechnical issues, the identification, vetting and contracting of geotechnical expertise by local government enables a quicker deployment when large events occur and enables the rapid assessment of life safety issues in buildings and on local roads. Further, it was also seen how simplifying complex terminology and agreeing on standard procedures was important.

With regard to tsunamis, lessons from this event have resulted in changes at a national level whereby MCDEM are now responsible for issuing evacuation orders in local tsunami events. Early messaging in response activities will reflect the initial uncertainty regarding tsunami generation. In addition, GeoNet, the national geo-hazard monitoring organisation, is moving to 24/7 staffed operations to support this arrangement, enabling evacuation messaging to be broadcast as quickly as possible.

Responsibility for evacuation orders in distant source tsunami events, where more time is available, remains with local CDEM, where local expertise can assess the coast they are familiar with. Locally, Canterbury CDEM has released new evacuation zones, which they were already developing at the time of this event, and are currently planning a campaign of public education inside and outside the zones, with simplified messaging and clear instructions on who needs to evacuate and under what circumstances. This will hopefully help avoid the type of confusion that occurred on 14 November, 2016.

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Kaikōura earthquake: Summary of impacts and changes in nearshore marine communities

By David Schiel, Shawn Gerrity, Tommaso Alestra, John Pirker, Islay Marsden, Robyn Dunmore, Leigh Tait, Paul South, David Taylor and Mads Thomsen

Introduction

The M_W 7.8 Kaikōura earthquake of November 2016 is commonly described as unprecedented. That is certainly the case for its impacts on the nearshore ecosystem in New Zealand. Over 100 kilometres of coastline was lifted by up to six metres. The upheaval happened within a few minutes at night on an incoming tide when mobile species such as fish and lobster (*Jasus edwardsi*) come inshore to feed.

The newly exposed reefs therefore gave a high, and mostly dry, snapshot of rocky reef communities. The marine community composition of many of the affected areas was not known in detail because the prevailing swell and turbid water conditions along the northeastern coastline of the South Island made it difficult to survey. Some areas, however, particularly at Cape Campbell in the north and Kaikōura in the south, had been meticulously monitored two to four times annually since 1992[1]. With the upheaval, there was therefore a unique opportunity to gauge what was there, quantitatively sample the communities present and, in some cases, compare changes to long-term data.

Our group (the Marine Ecology Research Group, University of Canterbury, and the Cawthron Institute) was out on those shores within a week of the earthquake, and along with scientists from NIWA, have spent over 2000 person-hours in the field since then. There was some background knowledge about earthquake impacts on the coastal zone because large earthquakes have occurred from time to time in other countries, especially Japan and Chile. In Japan, for example, minor subsidence (< 1 m) resulted in poor recovery of sessile invertebrates over three years[2]. However, most of what we know about marine impacts from earthquakes comes from Chile, where a series of large quakes over the past several decades have caused both uplift and subsidence of the coastal zone[3, 4].

The major lessons learned from these places is that large algal beds are greatly disrupted, mortalities of algae and associated organisms are high, and recovery takes many years, even if appropriate physical habitats are still available. Usually, large invertebrates like grazing snails suffer high mortality and their loss has consequences on ecological relationships such as grazing of algal material. Although all parts of the nearshore ecosystem are disrupted in these types of events, it is generally the disruptions to rocky reef communities that cause most concern. This is because rocky reefs support the most diverse benthic (bottom-dwelling) communities and coastal habitats.

This includes canopy-forming large seaweeds, such as kelps and fucoids, a diverse array of understory species, particularly red algae, and myriad species associated with algal beds that rely on them for food, shelter and settlement sites. Numerous invertebrates such as small isopods, amphipods and gastropods live and feed on algal fronds or the detritus that comes from them. Larger species such as pāua (NZ abalone, *Haliotis* sp.), large snails and coastal fishes feed either on algal material or on the small animals in algal beds. The two major concerns for these communities relating to the earthquake are therefore the loss of physical habitat – how much rocky reef remains and whether new reef was created – and the loss of biogenic habitat – the seaweeds that provide three-dimensional structure for other species. Both of these types of habitat were severely disrupted along the coastline of the northeastern South Island, with consequent impacts on fisheries such as pāua, cultural values relating to taonga (treasured) species, and ecosystem health. Here we briefly describe the impacts on coastal reefs and some of the changes we have seen over the past year.

Science plan and methodologies

The only way to know what was going to be lost from the earthquake was to get out to as many field sites as soon as possible after the earthquake and count and measure the species and habitats that were uplifted or newly accessible. As indicated elsewhere in this publication, access to coastal sites was a challenge, and so we concentrated on rocky intertidal areas. The coast was categorised into three uplift zones from small (near Kaikōura, 0 - c.1 m), larger (around Ward and Cape Campbell in the north, up to 2 m) and largest (around Waipapa, north of Kaikōura, up to 6 m). Within each of these zones we did structured surveys at several sites using transects from the upper limit of exposed organisms to the lowest level at low tide. Transects of 30 to 50 m were laid out horizontally along the shore at different tidal heights and then at least ten 1 m^2 quadrats were sampled along each transect for all species, including algae and invertebrates. The majority of species were identifiable for at least two months after the earthquake.

As part of a wider programme funded by the Ministry for Primary Industries, we targeted sampling of pāua and their habitats. Reproductive dynamics of pāua, key algal and invertebrates species were assessed to determine if there were sub-lethal effects on them related to the earthquake. Through community interactions, the fate of pāua that had been transplanted from newly exposed areas to subtidal habitats was assessed. One commonly asked question was: 'wouldn't the marine communities simply realign themselves down the new tidal gradient'? This would only happen, however, if there was intertidal and subtidal rock in these new zones. To determine this, we did subtidal surveys for rocky reefs and associated organisms along many sites. Of particular concern to us was the potential loss of recruitment habitat for pāua, the larvae of which settle from the plankton into very specific habitats featuring small rocks and boulders inshore.

Description of results to date

Compilation and analysis of our large database covering dozens of sites allow a comprehensive view of changes to the nearshore ecosystem in the different degrees of uplift zones and their initial recovery trajectories. Here we describe them broadly.

Witnessing intertidal and subtidal habitats, with all of their organisms suddenly exposed, remains one of the most astounding things any of us ecologists have seen. We were able to walk through what were formally subtidal habitats in many areas and see the full array of physical habitats and species that were present. There was massive mortality of seaweeds along virtually the entire coastline. The large habitat-forming algae, with plants up to several metres long, including bull kelp and other strap-like fucoid algae were festooned over rocks and quickly drying in the sun.

Figure 1: Uplifted reef north of Kaikōura near Waipapa. The vertical algae hanging from the rock on the left is bull-kelp (Durvillaea poha), which normally occurs at the intertidal-subtidal margin. Plants are about 2 m long. Below them are newly exposed smaller boulders. The dark algae are fucoids which can reach up to about a metre long. The white on the rocks is mostly bleached calcareous algae, which generally forms a primary cover on rocks and boulders from the low intertidal zone downwards. Photo was taken about a month after the earthquake (Photo: D Schiel).

Thousands of pāua, often greater than the 125 mm legal size, were exposed among boulders at many sites along the coast. Mortalities were high, often numbering thousands at particular sites, but many stranded pāua were relocated into the subtidal environment by local communities, commercial pāua divers, local iwi, and fisheries officers. The fate of these translocated individuals is not entirely clear, but they surely would have died had they been left on the newly exposed reefs. Coastal fishes were dead and scattered throughout the uplifted areas, particularly at the more severely affected sites around Waipapa to the north of Kaikōura. These included butterfish (*Odax pullus*) and coastal labrids (*Notolabrus fucicola* and *N. celidotus*). At Waipapa, thousands of lobsters, mostly juveniles, were dead, as were the many species of rocky reef snails, such as the turbinid gastropods (e.g., cat's eye snail *Lunella smaragdus* and Cook's turban *Cookia sulcata*).

Figure 2: The uplift occurred just after midnight on an incoming tide, when mobile marine animals like lobster and butterfish were actively feeding around submerged reefs. In some areas the speed and suddenness of the uplift was evident in the large number of these animals that were found stranded. Some areas of high uplift, such as Waipapa Bay (pictured), had hundreds of lobsters and fish left permanently above the waterline. Slower moving and sessile animals such as pāua, kina, and mussels had even less chance of escaping back to water (Photo: Marine Ecology Research Group).

In the high intertidal zone, virtually all of the limpets died. These are some of the most important grazing gastropods on coastal reefs. In areas around Kaikōura, thousands of limpets were eaten by seagulls, which apparently had one of the best reproductive years in over a decade because of the high, limpet-fuelled nutrition suddenly available.

While the full panoply of rocky shore communities was evident, death and decomposition were the major features,

Figure 3: Sea of green. Fast settling and generally ephemeral green seaweeds, often called sea-lettuce, settled throughout the middle and lower intertidal zone beginning about three months after the earthquake and lasting till around December 2017. Their longevity was aided by the massive loss and general absence of grazing invertebrates on reefs along much of the earthquake coast (Photo: D Schiel).

and the most overpowering sense was the smell associated with the wide-scale destruction. One consequence was that water quality was compromised in tide pools and in the new low intertidal zone, where dissolved oxygen was at or below the minimum level to sustain life.

Ecologically, several main factors stand out. One is that the very large bull-kelps *Durvillaea antarctica* and *D. poha*, which can reach several metres long and are dominant on wave-exposed shores on the South Island, are now largely missing. Grazing invertebrates have remained absent or in very low numbers on the rocks and boulders of the new intertidal zone, except on the cooler sides of rocks and within crevices. Fast-settling ephemeral algae such as sea lettuce (*Ulva* spp.) bloomed along most of the intertidal zone of the coast, forming a wide belt of emerald green that persisted into December 2017.

Presumably, the longevity of this green algae was aided by the lack of grazing invertebrates. On our much-studied reefs of Kaikōura, some of New Zealand's most diverse algal communities and their associated organisms simply disappeared from large stretches of reef. Interestingly, these reefs had relatively little upheaval, probably around 0.7 m. They are still mostly covered with water at high tide, but the water depth is only a few centimetres and now experiences extreme temperatures. Sensors put out before and after the earthquakes showed that lethal temperatures over 40°C were frequently reached, especially over the summer months.

The consequences were not only the loss of seaweeds initially, but the inability of the perennial seaweeds to recruit into such harsh conditions. There was some recruitment of perennial seaweeds at the lowest reef margins, but large portions of the formerly lush reefs are covered with shiny brown ephemeral algae.

One major concern is the loss of habitat for pāua settlement and recruitment. Sites such as Omihi, south of Kaikōura, had known juvenile pāua habitat down to a depth of around one to two metres. Much of this habitat was left high and dry after the earthquake. We have continued sampling for juvenile pāua to determine whether some survived the earthquake and whether the 2016 reproductive period had produced successful recruitment in 2017. We have found some 'hot-spots' for pāua recruitment and our efforts continue to identify key areas of appropriate settlement habitat to help gauge the likely long-term impacts on the pāua fishery along the earthquake coast.

The massive loss of seaweeds and invertebrates has almost surely disrupted the coastal food web. Recent studies by Otago University, for example, have shown that large algae such as kelps provide much of the food that supports mobile organisms in the coastal ecosystem, such as fishes. This is because fish feed on a wide range of invertebrates, which feed on kelp and other algae. One way to detect these shifts and ecosystem connections is through stable isotope analysis, which is currently being pursued.

