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The resilience context of transportation routes and recovery after the 2016 Kaikōura earthquake in New Zealand

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ABSTRACT

The Ward to Cheviot section of State Highway 1 is a key lifeline transportation route that runs through the Kaikōura township. Its strategic importance on the national state highway connecting the North Island via the Wellington-Picton ferry to the city of Christchurch in the South Island, and vulnerable location between the mountainous Kaikoura range and the Pacific Ocean make it a critical transportation route in New Zealand. The route has been a focus for understanding the resilience of transport networks from as far back as 2000, when this section was used as a pilot study in early research into transport resilience. A further resilience assessment of this section was completed as part of the national state highway resilience study in mid-2016, shortly before the November 2016 Kaikōura earthquake. Reconnaissance after the earthquake to assess damage and help with response provided the ideal opportunity to benchmark the resilience studies against the damage experienced. Post-earthquake landslides and debris flows triggered by storms caused additional damage and disruption during the recovery phase, leading to post-earthquake assessment of the corridor resilience to identify measures to enhance resilience as part of the recovery works. These assessments also enabled tactical measures to be put in place to ensure safety while allowing the recovery operations to proceed in the context of enhanced risk associated with storm events and potential aftershocks.

1 INTRODUCTION

The resilience of our built environment to natural disasters such as earthquakes is critical for the community. New Zealand's rugged terrain and high seismicity over much of the country means that infrastructure, transportation routes, residential developments etc. are formed on or in close proximity to hazardous terrain prone to damage from natural hazards. Understanding the resilience of infrastructure to natural hazards including earthquakes is important to be able to take initiatives to enhance resilience.

Research into the resilience of road networks in 2000-2006 by Opus led to the development of resilience principles and metrics to assess the resilience of road transportation routes on a more systematic and consistent basis. This work included a pilot study to assess the resilience of the State Highway 1 corridor along the Kaikōura coast on the South Island of New Zealand (Brabhaharan *et al*., 2001).

The magnitude 7.8 Kaikōura earthquake that struck on 14th November 2016 caused widespread damage across the northeast part of the South Island, including severe damage to the road and rail networks from fault rupture, strong ground shaking, and coseismic landslides. The rail corridor was closed for over 9 months. In particular, the coastal state highway corridor was closed for 13 months due to landslides and embankment failures. The long outage of this nationally important corridor and long detours associated with the only distant alternative route caused major disruption and highlights the need for prior planning to identify resilience gaps and to plan for event response and/or invest in strengthening key vulnerabilities. The availability of pre-earthquake resilience assessments of this corridor allows comparison of actual damage with assessed vulnerabilities, as well as underpinning the post-earthquake assessment of the corridor resilience. Assessment of the post-earthquake resilience was critical to the development of recovery and risk mitigation strategies that incorporated resilience benefits.

This paper presents the strategic resilience context of the route, the impact and recovery operations from the Kaikōura earthquake, and a comparison of pre-earthquake resilience assessments and post-earthquake earthquake resilience. It also illustrates how the strategic resilience context and ongoing assessments were used to inform both recovery standards and facilitate construction work.