There is obviously much to be done to understand how the ecosystem will re-assort itself. The northeast coast of the South Island is normally highly exposed to waves. The sea bottom is predominantly sand and gravel, and sediment deposition can be high. This is most likely exacerbated by the continual erosion of cliffs along much of the Kaikōura coast. As well, the deterioration of the reef system itself is ongoing and severe in places. Most of the boulders and reefs are soft sedimentary rock, which is thoroughly dried out and has become unstable and is eroding greatly. Resultant fine-grain sediments have accumulated in the low intertidal zone where in many places they have smothered rock surfaces. Fine sediments can also remain in the water column and alter the quantity and spectral quality of light

Figure 4: Before (left) and after (right) the earthquake comparison of the rocky reef at Kaikōura that has been studied for over 25 years. This had been one of the highest diversity reefs in New Zealand until the earthquake. It is now devoid of macroalgae except at its lowest margins (Photos: S Gerrity).

Figure 5: Research associate Shawn Gerrity turns over small boulders in the search for surviving juvenile pāua . Much of the habitat of this species was uplifted (Photo: D Schiel).

necessary for benthic algae to grow. As yet, we do not know the full extent of subtidal rocky reef along the coastline and whether there is even the capability of the marine organisms to re-align themselves downwards onto deeper reefs. Multi-beam surveys currently being done in some key areas of this coastline, as well as our own subtidal surveys, will help clarify this.

There is much that remains to be known about the recovery dynamics of this coastal zone. The human element is also of particular concern. Prior to the earthquake, many of these areas had isolated embayments and beaches that were relatively inaccessible, except at very low tides. Such areas served as haul-out places for seals, nesting sites for coastal birds and refuges from harvesting because of general inaccessibility. Many of these areas are now readily accessible at all stages of the tide. For example, it is now possible to drive around the coastline to Cape Campbell in the northeast of the South Island, an area that was formerly hard to visit, except through farmland. This has brought new pressures to the coastline including tourism and its associated people and vehicular pressure, access for fishing, particularly for highly desirable inshore organisms like pāua and lobsters, and potentially elevated levels of illegal fishing (e.g., undersized or over-limit catches, and for pāua, which is prohibited from being fished commercially and recreationally).

In our estimate, recovery of this ecosystem will take many years. In the meantime we will have to face and solve new management issues associated with the reconfigured coastline and the marine environment.

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Marine life impacts and ecology: Effects on cetaceans, fur seals and pāua

Seal management during reconstruction work

Jo Gould and Manea Sweeney

The earthquake that occurred on 14 November 2016 created an unprecedented situation. Two large landslides came down near Ōhau Point, placing the Ōhau New Zealand Fur Seal Sanctuary and breeding colony at the centre of 'the red zone' north of Kaikōura. The NZ Transport Agency and KiwiRail, through its delivering agency the North Canterbury Transport Infrastructure Recovery (NCTIR)* team, worked closely with the Department of Conservation (DOC) to manage impacts on seals during the coastal road and rail reinstatement works.

The Ōhau New Zealand Fur Seal Sanctuary (protected under the Kaikōura (Te Tai o Marokura) Marine Management Act 2014) was the largest breeding colony on the east coast of the South Island prior to the earthquake. Seals are a taonga species to Ngāi Tahu. DOC had grave concerns about the impact of the slips on the seals and their habitat. In the weeks immediately after the earthquake DOC and NCTIR ecologists carried out site visits to assess the damage caused by the earthquake.

The earthquake happened largely before female seals returned to the colony to give birth and mate again. However, given the likely presence of some males, it is possible a number may have perished during the landslides. In late November, no seals were present at Ōhau Point apart from a few bulls in between the two slips. By mid-December 2016, seals had returned in large numbers and had begun pupping. We estimated there could have been up to 2,000 pups present over the 2016/17 breeding season from Ōhau Point to Paparoa Point.

The reinstatement works had the potential for further significant adverse impacts on seals, particularly on pups, including:

- disturbance from helicopters, machinery and falling debris, particularly between December to April due to the presence of young pups and the potential for mother/pup bonds to be broken;
- death, injury or burial from rock fall – young seal pups tend to hide when threatened; and
- starvation of pups due to mother/pup bonds being broken, or mothers being killed or injured.

NCTIR and DOC worked together from the beginning to develop and implement plans to avoid adverse effects on seals during construction works. Over February and March 2017, a four-week trial was implemented to test ways of relocating or excluding seals from areas of construction work. Methods tested included: ground herding by people, helicopter hazing (herding), physically moving pups, and using electric fences to exclude seals from areas. DOC granted a permit under the Marine Mammals Protection Act 1978 (as part of special earthquake recovery emergency legislation established by the government), to allow trained and experienced seal handlers to move the seals out of harm's way during the work.

Seal handler Alastair Judkins at work, August 2017 (Photo: NCTIR)

The trial found that ground hazing by people was 100% effective in removing adults and juveniles from an area, and 50%-70% effective in removing pups. Catching and carrying pups hiding under rocks to a nearby area effectively moved 95%-100% of remaining pups (they were left in locations close by where their mothers could find them). This method continued to be a key mitigation tool during the reinstatement works at sites where it was safe for people to access.

Electric fences proved effective in keeping seals out of an area as long as they were regularly checked and maintained, especially in wet conditions.

Helicopter hazing, where a low-flying helicopter actively herds seals away, was used in places that were not safe for people to access. It was estimated that helicopter hazing removed more than 80% of adult and juvenile seals from an area, and 40%-60% of pups.

At the height of construction work NCTIR employed a full-time team of up to six seal handlers, shepherding seals away from construction work. Seal management was integrated into construction work plans. Seal handlers worked day and night shifts as the construction crews worked to establish access around Ōhau Point. A 'seal hotline' phone number was also established for construction crews so that they could call in expert assistance to work sites when necessary.

In all, the team moved seals more than 11,000 times between February and December 2017. Fences and seawalls near Ōhau now keep seals clear of the highway, railway and construction sites.

Overall, Kaikōura's fur seals are proving to be resourceful and resilient to the effects of the earthquake and reinstatement works. Although their habitat has changed, they seem to be adapting well and have started to colonise new areas to the north and south of Ōhau Point. New seal viewing areas will be created along SH1, at Ōhau Point and Paparoa Point.

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* NCTIR is an alliance comprised of HEB Construction, Downer, Fulton Hogan and Higgins.

The effect of the Kaikōura earthquake on sperm whales

Marta Guerra, Will Rayment, Tamlyn Somerford, Roger Williams, Lucy Wing, Amandine Sabadel, Liz Slooten and Steve Dawson

Kaikōura is one of the few places in the world where sperm whales can be reliably found close to the coast[1]. This is thanks to the Kaikōura Canyon, an enormously productive submarine valley, which is an important feeding ground for male sperm whales[2]. Sperm whales are deep-diving predators, reaching depths of more than a thousand metres to find their prey. They feed on squid and fish, including species that live near the seafloor. Although the habitat of sperm whales is in deep waters away from the shore, this did not necessarily exempt them from being affected by the Kaikōura earthquake.

Earthquakes produce some of the loudest sounds in the ocean. Sperm whales, like dolphins and other toothed whales, have very sensitive hearing. They rely on sound for communication, navigation and foraging. Loud noise can mask important sounds, interfere with sound processing, and cause hearing damage[3]. In the case of sperm whales, noise can cause them to leave an area and/or stop vocalising[4]. The earthquakes would have been extremely loud to the sperm whales that were present off Kaikōura, and may have been a temporary source of distress. Within the canyon, the earthquake caused major mudslides, which flushed extensive areas of sediment-based communities from the seabed[5]. Some of the affected areas were extremely rich in seafloor-dwelling invertebrates, such as sea-cucumbers, polychaete worms, and irregular sea-urchins. The density of these animals resulted in the Kaikōura Canyon being considered 'the most productive non-chemosynthetic habitat recorded to date in the deep sea'[6]. The removal of these organisms is likely to have had consequences for the food web in the canyon.

After the earthquake, the whales changed some of their foraging habits[7]. The whales searched for prey over a more diffuse area than usual, and a previous hotspot in the upper canyon, where whales were found at least half the time, was avoided. This hot-spot zone was one of the areas affected by mudslides, where the organisms living on the seabed were removed. It is likely that their absence translated into a decrease in food resources, potentially reducing the availability of prey for sperm whales. During the two months following the earthquake, the sperm whales spent more time at the surface, between dives, than is usual (see Figure 1). This probably reflected changes in their diving behaviour, such as a need to dive for longer or deeper to find food. A further sign of potential disturbance is that in the two months after the earthquake there were very few sperm whales at Kaikōura compared to previous summers (five vs an average of 18).

Sperm whale fluke (Photo: Marta Guerra).

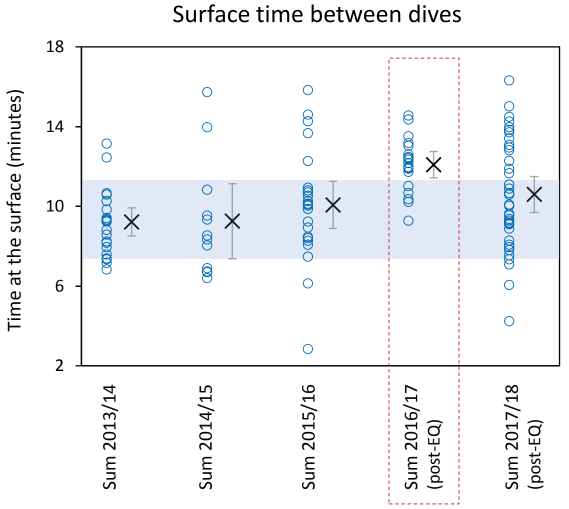

Figure 1: The time spent by sperm whales at the surface between dives. Circles represent individual data points, while crosses are the average for each period. Error bars are 95% confidence intervals. During the two months following the earthquake, sperm whales were spending on average 2.5 minutes longer at the surface. Note that these are preliminary results.

Our research group is currently analysing samples of sperm whale skin to help understand if the changes in diving behaviour and distribution reflect fluctuations in the sperm whales' food web. In a chemical demonstration of 'you are what you eat', changes in a predator's diet are reflected in its tissues. Thanks to the whales' natural sloughing of skin, we can collect pieces of sloughed skin from known individuals and analyse them for their stable isotope signature. The results of these analyses will help us to better understand the effect of the earthquake on the food resources of the whales.

The observed changes in foraging behaviour suggest that the sperm whales were influenced by the earthquake in the short term. Over recent months, some of their foraging patterns appear to be returning to pre-earthquake levels. In addition, the number of whales at Kaikōura this summer was higher than during the summer after the earthquake. This suggests that the impact of the earthquake on the whales might be subsiding. This is good news, but it is important to continue to monitor the population to understand any long-term effect. This is especially important because the number of sperm whales foraging at Kaikōura has declined over the last two decades, for causes that remain unknown[8]. The main focus of our research is trying to understand the factors influencing the decline, in order to establish the necessary protection measures to ensure the long-term health of the population.

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Pāua and the Kaikōura earthquake: Management and research responses

Tom McCowan

The pāua fishery along the Kaikōura coastline was a severe casualty of the November 2016 earthquake. Mass pāua mortality as a result of coastal uplift was one of the most immediately obvious effects of the event. Despite the efforts of dedicated locals and commercial divers to relocate stranded pāua in localised areas, the fishery suffered a major blow.

Around Kaikōura, pāua (NZ abalone, *Haliotis* sp.) typically inhabit rocky, shallow, sub-tidal waters to depths of 5 m. Adults broadcast spawn, after which larvae settle on coralline algae-covered rocks in depths of 1-2 m. Surviving juvenile pāua (<80 mm) then inhabit boulder habitats in the intertidal zone to 1-2 m, and slowly emerge out to greater depths once they reach maturity. The uplift of up to 5 m, caused by the November earthquake, resulted in a massive loss of habitat critical to all pāua life-stages.

Initial observations of the effects of the earthquake on pāua populations varied across specific locations depending on the amount of uplift, the shoreline gradient, and the abundance of pāua in the area. In some areas there was little or no pāua mortality or habitat loss, while in others, tonnes of pāua were stranded and hectares of habitat was lost. In the short- to medium-term, this has resulted in massive pāua mortality, and impaired recruitment due to habitat loss and reduced spawning biomass. In the long term, there may be a reduced carrying capacity due to reduction in available habitat for adult pāua. These factors could all have long-term implications for the pāua fishery.

The Ministry for Primary Industries (MPI) responded immediately to the event. MPI closed the pāua fishery (and all other shellfish) along the extent of the earthquake-affected area from Marfells Beach in the North to the Conway River in the south. This closure is intended to remain in place until at least November 2018.

An aggregation of adult (130 mm+) and juvenile (<80 mm) pāua. It is unusual to see juvenile pāua exposed in habitat like this. We suspect that they may have been forced to leave their normal habit under boulders (cryptic habitat) due to influx of fine sediments resulting from slips and other earthquake effects (Photo: Tom McCowan).

Measuring pāua during biomass estimates using underwater electronic callipers. Pāua that have been measured are marked with a yellow crayon so they are not re-counted during that survey (Photo: Tom McCowan).

The closed pāua fishery area is iconic to the Kaikōura region. It is one of the most accessible and popular recreational pāua fisheries in the country and has particular customary significance with several mātaitai and taiāpure reserves. The closed area also spans part of two commercial pāua quota management areas (QMAs), PAU7 (Marlborough) and PAU3 (Kaikōura). This area accounts for approximately 15 tonnes of annual catch from PAU7 and 47 tonnes from PAU3 (approximately 16% and 50% of the respective QMA's catch). Following the closure, industry voluntarily 'shelved' quota in PAU3 to prevent a shifting and concentrating of effort into remaining open areas. The Minister subsequently formalised the shelving by total allowable commercial catch reductions (TACC) in September 2017 in PAU7 and PAU3 of 10% and 50% respectively.

Since the event, MPI has supported projects to quantify the loss of pāua from the fishery, and to survey adult biomass and juvenile pāua recruitment to monitor the rebuild of the fishery. In early 2017, preliminary analyses overlaid fine-scale commercial pāua catch data (from an industry-based 'data logger' program) with digital elevation maps from Land Information New Zealand (LINZ) to estimate that 21% of previously fished areas had been impacted by the uplift.

Over the past few months the Paua Industry Council Ltd., with the support of regional dive crews, has been undertaking surveys to estimate the spawning pāua biomass and monitor discrete adult populations. Biomass estimates (measuring and counting pāua within a fixed area) have been undertaken using novel methodologies that employ underwater electronic calipers to measure and count pāua, and units that record GPS and dive activity to delimit the areas surveyed.

To date, 41 sites spanning the extent of the affected coastline have been surveyed, with more than 14,000 pāua counted and measured across all sites. Within these sites, 83 monitoring points have been set up around discrete pāua aggregations to allow monitoring over time. Results from these surveys will be complemented by the University of Canterbury's concurrent research of monitoring intertidal ecology, including juvenile pāua recruitment.

Preliminary observations from dive surveys have been encouraging in some locations, with a very high abundance of large pāua. However, pāua biomass appears to be very low in areas more severely affected by the uplift. Dive survey results will need to be reviewed alongside results from juvenile recruitment monitoring surveys, as well as estimates on what the new available habitat might be. A precautionary approach is required for decisions on when and at what level the fishery might be re-opened. It is hoped that with patience and correct management this fishery will return to being one of the best pāua fisheries in New Zealand.

Reconnecting a fractured community

By Lucy Brake

'Nature in her most devastating form has rekindled a fellowship of family and community that provides us the incentive and purpose to move collectively forward as one.'

These are some of the first words of 'Reimagine Kaikōura – *Pōhewatia anō a Kaikōura*', Kaikōura District's Recovery Plan 2017, which sets the foundations for a community to rebuild and restore itself. This document is built around the experiences of the community and the knowledge gathered during the first months after the earthquake and helps guide what the coming years will deliver.

We spoke to experts who are involved in the response and recovery of Kaikōura to offer some valuable insights into community preparedness, how major disasters really impact on coastal communities, and what we can possibly do better when faced with similar disasters.

Social recovery evolves into business as usual

With a focus on morphing social recovery into business as usual, Susi Haberstock, Community Services & Development Manager at Kaikōura District Council, and the Department of Internal Affairs (DIA) funded Outreach Team are instrumental in leading the post-earthquake social recovery. From Susi's perspective, the greatest social impact on the coastal communities from the Kaikōura earthquake has been the isolation brought about by the road closures. "Being physically cut off by inaccessible roads caused some problems, including increased feelings of anxiety, but for small communities that relied heavily on each other before the earthquake, they were never so connected with everyone helping each other out."

The social recovery task list is extensive and whilst many of the proposed actions are still being actively worked on, a number have been successfully completed. One of these is delivering a coordinated approach to planning and managing outreach activity for Kaikōura District. "We were already collaborating with other agencies before the earthquake, but the earthquake relief fund supported a consistent coordinated approach to outreach activity, including consistency with mapping, and understanding and analysing needs," notes Susi.

The $5.41 million Lottery Hurunui Kaikōura Marlborough Earthquake Relief Fund was set up with the aim to support the local communities and residents affected by the earthquake. One of the focuses of the Relief Fund was to reduce the social isolation. Kaikōura District Council used the funds for positions that could deal with recovery issues exclusively.

There are many parts of the social recovery work that were very successful. "Having someone paid by MCDEM (Ministry of Civil Defence & Emergency Management) to help set up the recovery framework was critical to its success," observes Susi. "In addition, having the financial backup of the DIA for the earthquake relief-funded recovery position was essential." But at the end of the day, the resilience of the local community, and their willingness to help each other, has been the defining factor in Kaikōura's recovery. "The community events helped people reconnect and help them understand that the social fabric of our little coastal village has changed forever."

Linking communities

Helping locals and newcomers feel welcome and connected within Kaikōura is a role that Vicki Gulleford, Community Connector at Kaikōura District Council, takes very seriously. She says that her work has provided an important point of contact for outside agencies servicing the area. "The Connector has links to many of the agencies, groups and services within our community and has been able to help externals make appropriate and helpful connections." Her work has also revolved around establishing Te Hāo Mātauranga; a community learning hub that aims to create, promote and encourage learning opportunities within Kaikōura. "Te Hāo Mātauranga has been a pivotal part of the Kaikōura District Council recovery plan with many projects established that enable the community to learn new skills and develop resilience," observes Vicki. Supporting community events and encouraging ways for people to connect is another key part of the work she has been involved with, such as the highly successful event 'Our Amazing Place'. This connected families and whanau with the key agencies and services working in the community, where 22 services were represented with over 250 participants.

Amazing Place event – Rachel Vaughan from the All Right campaign connecting with local whānau (Photo: Te Hāo Mātauranga).

Vicki, like Susi, sees isolation and loneliness as being the greatest social impacts on the coastal communities from the Kaikōura earthquake. "Having the roads closed has led to feelings of physical isolation, difficulty in getting to the places you need to go, trouble with appointments out of town," she points out. "The majority of residents have not made the long trip around to Blenheim. Many people have family and friends there; this has meant relationships have suffered." Vicki has seen and talked with many people working longer hours as a result of employment changes, plenty of people who feel lonely as their partner is not at home as often, and children who have parents working different or many hours resulting in a change in routine and less family time together. "People often try to counter these impacts from isolation and loneliness with increased use of alcohol to help blur or deaden the feelings," says Vicki. "This in turn leads to increased emotional turmoil, violence, mental unwellness, etc."

From Vicki's perspective the Relief Fund has been a critical part of the social recovery work. "Having this fund has been a real blessing – without this we would not have been able to support our community in many ways. From employing social recovery workers to helping fund travel for school groups and everything in between – we have been so grateful for this support." Vicki says that whilst the social recovery work is still ongoing and the community will feel the effects of the earthquake for a long time, the care and empathy they have received from Cantabrians in particular has been really helpful and appreciated. "I believe our children have experienced lots of normality with schools having a practical 'get on and do it' attitude – school is a constant and a safe place for so many of our children. I take my hat off to our many teachers and principals for the work they do."

With the value of hindsight Vicki believes that a longer period for the 'recovery' would be a necessity if facing a similar crisis response again. "We ended our recovery period before our roads were reopened – this didn't make a lot of sense to me as we need to be connected to the wider world and have the general business of being a state highway based town for our community to have a chance to get back to normal and recover."

Talking preparedness

Delivering civil defence at a local level through public education and engagement can be a very challenging task and people might think that after an earthquake as large as Kaikōura's that it would be easy to inspire people to be prepared. However, Kd Scattergood, Emergency Management Officer in Kaikōura, found she was facing a different kind of challenge after the earthquake. She says that research, both within NZ and internationally, indicates that immediately after a disaster the preparedness rates rise sharply. In Kaikōura, the 2017 residents satisfaction survey, conducted a few months after the earthquake, showed that around 90% of households in Kaikōura considered themselves prepared. "Anecdotally, we'd also seen that the community was more engaged with each other post-earthquake and that people knew what worked and what did not during the earthquake," observes Kd. "However, directly after the disaster, even though our risk of an earthquake was greater than ever, I was cautious about re-traumatising people by talking about disaster risks."

In the months following the earthquake, the messaging focused on "just continue to do what worked and fix what didn't". They mostly used Facebook, the local newspaper and talking one-on-one with people as the channels for communication. In March, a couple of tourism and disaster workshops were held and as a result of the feedback, Kd ran personal preparedness workshops in April. She was concerned about how to deliver preparedness talks to people who have survived such a large event, but as it turned out people just really wanted to focus on sharing their stories of the night of the quake, the Christchurch quake, the response and recovery. "Looking back, I wish I would have held more workshops around people just telling their stories to each other." After April Kd concentrated on aligning her engagement and education with other community meetings which allowed her to interact with a large number of people without any additional energy on her part or theirs.

"As last year progressed, the biggest challenge was and continues to be fatigue. People were, and some still are, very tired, both emotionally and physically. Kaikōura is booming with the rebuild and people are now busy with the summer tourists since the road reopened," notes Kd. "My focus since the winter has been trying to get people to do what they can, when they can, in a low-key way." She is now hoping to start re-engaging with communities to develop community-led disaster plans which match what communities need with the amount of energy the average family has around the issue of civil defence and the resources of a small council.