2 STRATEGIC RESILIENCE CONTEXT

2.1 Strategic importance

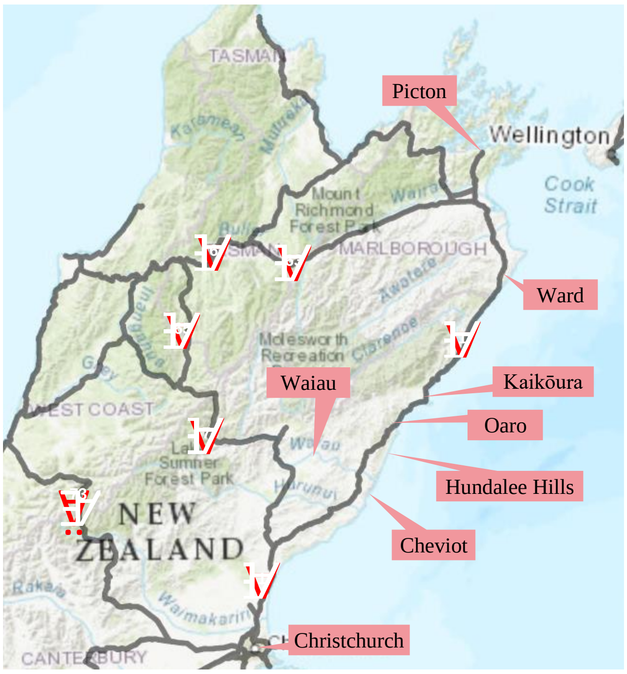

Figure 1: Map of the regional state highway network in the upper South Island

The state highway network in the upper South Island is shown in Figure 1. The study area consists of a 150 km section of State Highway 1 (SH1) between Ward in Marlborough and Cheviot in north Canterbury. This section of the state highway passes through rolling hill country in Marlborough, along a narrow coastal strip to the north and south of Kaikōura, then through steep, windy hill sections through the Hundalee Hills and Cheviot Hills south of Oaro.

The SH1 corridor is classified as a National Strategic High-Volume State Highway and is a high productivity motor vehicle (HPMV) route (James, 2016). This section of SH1 is a tourist route for motorists and cyclists and is the primary freight route in the South Island, providing critical freight access between Christchurch and the North Island via Picton. The route provides access to tourist destinations such as Kaikōura, and there are important state highway connections with SH63, SH6 and SH7 that link SH1 with Nelson, Tasman and the West Coast (James, 2016).

2.2 Natural hazards and incidents

Given the high importance level of the SH1 route, it is important to understand both the resilience of the route to natural hazards and its resilience contribution to the wider network. Systematic studies of the resilience impacts of large earthquakes and other hazard events on the state highway have been carried out (e.g. Brabhaharan *et al*., 2001; Mason and Brabhaharan, 2017), which provide understanding of the distribution and magnitude of potential impacts from natural hazards, and consequently the resilience of the route in the context of the wider region. The predominant natural hazards in the region are storms, coastal erosion, landslides, earthquakes, tsunami, and sea level rise.

Natural hazards occur in a range of intensities, from low intensity storms and other meteorological hazards, small landslides, or minor coastal erosion (which occur frequently with a high probability) to very high intensity events which occur with a low frequency or low probability such as large magnitude earthquakes, major storms or large tsunami. The impacts of these hazards on the transportation system will also vary. Natural hazard events and vehicle crashes result in temporary road closures as well as longer term outages and consequential risks to route security. The vulnerabilities of the regional state highway network to the impacts of a large earthquake are shown in Figure 2, and discussed further below in the following section. Many parts of the route are narrow and winding, with significant safety hazards and frequent crashes (James, 2016).