Success in working together

Kd highlights how in the welfare space, prior to the earthquake, a couple of important things happened. They held a Civil Defence Centre training which included members of the newly revitalised Red Cross, the Māori Wardens, community members and iwi. During the earthquake response and into recovery, the Red Cross and the Wardens worked together. The Red Cross activated minutes after the ground stopped shaking and over 700 people were fed during the first night at Takahanga Marae. This year, Council's emergency management will be working with the Red Cross, and the Māori Wardens to create a Community Response Team to promote resilience, preparedness and providing help in an emergency. Kd is very excited about the opportunity this project presents.

"Research shows, and I truly believe, that community groups and neighbourhoods who had strong ties before the earthquake were able to do a lot of good, fast, work during the response," says Kd and notes that these same communities continue to be able to engage with each other and local and central government during recovery. "A lovely example is the (mostly) retired ladies who run the op shop in town, they went from raising funds for the hospital, to offering the elderly a place to gather for a cup of tea during the weeks following the response and continue to be focal point for the larger community."

Another example of the importance of collaboration is Te Korowai o Te Tai o Marokura (Kaikōura Coastal Guardians), who have been meeting together since 2005 to talk through the difficult issues around marine use and coastal management. This group includes members from commercial, tourism, recreational users and others, and they have produced after many meetings and consensus building the Kaikōura Marine Strategy, which the New Zealand Government used to enact the Kaikōura Marine Management (Te Tai ō Marokura) Act in 2014. "During the response and into the recovery, they have been able to talk with authority to the NZ Government and other agencies about the challenges facing the coastal environment," shares Kd. "Without the 11 years of hard work Te Korowai put in before the quake, the Kaikōura marine area may not have had a local body who could advocate with authority about the values the Kaikōura community share around the coast, marine life and its management."

Sharing lessons learnt

There are many lessons that other communities and councils can learn from the Kaikōura earthquake response and recovery in regards to civil defence planning for evacuations from coastal areas. From Kd's perspective it is all about keeping the messages simple: Long/strong/gone. "Once people get safe, then they can worry about whether they needed to evacuate because things are very uncertain at the beginning of a disaster. This is the most critical lesson for coastal communities – never wait to evacuate." She also points out the importance of helping to make sure family and friends – particularly the elderly – have a plan. "Talk to people about having an evacuation plan for older parents, which include someone living very close (one or two houses away) to help evacuate them."

Each situation is different and the importance of each community looking at their own surroundings, such as landslide danger during earthquakes in hilly areas along the coast, can be overlooked says Kd. "It's hard to go up when the mountain is coming down as well. People need to really look at their individual situation both in terms of landscape and personal circumstances when coming up with their plan. I also think we need to really keep explaining why 'drop, cover, hold' is best practice in an earthquake and the importance of strapping things down."

There are lots of things Kd reflects that she could have done differently. She points to things like wearing more comfortable shoes, making sure family know how hard it is on them to have someone leave to work in the Emergency Operations Centre (EOC), and also making sure everyone in the EOC takes more breaks. In terms of recovery, it is important to plan for information overload both with the community and within the EOC. "The demands on Council staff are enormous as they go from full response mode to a new crazy work environment all while dealing with their own personal disaster situation," observes Kd. "In the EOC, we have made improvements in our systems. We just know more about what to expect. We now have a practices plan so that whoever arrives first to set up the EOC can set it up in about 30 minutes regardless of if they have worked in an EOC before." On a larger scale, she says that scenario planning is crucial whenever possible to look at what could happen and how to mitigate effects. "However, it is hard to do this effectively as so many players are involved to make it meaningful, most of whom are not involved in emergency management full-time."

She also notes that in terms of public education, prior to the disaster she would have tried to make everyone in the community (including herself) read and understand their insurance. "This is the one thing that would have made the most difference after the initial response." In addition, there should be more focus on business continuity plans. "In my opinion, disasters are scary but unless you are very unlucky, for the most part, it's the day-to-day wear and tear of recovery that impacts individuals, families and communities the most."

The Harbour reopens – Ngāi Tahu's perspective

By Kaituhi Deborah Nation

On 14 November 2017, the Kaikōura community gathered to commemorate the one-year anniversary of the earthquake, and to celebrate the official reopening of Kaikōura Harbour. The harbour reopening was met with celebration, as it clears the way for local tourism and fishing businesses to return to full operation. "We're not out of the woods – we've got a lot more work to go," says Brett Cowan, of Te Rūnanga o Kaikōura. "But it's an indication of how diverse groups can come together in one collaboration with a common purpose. Our differences have been benched, and everyone has been getting onto dealing with the imminent need. In that regard we have a true sense of kotahitanga."

Deborah Nation's full report can be read at http://ngaitahu.iwi.nz/our_stories/one-year-on-tk76/ This excerpt has been published with kind permission from Te Rūnanga o Ngāi Tahu.

The Kaikoura community gathered to witness the opening of the harbour (Photo: Ngāi Tahu).

Section 3: Longer-term response & rehabilitation

Main North Line post-quake (Photo: NCTIR)

The transport infrastructure recovery: Moving mountains to reconnect communities

By Manea Sweeney, Richard Reinen-Hamill, Tony Fairclough, Steve Procter, Daniel Headifen and Deborah Diaz

The Kaikōura earthquake devastated transport infrastructure on the upper South Island's eastern seaboard, isolating many coastal and rural communities overnight. The instant disruption to tourism, freight and primary industries was felt nationwide. Over one million cubic metres of rock and landslide debris fell onto State Highway 1 (SH1) and the South Island Main North Line railway (MNL). Harbour facilities, vital to tourism and fishing industries, also become non-functional after seabed adjacent to the Kaikōura Peninsula rose by about a metre.

This destruction occurred on a coastline renowned for its scenery, ecosystems and tourism experiences. The coast is of great cultural significance to Ngāi Tahu and much of it forms part of the conservation estate. The district is home to many Threatened and At Risk species, some unique to the area.

This article outlines the North Canterbury Transport Infrastructure Recovery (NCTIR) team's extraordinary effort to clear coastal landslides and reopen the transport network, the seaward realignment of SH1 and the MNL, and the excavation of the South Bay marina and navigation channels.

Unprecedented scale

The transport recovery had many logistical challenges to overcome. Emergency works, design and construction occurred simultaneously to expedite the programme. The scope and volume of repairs was enormous. There were more than 3300 separate 'things to be fixed', including land and structures. Despite this, the NCTIR team achieved its targets of reopening the railway by September 2017 and the highway by December 2017.

There were approximately 1500 damage sites on SH1, spread over 194 km between North Canterbury and Marlborough. There were over 950 damage sites along 150 km of the railway, including 20 tunnels. In some places the highway and railway were completely displaced onto the foreshore. More than 100 bridges were affected, as was the Kaikōura Inland Road (Route 70).

The government established the NCTIR alliance in December 2016 to keep traffic moving on alternate routes and restore the network. It was the first time the NZ Transport Agency, KiwiRail and construction firms Downer New Zealand, Fulton Hogan, HEB Construction and Higgins collaborated on such a scale. The MNL repairs represented the largest rail construction effort in the South Island since World War II.

The recovery alliance sought to merge the knowledge of local contractors with resources from all over New Zealand. During 2017, the NCTIR team grew to 1700 people from over 100 organisations. Temporary accommodation facilities were built at three locations along the coast, including a prefabricated village for 300 people in Kaikōura township. The project included elements of social integration with local communities, providing opportunities for local suppliers and employment in order to counteract the earthquake's negative economic impacts.

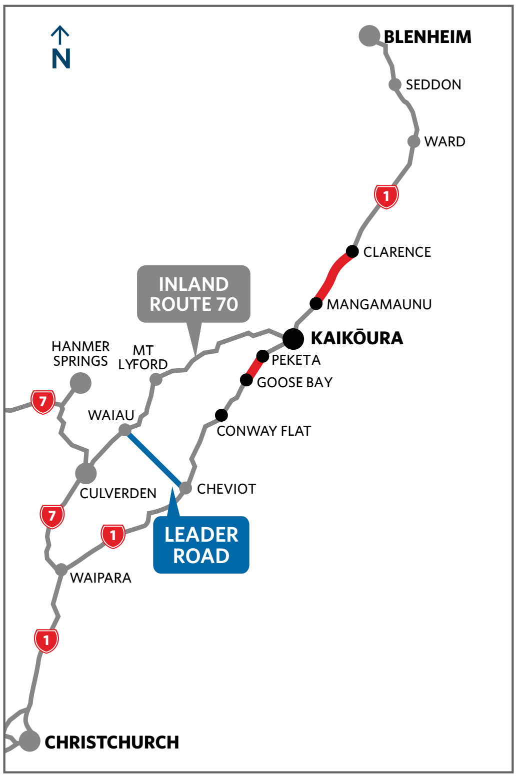
Vertical earthworks

About 80 landslides blocked SH1 and the MNL between the coastal settlements of Ōaro and Clarence. Before construction could begin in earnest, mountains needed to be moved and unstable hillsides made safe. The narrow rail and road transport corridor, winding like a ribbon between mountains and the sea, compounded complexities.

Even as helicopters and naval ships delivered emergency supplies and evacuated tourists in the earthquake's aftermath, work to re-establish road access to Kaikōura was underway. Temporary fords or bailey bridges were built across streams and rivers. Smaller slips were cleared, and temporary tracks constructed around larger landslides. On the Kaikōura Inland Road, new switchbacks were cut into steep hillsides where the road had completely fallen away.

Within six weeks of the main earthquake, the NZ Transport Agency opened the roads south and inland of Kaikōura – even if only one lane of traffic could get round some of the landslides, which were constantly monitored for movement. Ten massive landslides north of Kaikōura would take 10 months to clear.

Tackling the largest landslides, some up to 300 m high, involved helicopters dropping monsoon buckets of sea water on the slopes to wash down loose rocks and dirt. Abseilers used pick axes and crowbars, or pumps and airbags, to dislodge large boulders. If any particular boulder could not be moved, explosives were deployed. The aim was to clear the hillsides back towards stable ground or bedrock, making it safe for crews to work below the slopes and improve the transport corridor's long-term safety.



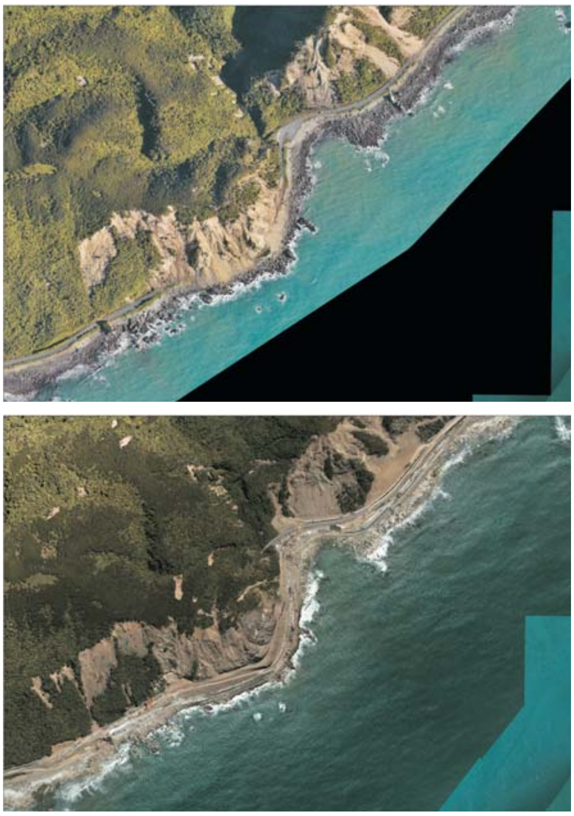
Map of locations on SH1, with road closures and alternate routes as they were at the beginning of September 2017 (Graphic: NCTIR).

Un-remediated earthquake-triggered landslides exhibited ongoing instability in heavy weather, and 2017 was a particularly wet year for the district. Additional rainfall-triggered slips and landslides needed to be cleared repeatedly. For example, a landslide at the southern end of Half Moon Bay, approximately 20 km north of Kaikōura, that was initially estimated to consist of 10,000 cubic metres of material, ultimately generated nearly 80,000 cubic metres. Over 6,600 truck movements were required to clear it.

All landslide material had to be transported along the coast through narrow and congested work sites, resulting in a need to manage conflicting construction priorities. Material was often relayed to temporary stockpiles, some which grew to be over two storeys high, before transportation to permanent placement sites.

During 2017's winter months, much of the recovery effort focussed on clearing the slips north of Kaikōura where the network had sustained the most damage. KiwiRail's specialised construction trains gradually advanced into the damaged areas to perform temporary track repairs and carry supplies the length of the seaboard. To reach Kaikōura, the first work train travelled on temporary tracks around slips. One tunnel was so severely damaged that people could not enter it without the roof being propped. The train – carrying rails, sleepers and ballast – was extended in length with empty flat deck cars so it would be over a kilometre long, as it needed to be pushed/pulled through the tunnel by locomotives at each end, so the locomotive engineers were never in the tunnel.

It wasn't until Spring 2017 that construction materials and machinery could be moved between sites north and south of Ōhau Point, 27 km north of Kaikōura, where the largest landslide had fallen. Ōhau Point had long been a challenge for land transport – in the 19th century the path round the



SH1 at Ōhau Point in December 2016 (top) and in November 2017 (bottom) (Photos: NCTIR).

high bluff was in places too narrow for horses to pass. Securing that landslide with mesh and rockfall protection was critical to the re-opening of SH1. Abseilers using drill rigs suspended by ropes bolted the hilltop to keep it from moving. Once those anchors were in place, helicopters hung sheets of mesh, which were then fastened into place by hand.

Abseilers clearing loose rocks to stabilise the cliff face (Photo: NTCIR).

On the foreshore below, the teams investigating, designing and building the seawalls had to wait until the upslope stabilisation works had been essentially complete, with rockfall risk and landslide hazard appropriately mitigated. Only when the hillside above had been made safe could seawall construction teams work towards each other from each side of the Point, and sometimes surveyors and designers completed their work the day before construction commenced. The seawall teams completed the minimum height of the wall around Ōhau Point just four weeks before SH1 re-opened.

Realignments on seawalls

Early opening of the transport corridor often added complications and conflicted with the need for resilience work in areas where hillsides were expected to exhibit ongoing instability risk. Seawalls, revetments, bridges and tunnels were all considered on a case-by-case basis as potential solutions to by-pass the largest slips. A decision to build seawalls in order to relocate sections of SH1 and the railway seaward and away from a potential landslide impact footprint was largely a pragmatic one, with due consideration being made of the cost, material availability, reopening targets, and a desire to minimise the work's coastal footprint and associated environmental impact.

The seawalls have been designed as flexible structures, capable of providing high levels of geotechnical and structural performance in future seismic events. The downside of using vertical seawalls is the lack of wave energy absorption, and potential for wave overtopping. However, many historic coastal works along this seaboard had used variations of a vertical seawall design, which had generally performed well, providing over 70 years of service in some instances.

The construction of seawalls meant working whenever tide and weather conditions allowed, day and night. Excavators placed sandbags, each weighing more than two tonnes, and larger boulders reclaimed from the beach to help protect the work site from wave inundation while the seawall foundations were poured. Foundation works were often located below the high tide level, requiring careful construction planning and design to maintain safety for the construction crews.

The foundations for any seawall are critical to its performance and the level of these was driven by the requirement for a good key into bedrock, which was extremely variable. The seawall blocks were placed on the foundations in layers, carefully tied back using high-strength geogrid. They were backfilled using a cement-stabilised fill, designed and constructed to give consistent strength properties, to allow early trafficking and ensure future seismic performance.

Seawall construction work underway near Ōhau Point (Photo: NTCIR).

A custom seawall block was developed to increase the durability of the finished structure and allow a high degree of installation precision and consistency while being relatively easy to construct. Essentially, the 5-tonne blocks are structurally independent of one another to permit flexibility of the structure as a whole, relying on the geogrid and associated dowel connection to hold them in place during a future earthquake event. Approximately 7000 seawall blocks were required for 2.8 km of seawalls.

A new coastal dynamic

More than 100 bridges needed repair or replacement, with some structures illustrating the new dynamic between infrastructure and earthquake-affected land in coastal zones. One such example is found at the mouth of Tirohanga Stream in Marlborough, where the Kekerengu fault moved, dropping the ground by 2.2 m to the north of the fault line and raising the ground by 0.3 m to its south. The elevation of the coastal outlet was quickly re-established to its pre-earthquake level by river and sea erosion, resulting in an area of permanent inundation in the backshore.

Rail Bridge 129 dropped 2.2 m and moved 5 m laterally. Its replacement is located 65 m further north than the original bridge, away from the fault, and it has been built on a raised embankment designed to significantly reduce future flood risk and to provide a high level of performance in a future seismic event. Given the remote location, pre-cast components were manufactured on site. Fifteen rail deck segments make up the new 46 metre, three-span bridge. Continual maintenance of the outlet was required during construction to allow ponded water to drain and keep water levels down in the construction area.

At Irongate Stream, approximately 17 km north of Kaikōura, the alignment of SH1 has been moved seaward and away from a large landslide. A new 144 metre, seven-span bridge

Rail Bridge 129 at Tirohanga post-quake (Photo: NTCIR).

sweeps from a rock bluff at the southern end and lands on a new abutment immediately adjacent to a new pre-cast block vertical seawall.

Taking about three months to complete the superstructure, the Irongate Stream bridge is the fastest build of its kind in New Zealand history. Its 91 bridge beams were prefabricated at four locations across New Zealand and transported to site in accordance with a 'just in time' delivery philosophy to reduce construction time and meet the road opening target. The old road above the new alignment will eventually be used as a rockfall catchment bench.

Work on the new, seven-span Irongate Bridge, north of Mangamaunu, nearing completion (Photo: NCTIR).

Reopening the transport network

Freight trains returned to the MNL on 15 September 2017, just 10 months after the earthquake. Weather had been a constant challenge, including two ex-cyclones in April 2017, which exacerbated earthquake damage. Freight trains initially ran only at night so construction could continue by day.

In the weeks leading up to SH1's 15 December opening, the weather meant the NCTIR team was required to work day and night and had to find innovative solutions to accelerate the construction programme. One such innovation was the use of helicopter updraft to dry the road sub-base so that chip seal could be laid.

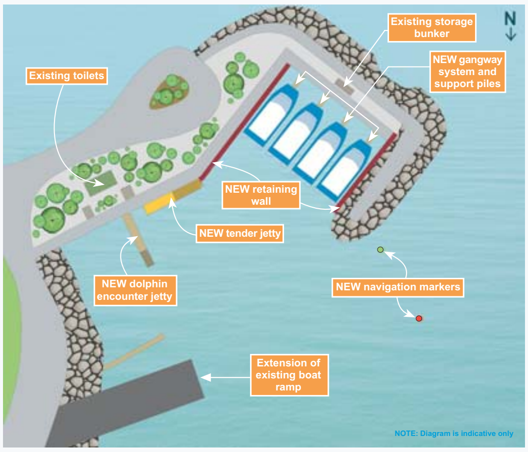
In all, 1700 people worked more than 2 million hours to move the fallen mountains and reconnect the North Canterbury and Marlborough communities that were isolated by the earthquake. The landscape remains fragile, as evidenced by wave overtopping of partially completed seawalls and further slips during ex-tropical cyclone Gita in February 2018. There are still significant resilience and improvement works to do and NCTIR continues to work toward the goal of 24/7 road and railway operation.

Kaikōura Harbour

The South Bay marina is a key piece of infrastructure for regional tourism and commercial fishing. The earthquake lifted the seabed underneath by approximately 1 m, resulting in significant new navigation hazards. The marina, and Coastguard Kaikōura's neighbouring boat ramp, were largely unusable outside of high tides. Due to the facilities' importance, repairs needed to be staged to maintain a minimum level of service for stakeholders throughout the repair programme.

Both the inner and outer harbour required excavation, in particular the breaking up and removal of limestone bedrock uplifted by the earthquake. This work had to be completed before the replacement structures, such as the mooring piles, vertical seawalls and jetties, were constructed.

Close collaboration with tourism operators and key stakeholders meant improvements were incorporated into the final marina design to facilitate future growth and prosperity, such as the ability to berth larger vessels and the safe transfer of tourists from cruise ship tenders.



Plan showing the redevelopment of Kaikōura Harbour (Graphic: amended from a diagram published by NCTIR).

Work underway on repairing Kaikōura Harbour (Photo: NTCIR).

Emergency legislation – framework for a fast recovery

By Manea Sweeney and Bill Harrington

Genesis of the Order in Council for the transport network

Work on repairing the road and rail transport infrastructure began almost immediately after the 14 November 2016 Kaikōura earthquake, relying on emergency works provisions in the Resource Management Act 1991 (RMA).

While these emergency works were progressing, the Hurunui/Kaikōura Earthquakes Recovery Act 2016 was developed under urgency.

The purpose of the Recovery Act was to assist the earthquake-affected area and its councils and communities to respond to, and recover from, the impacts of the Hurunui/Kaikōura earthquakes. The intent of the Act was broad and included providing for short-term, medium-term and long-term recovery, including safety enhancements and resilience improvements to infrastructure. The Recovery Act came into force on 13 December 2016.

In simple terms, it wasn't a piece of legislation simply about recovery and reinstatement of what existed prior to the earthquake, but also allowed for something better to be left behind.

A key mechanism of the Recovery Act was Section 7, which enabled the Governor-General, by way of an Order in Council made on the recommendation of the relevant minister, to grant exemptions from, modify, or extend any provisions of specific enactments in connection with the earthquake-affected area. This followed from adapting lessons learnt from the Canterbury earthquakes and the emergency legislation applied in that context.

The Hurunui/Kaikōura Earthquakes Recovery (Coastal Route and Other Matters) Order 2016 (the OIC) was recommended under the Recovery Act by then Acting Minister of Civil Defence, Hon Gerry Brownlee. The purpose of the OIC was to enable the restoration of State Highway 1 and the Main North Line between Picton and Christchurch without undue delay.

The OIC was extensively tested by a range of people with expertise including a retired High Court judge; specialists in Māori traditional knowledge, protocol, and culture; specialists in environmental management and wildlife conservation; and stakeholders from within the earthquake-affected communities.

The Governor-General signed the OIC on 20 December 2016. The OIC modified provisions of the RMA, and nine other pieces of legislation, to streamline restoration work approval processes while also ensuring fit-for-purpose environmental and stakeholder management processes remained in place.

The OIC and the processes prescribed under it were ultimately the driving force behind delivering the government's objective of earthquake recovery without undue delay – not only for the people of Kaikōura, Hurunui, and Marlborough, but also New Zealand.

Approvals under the Order In Council – an enabling philosophy

The OIC provided truncated approval processes for resource consent applications and other legal approvals relating to restoration works on the coastal route. Restoration work was broadly defined in the OIC and included both the repair and rebuild of the coastal route, as well as safety and resilience improvements and enhancements.

Throughout 2017 the North Canterbury Transport Infrastructure Recovery alliance (NCTIR), on behalf of the New Zealand Transport Agency and KiwiRail, obtained various suites of approvals to enable restoration works on the coastal route. These approvals included resource consents; conservation concessions; and wildlife, freshwater fisheries, and marine mammal permits. The truncated approval processes set out in the OIC limited the amount of information required to be provided by the applicants to only broad summaries of activities accompanied by desktop effects assessments. This approach enabled the works to proceed at pace while ensuring good environmental procedures were being put in place.

A unique part of the truncated approvals process was that the OIC contained a pre-written set of conditions, which applied to all approvals. The conditions also required the establishment of a range of environmental and stakeholder management processes under which all works had to be managed. This included:

- **Ecological principles**, which had to be written by the project ecologist with input from a cultural advisor, and which had to be taken into account in relation to all restoration works.
- The development of a project-wide **Construction Environmental Management Plan** (CEMP) and **Erosion and Sediment Control Plan** (ESCP), which provided a broad framework for the development of site-specific plans. This was incorporated noting the extreme circumstances of huge slips that required large-scale earthworks to clear the transport network.
- The appointment of an **Iwi Cultural Adviser** from Te Rūnanga o Ngāi Tahu to develop cultural indicators and provide on-site guidance across all works.
- The establishment of the **Restoration Liaison Group** (RLG) containing members of a range of key stakeholders who would meet regularly with the project team to receive updates, disseminate information back to the community, and communicate any issues or concerns raised. This Group has now been in operation for 16 months and has provided a crucial forum to discuss and identify challenges relating to the post-earthquake context.
- The requirement for **all permanent works in the coastal marine area (CMA)** to be designed by a suitably qualified and experienced engineer and ecologist, with consideration of climate change and the ecological principles.

- The development of a **Landscape Design Framework** (LDF), which provided high-level guidance to all design teams to assist in creating consistent and appropriate designs within a highly-valued coastal environment.

The philosophy behind these pre-written approval conditions was to enable a fast paced, flexible and responsive recovery programme while still retaining appropriate environmental and stakeholder management processes.

Where the rubber hits the road (or where the steel hits the track?) – implementation

NCTIR quickly established a diverse environmental team as emergency works continued up and down the Kaikōura coast. The team rapidly expanded to include planners, ecologists, archaeologists, construction environmental advisors, cultural monitors, landscape architects, wildlife experts, and seal wranglers. The team immersed themselves both within the construction crews in Kaikōura, and within the design team largely based in Christchurch. The successful implementation of the broad OIC approvals framework was reliant on the team owning and championing environmental management processes, and taking responsibility for these processes right through design and construction.

The dynamic Kaikōura coastline posed numerous challenges throughout construction, including management of flora and fauna values (including the local population of the New Zealand fur seal), working alongside and within a highly variable and active ocean, and working within a highly constrained corridor wedged between this ocean and the Kaikōura ranges.

These challenges required innovative measures to be developed on the ground in response to particular issues – such as using low-flying helicopters to move seals away from construction areas.

Ultimately, the emergency legislation, and the OIC established under it, provided a robust framework for a rapid recovery and restoration of a critical transport link for local communities, the South Island, and the New Zealand economy. Its implementation has also demonstrated the importance of integrating key regulatory stakeholders (such as Councils, Heritage New Zealand, and the Department of Conservation), Treaty partners, Te Rūnanga o Ngāi Tahu, and community groups (such as Kaikōura Marine Guardians) to help ensure that transport infrastructure is built that addresses sensitive values as well as creating a lasting legacy for this iconic coastal environment.

Electric fishing as part of implementing CEMP (Photo: NCTIR).

NCTIR archaeologists at work (Photo: NCTIR).

Post-quake planning – tourism and surfing in Kaikōura

Hamish Rennie, David Simmons, Jo Fountain, ER (Lisa) Langer, Andrea Grant, Nick Cradock-Henry and Tom Wilson

Drive through Kaikōura and the contribution of the sea, sea creatures and seafood to the character of the town is apparent, from the name itself (meaning crayfish meal), to the crayfish pot design of the District Council headquarters, the marine mammal viewing activities promoted to tourists, and the imagery and naming of many of the hospitality establishments in the township. Prior to the 2016 earthquakes, Kaikōura was well recognised for its socio-economic dependence on travellers, many of them attracted to break their longhaul trips at Kaikōura by marine-based tourism and recreational opportunities such as whale watching and surfing. The closure of the road and rail links north and south due to the earthquakes of 14 November 2016 isolated the township, but the altered landscape also created new tourism opportunities. For New Zealand's smallest mainland district, in both population and rating base, how to address these opportunities became a significant planning and infrastructure issue.

The tourism flows into the Kaikōura District can be described as comprising three distinct groups: travellers on State Highway 1 taking advantage of attractive seascapes midway between the Canterbury Plains and the Picton Ferry Terminal to stop and recuperate before travelling onward; tourists for whom specific tourist attractions make Kaikōura a key destination on their New Zealand holiday; and Canterbury residents spending a few days at a holiday bach or campground[1]. The primary local businesses that benefit are the fuel, food, and accommodation services, and those specifically offering marine tourism opportunities.

The importance of the Kaikōura tourism industry is reflected in the fact that, in 2013, 25.5% of the population was employed in the accommodation and food sector, with another 15.3% employed in retail. As was seen in the post-Christchurch earthquakes, the post-quake accommodation and services shifted largely from catering for tourists to catering for recovery workers, especially infrastructure. Marine-dependent businesses, such as Kaikōura whale watching and commercial fishing, suffered significant income losses, whereas some smaller service sector businesses were less affected financially, but found their clientele and peak business periods changed in the short term. However, the peak tourist season of January shows the impact of the earthquakes and associated access difficulties. In January 2016, there were 28,662 guest arrivals with an accommodation occupancy rate of 62%. The following January the guest arrivals fell to 8,845 and the occupancy rate to 29% (Statistics NZ accommodation survey data).

Many tourists used to take advantage of attractive seaside camping grounds spread along the highway, especially for recreational fishing and surfing. Immediately after the earthquakes, approximately 1200 tourists were stranded in Kaikōura, many of them fed and supported by the local marae of Te Rūnanga o Kaikōura for the hapū of Ngāti Kuri, Ngāi Tau. Many had to be evacuated by sea or air. The unknown altered bathymetry of the seabed and closure of the town's marina and docking facilities due to uplift and damage meant that such sea evacuation was hazardous, in so far as it had to be undertaken by ship-to-ship transfer. The fortuitous presence in New Zealand of well-equipped foreign naval vessels willing to be redeployed played a significant role in the sea evacuation and immediate response. This also highlighted both the potential for sea-based servicing of our isolated communities in the post-disaster period, but also the need for good local bathymetric data and rapid response bathymetry measurement systems and processes.

The re-opening of the road and rail routes north and south of Kaikōura became the major focus of recovery. This also became the focus of significant planning conflict at Mangamaunu, 16 km north of Kaikōura.

The surf breaks at Mangamaunu are among the 17 breaks identified as nationally significant in the New Zealand Coastal Policy Statement 2010 (NZCPS). A consent authority (e.g. a regional or district council), when considering an application for a resource consent under the Resource Management Act 1991 (RMA), must have regard to the policies of the NZCPS. Policy 16 of the NZCPS states:

'Protect the surf breaks of national significance [e.g. those at Mangamaunu] by:

(a) ensuring that activities in the coastal environment do not adversely affect the surf breaks; and

(b) avoiding adverse effects of other activities on access to, and use and enjoyment of the surf breaks.'

Surfers indicate that the scenery of the area contributes to the enjoyment of the surf breaks. The Mangamaunu seascape's value is indicated through it featuring in a 2017 set of New Zealand Post's *Scenic Definitive* stamps. The break was little affected by the earthquake with just a slight shift in the location of particular wave characteristics being reported by surfers.

The Christchurch experience had highlighted the usefulness of coordinated recovery planning and collaborative responses to infrastructure restoration activities. In Kaikōura, approaches to planning issues took two paths: first, the development of a Recovery Plan (*Reimagine Kaikōura*) for the district and, second, the passage of the Hurunui/Kaikōura Earthquakes Recovery Act 2016. This Act provided special powers through national regulations (Orders in Council) that enabled the normal resource consent provisions of the RMA to be modified in particular circumstances. North Canterbury Transport Infrastructure Recovery (NCTIR – an alliance of NZ Transport Agency (NZTA), KiwiRail, Downer, Fulton Hogan, HEB Construction and Higgins) was established by the government in December 2016 to restore the road and rail infrastructure.

The Hurunui/Kaikōura Earthquakes Recovery (Coastal Route and other Matters) Order 2016 requires any coastal route restoration work by the NZTA or KiwiRail to be classified as a controlled activity for the purposes of the RMA and to not be publicly notified (although a number of people specified in the order are to be given 15 days to respond to an application to grant consents for restoration work). Any consent NZTA or KiwiRail apply for under this Act and Order prior to 1 April 2018 must be granted, subject to conditions that Kaikōura District or Canterbury Regional Councils might impose on matters specified in the Order. To avoid delay, applications for consents under the Order need only provide a broad description of the work proposed and desktop assessments of the effects. Appeals to the Environment Court are not possible. This has enabled NCTIR to bypass the normal RMA 'checks and balances' processes of public hearings, full assessments of environmental effects, and the discipline imposed through the potential to have decisions challenged in the Environment Court.

NZTA and KiwiRail lodged applications in March 2018 for restoration works including a 10 m seaward movement of the footprint of works consented a year earlier to create a shared pedestrian and cycle way and an amenity area at Mangamaunu. This included revetments on the beach, but was intended to provide safe road access and parking, specifically for surfers and tourists. Surfer representatives and local community members expressed concern over the potential impacts of the restoration works on the surf break and vainly sought that the normal RMA process be used to enable greater scientific scrutiny of the claims made by the applicants.

Consent was granted on 29 March 2018, two days before expiry of the empowering Order. In its decision to grant the consents, the Kaikōura District Council noted (p.6) that the broad description of the proposed restoration works 'does not enable a full understanding of what is proposed and why it is proposed'. Consequently, as part of the consent conditions, NZTA and KiwiRail are required to meet with representatives of groups (including surfers) identified by the Council to discuss the proposed plans for Mangamaunu works. Partly through this process, despite having no ability to deny the consent, the Council sought to address 'legacy effects' of the restoration works on matters such as community cohesion and outstanding landscapes.

The restoration works also have implications for the Māori community. A small marae is located at Mangamaunu for the hapū of Ngāti Kuri and Te Rūnanga o Kaikōura of Ngāi Tahu. A mātaitai reserve (an area for non-commercial fishing managed by tangata whenua) also lies in the coastal waters of Mangamaunu. The need for the cascading implications of the restoration works to be discussed with the hapū on a continuous basis to ensure that cultural input is maintained for on-going protection of historical sites and integrity of the cultural footprint of the area has been recognised in the consent conditions. These make specific provision for ongoing consultation with local iwi representatives through a Restoration Liaison Group.

These issues have highlighted the challenge and tension between the necessity to recover key 'lifeline networks' and the concurrent need to consider and address long-term legacy effects. Our research interviews found that local government, the community, Māori or non-Māori, and surfers generally did not want to be seen to be holding up progress on restoring the road and rail networks. Nor were they opposed in principle to a cycleway, indeed there was some strong support for the tourism benefits a cycleway might bring. They were also aware of the employment advantages being offered by NCTIR to locals and the benefits being received by local businesses from NCTIR's patronage. At the same time the council and the community knew that long after the lifelines had been restored, the community would be left with the legacy effects to live with. While some access and facilities for surfers and other coastal users may be improved, these are not essential to the restoration of the main networks. If the surf break is adversely affected by the structures associated with the cycleway, this will be remembered as an example of short-term expediency over-riding protection of a rare surfing break.

Kaikoura marina being dredged out to make it usable again (Photo: Hamish Rennie).

Finally, although some aspects of the recovery from the earthquakes are problematic, the alterations to the landscape have highlighted the potential to develop new tourism opportunities as part of building greater resilience in the local community. In addition to the cycleway, our research has identified the potential to develop a GeoPark for Hurunui-Kaikōura. A GeoPark is a special form of UNESCO recognition of the educational and cultural values of particular geological landscapes and their associated ecology.

Unlike a standard New Zealand national park, a GeoPark does not 'lock-up' the landscape as a protected area, but recognises an interconnected area of geological features that are intrinsically linked to the culture of a place and provide globally significant educational opportunities about geological processes and associated ecosystems. Whale watching, for instance, builds on the heritage of whaling and is intimately linked to the development of Kaikōura, but it occurs due to the environment provided by the submarine canyon, a geological feature. The canyon in itself would be insufficient to warrant a GeoPark, but in combination with the visible shoreline uplift, sea springs, fault escarpments, landslide created lakes, and generally improved surfing conditions and beach at Kaikōura, there is potential to boost integrated land-sea tourism through a GeoPark. The long term may see a more diverse and valuable coastal tourism economy for Kaikōura.

This research was supported by the Resilience to Nature's Challenges National Science Challenge (funded by the NZ Ministry of Business Innovation and Employment).

Reference

[1] Simmons, DS, and Fairweather, JR (1998). *Towards a tourism plan for Kaikōura*, Report No. 10, Tourism Research and Education Centre (TREC), Lincoln University, p.35.

Earthquake damage and effects at CentrePort

By Alistair Boyce, Rob Presland, Eng Chin, Anthony Delaney and James Lake

Introduction

The port facilities at CentrePort in Wellington form a vital element of infrastructure for the Wellington region and the national economy. The port services a wide variety of seaborne trade, including container imports and exports, log exports, car imports, oil, road and rail ferries, and cruise vessel visits.

The earliest wharf structures in Wellington Harbour date back to the 1860s. Substantial reclamation works, forming the bulk of the current port site, commenced from the early 1900s with a number of seawalls and wharf structures built. In the 1960s and the advent of containerisation, a substantial additional reclamation was built, along with the Thorndon Container Wharf structure.

These trades are operated from the Aotea Quay/Thorndon Quay wharf along the eastern edge of the reclamation, and from the three finger wharves located west of the reclamation. The reclamation itself is used for the storage of containers and logs, and also contains a number of port facility buildings.

The 14 November 2016 earthquake caused significant damage to a number of port infrastructure assets, and this article discusses the earthquake damage and recovery works for five of those assets, listed below and also shown in Figure 1:

- Reclaimed area
- Thorndon Container Wharf
- Kings Wharf
- Aotea Quay Wharf
- Inter-islander Linkspan.

A number of other CentrePort assets were damaged during the 2016 earthquake. As this article is for the NZ Coastal Society it focusses on wharf assets only.

Extent of earthquake damage

Reclamation liquefaction and lateral spreading

The reclamation area behind Thorndon Container Wharf and Aotea Quay was built in the 1960s by end-tipping silty, sandy gravels from truck and barge onto the original seabed. Fill above the ground water level was compacted. This reclamation fill is up to 20 m in depth at the southern end, decreasing in thickness northwards. The underlying seabed comprises a 1 m thick layer of marine deposits (medium dense sand and firm silt), overlying alluvium (very dense sand and gravel interbedded with lenses of very stiff silt).

A heavy-duty pavement was constructed over the top of the reclamation fill and the area used for various trades, including use as a container terminal towards the southern end of the reclamation where the reclamation fill is thickest. Within this area the terminal containers are stacked in blocks up to six boxes high.

Widespread liquefaction of the gravel fill was evident as observed through the ejection of gravel, sand and silt to the pavement surface. Significant ground cracks and fissures caused by vertical and lateral ground movements were also observed. In addition, the entire reclamation also experienced wholesale settlement. These cracks and fissures required the closure of several areas of the terminal to container operations.

Thorndon Container Wharf

The Thorndon Container Wharf is a 585 m long marginal wharf constructed along the eastern side of the main reclamation. Note that a marginal wharf is defined as a wharf which runs parallel with the seawall along its full length, and that the embankment and wharf act together as a system. The wharf is used for the loading and unloading of container vessels using two 750 tonne ship-to-shore (STS) gantry cranes.

Figure 1: CentrePort asset locations (Graphic: CentrePort).

Liquefaction within the container terminal (Photo: CentrePort).

The wharf structural form consists of precast concrete deck units spanning 3.66 m between transverse capping beams. Each transverse capping beam bent line is supported by seven rows of prestressed concrete piles. Along the seaward and landward pile rows the pile spacings are halved to support a longitudinal capping beam carrying the STS crane loads. The landward capping beam is also supported by diagonal raker piles at each bent line.

The reclamation fill on which the wharf was constructed comprises silty, sandy gravel sourced from local greywacke quarries end-tipped into the sea. The batter slope underneath the wharf was formed to an angle of 1.5H:1V by placing filter rock (25 mm to 150 mm) and a protecting layer of rock armour (400 mm to 800 mm).

The earthquake shaking caused liquefaction of the gravel fill reclamation. In its liquefied conditions and under the inertia loads from the shaking the reclamation spread laterally pushing the wharf between 0.2 to 1 m towards the sea. This lateral displacement caused significant damage to the wharf piles, especially those piles along the landward edge of the wharf. In addition, raker piles located along the landward pile row rotated due to the kinematic movement and pushed the landward section of deck upwards by around 0.2 m. The lateral spreading also caused the ground immediately behind the wharf to drop by up to 0.6 m.

During the earthquake the two STS cranes on the wharf lifted around 0.6 m off the deck along the seaward crane rail, and dropped back down onto the wharf 0.2 m away from this rail. Components of the cranes, including the booms, gear boxes, cable systems and electrical feeds were significantly damaged as a result of the earthquake.

The extent and severity of the earthquake damage to this wharf caused the immediate closure of the wharf to all operations.

Kings Wharf

Kings Wharf is a 250 m long marginal wharf located on the western side of the main reclamation. This wharf is primarily used for the marshalling of traffic for the adjacent roll-on/roll-off shipping linkspan structure.

The wharf consists of driven hardwood timber piles with hardwood timber cap beams and joists supporting a concrete deck slab.

The reclamation fill alongside the wharf liquefied during the earthquake and the resultant kinematic movement pushed the wharf seawards by up to 1 m, and also resulted in ground settlement behind the wharf of over 0.5 m. This kinematic movement caused considerable damage to a number of the timber piles supporting the deck.

As a result of the earthquake damage a significant portion of the wharf has been closed to pedestrian and vehicular traffic.

Aotea Quay Wharf

The Aotea Quay Wharf extends north of the Thorndon Container Wharf providing approximately 1100 m of berth for log ships, cruise ships, fuel bunkering, cement ships and bulk carriers. The wharf structure consists of a series of reinforced concrete piles, deck beams and deck slab. The landward side of the wharf is supported on a mass concrete seawall up to 15 m high. Hydraulic fill was pumped in behind the 1930s seawall to form the reclamation in this area of the port.

Lateral spreading and/or the inertia loads from the shaking of the reclamation behind the wharf has led to displacement of the seawall and wharf toward the sea, particularly in the southern half of the wharf (AQ1-AQ3 berths).

Inter-islander Linkspans

Inter-islander ferries operate from two berths located near Kaiwharawhara, to the north of Aotea Quay Wharf. The rail ferry terminal 2 (RFT2) berth services road and rail ferries, with the RFT3 berth servicing ferries for road vehicles only.

At the time of the earthquake the *Aratere* was berthed at RFT2. Earthquake shaking resulted in the ferry pulling off the berth and damaging the stern pin connection to the linkspan. As the linkspan was supported off the stern of the vessel, and the span lifting mechanism dis-engaged, the ferry pulling away from the berth resulted in the linkspan 'dropping' down to its lower stopper position.

There was no other significant damage to the ferry linkspans as a result of the earthquake. Operations resumed from the RFT3 berth within a week after the earthquake.

Thorndon Container Wharf temporary securing works

This section discusses the temporary works carried out to the Thorndon Container Wharf, as part of the overall works to enable the resumption of container operations at the Port. Other works include repairs to the two STS cranes, HV electrical, lighting and pavement works.

Following the earthquake, WSP Opus, Holmes Consulting and Tonkin + Taylor were engaged by CentrePort to design works to secure the two STS cranes and restore crane operations over a 135 m length of Thorndon Container Wharf. This design work was carried out in close collaboration between the various designers, as well as HEB Construction, who were engaged by CentrePort to construct the works.

The design work focussed on the areas described in the sections below, and as shown in Figure 2, in order to restore limited STS crane operations on the wharf. The construction work was successfully completed in mid-September 2017 and the wharf reopened for container operations.

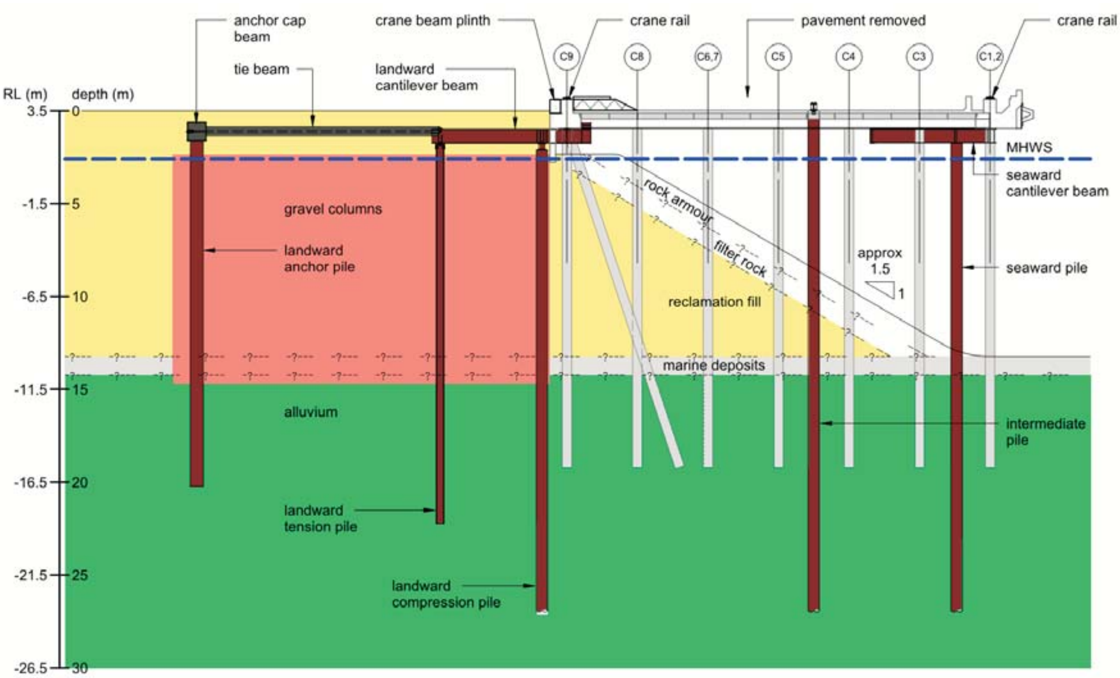


Figure 2: Details of securing works to Thorndon Container Wharf (Graphic: CentrePort).

Provide gravity support to the landward and seaward crane rail beams

Due to the extent of damage to the wharf piles, especially those along the landward row, the piles could not be relied upon to support the wharf and operational loads from the cranes. This damage also posed significant issues for the constructability of the works given the need to minimise health and safety risks to the workers.

The solution adopted for restoring vertical support to the cranes was to install two piles behind the retaining wall along every wharf pile bent line along with a cantilevered steel beam over the tops of these piles. The cantilevered beam extends through the retaining wall to support the underside of the landward crane rail beam. The crane loads acting on this cantilevered steel beam would result in the new front pile going into compression, and the rear pile into tension. All of this work was completed without requiring workers to be underneath the wharf during the construction works.

A similar cantilevered beam arrangement, requiring a new steel pile at every pile bent line, was also successfully installed along the seaward row of piles.

Secure the wharf from further lateral displacements

The landward cantilevered steel beams were connected with tie-backs to new anchor piles driven 20 m behind the wharf to limit the wharf's seawards movement in another design earthquake. As part of this work, gravel columns were also installed in the ground between the wharf and the anchor piles to:

a) prevent liquefaction occurring in a future design earthquake

b) provide passive resistance to the anchor piles, and

c) reduce the magnitude of the ground lateral movement.

Implement additional seismic mitigation risks

Additional seismic risk reducing measures were also implemented to provide a higher level of seismic resilience for the temporary works:

- Removal of the hardfill from the deck to reduce the overall seismic mass of the structure.
- Form seismic gaps at each end of the 125 m length of wharf to separate the temporary works from the adjacent sections of damaged wharf.

View along landward edge of Thorndon Container Wharf (Photo: CentrePort).

Pile damage under Thorndon Container Wharf (Photo: CentrePort).

- Installation of an additional row of piles midway across the deck to provide gravity support to the deck should a future earthquake cause loss of load carrying capacity to the original piles on the landward half of the deck.

Container terminal works

The extent of earthquake damage to the land within the container terminal area required a modified container terminal to be implemented before the wharf reopened in September 2017. This new terminal area allowed for over 2,000 containers, plus nearly 150 refrigerated containers, in a stack configuration. Temporary pavements were required to be constructed behind the wharf and along running roads for the container-handling traffic.

The temporary works were designed to not require container-handling traffic on the wharf deck. All container operations are now carried out by a crane backreach operation, where the cranes load and discharge boxes from the area immediately behind the landward crane rail. This operation, and the stack configuration, are significantly different to how the containers were handled pre-earthquake, and required CentrePort to make a number of changes to the way they operate the terminal area in order to maintain operational efficiency.

Other works

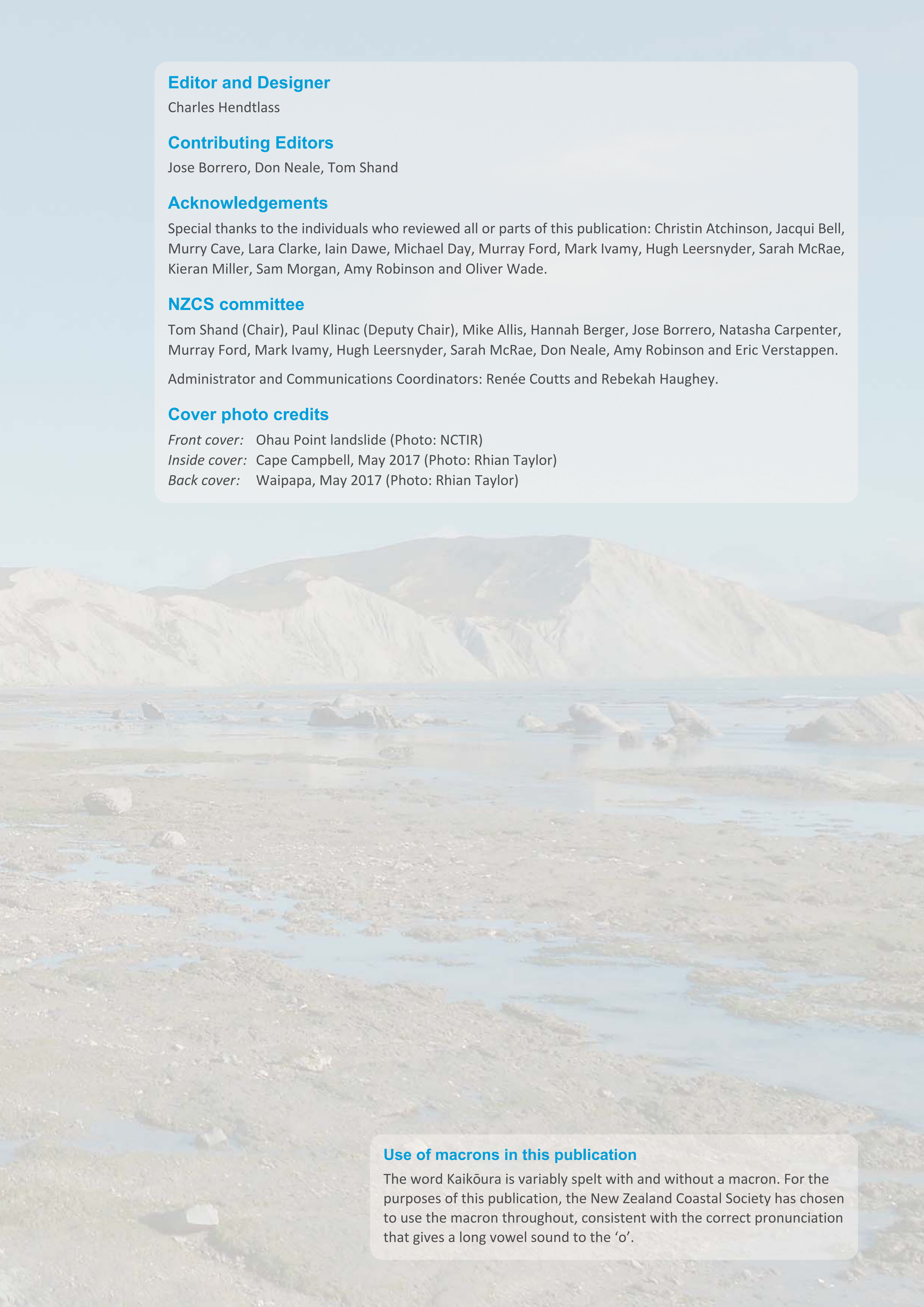
Other works were also completed to allow the wharf to reopen for container operations, including :

- Installation of land-based mooring bollards for vessel mooring lines, which were required due to the extent of damage to the adjacent sections of wharf.
- Repair works to the two STS cranes, including raising the seaward legs of the cranes due to differential settlement across the wharf.

Conclusion

The work on Wellington’s port area is a vivid demonstration of the wide-ranging effects of the Kaikōura earthquakes, occurring well away from event’s seismic origins in the eastern South Island. While the Kaikōura district has borne the brunt of the earthquake’s might, the event has had implications throughout New Zealand. The many strands of our collective response to what happened on 14 November 2016 will surely serve as a lesson for building a resilient future, in the face of large-scale natural events.

The authors acknowledge the contributions of other members of the project team, including: CentrePort, Holmes Consulting, Tonkin + Taylor, WSP Opus and HEB Construction for their involvement in earthquake recovery operations at the port.



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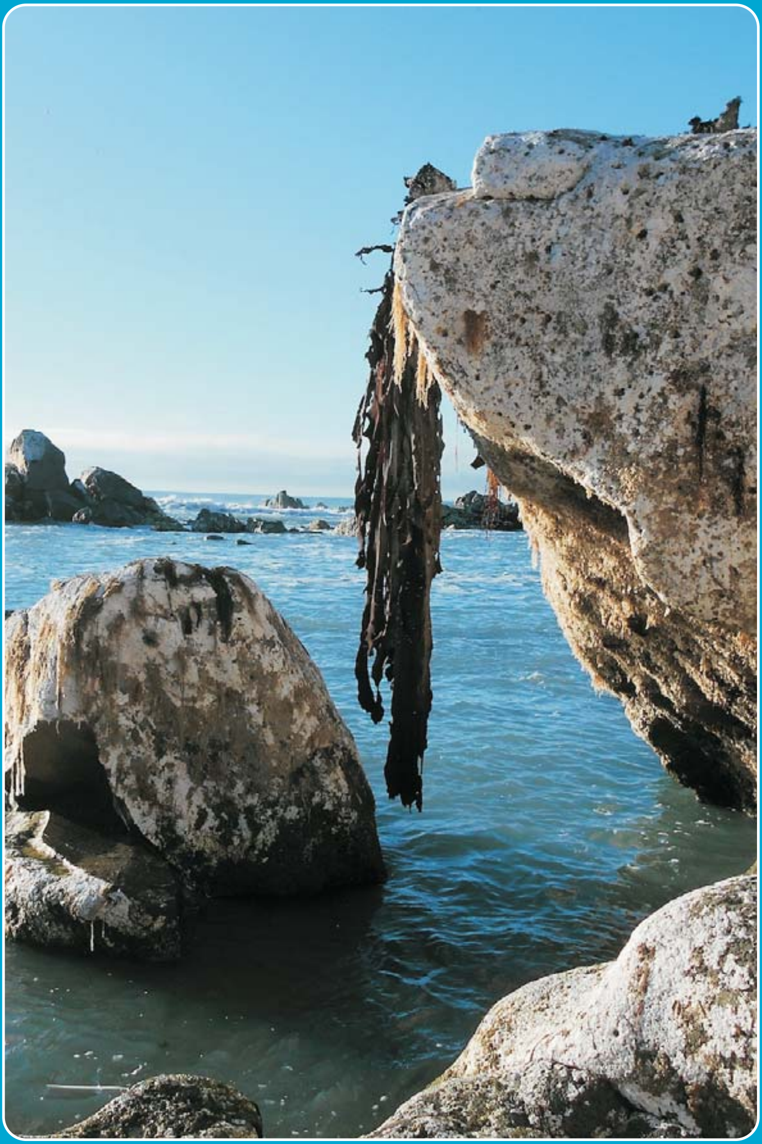
Use of macrons in this publication

The word Kaikōura is variably spelt with and without a macron. For the purposes of this publication, the New Zealand Coastal Society has chosen to use the macron throughout, consistent with the correct pronunciation that gives a long vowel sound to the ‘o’.



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