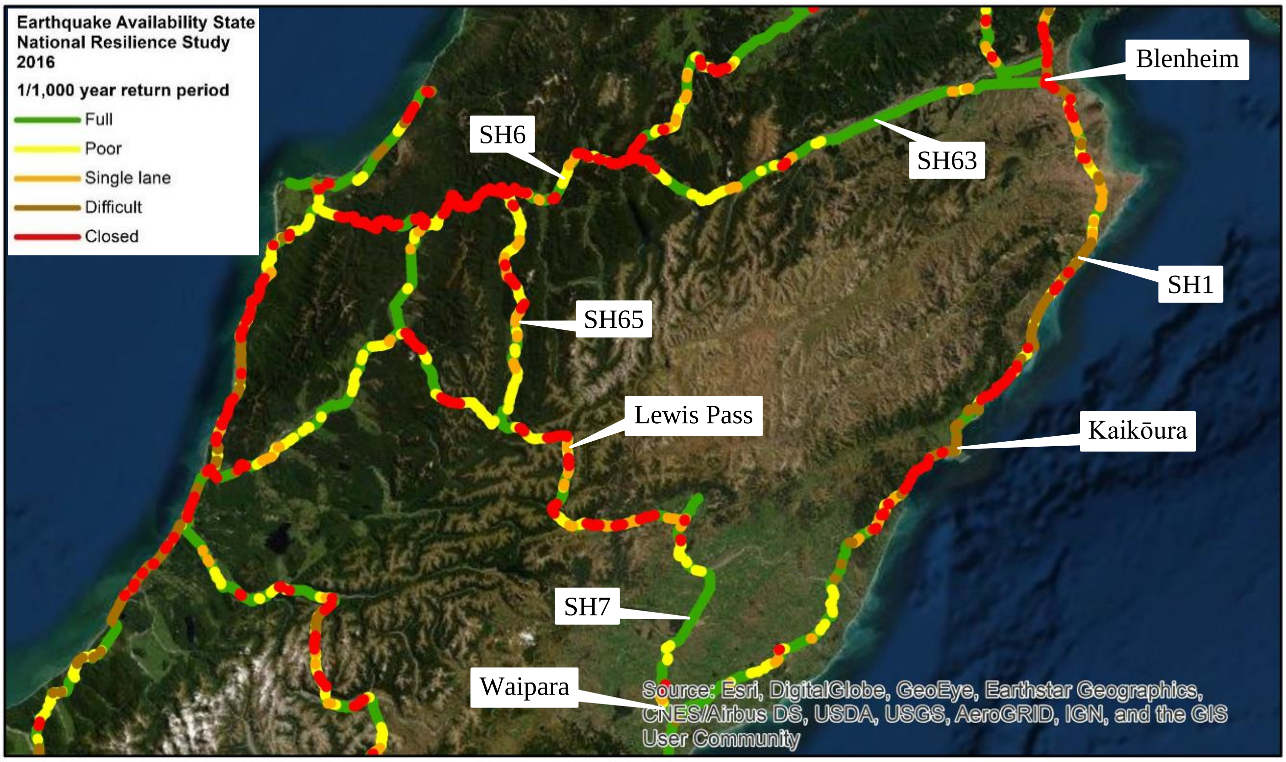

Figure 2: Earthquake availability state map of state highways in northern South Island (after Mason and Brabhaharan, 2017)

2.3 Resilience context

Resilience is the ability to remain functional or quickly return to functionality when exposed to shock events or progressive events. Network resilience requires routes to be robust with good redundancy and connectivity to provide access to communities (Brabhaharan, 2006).

The transport network in the upper South Island is highly vulnerable to natural hazards, and critical sections are vulnerable to short to moderate closures in moderate hazard events and major closures for many months in larger hazard events. When the state highway corridors are closed, alternative detour routes are limited and lengthy, due to the remoteness and mountainous terrain of the upper South Island and lack of available local or rural roads. This vulnerability was realised after the 2016 Kaikōura earthquake, when closure of the coastal section of SH1 resulted in traffic being forced to use the alternative inland route via SH63/SH6/SH65/SH7, adding 144 km to the journey (Davies *et al.*, 2017). Figure 2 shows that these alternative routes also cross steep terrain that is prone to damage and lengthy closures from natural hazards, indicating the vulnerability of the upper South Island transportation network.

The resilience context of the route is therefore characterised by high strategic importance, coupled with high vulnerability to hazards and poor network redundancy and connectivity, resulting in a high criticality for resilience on a regional to national level.

3 KAIKŌURA EARTHQUAKE

A severe magnitude 7.8 earthquake struck 15 km north-east of Culverden in the South Island of New Zealand, at 12:02 am on Monday 14th November 2016. This was followed by numerous aftershocks. At least 21 faults ruptured on and offshore of the north-east of the South Island of New Zealand. The ruptures began on The Humps Fault near Culverden and continued north-eastwards for ~180 km (Stirling *et al*., 2017). Ground shaking was strongest in the epicentral region near Culverden, and to the northeast between Kekerengu and Seddon. The strong shaking near Ward is possibly due to the southwest-to-northeast earthquake rupture sequence directed towards this part of the South Island (Kaiser *et al*., 2017). The ground shaking attenuated rapidly towards the south, with minimal shaking south of Amberley (57 km south of epicentre), but moderate shaking affected areas as far north as Wellington across the Cook Strait.

3.1 Damage and outage of transportation infrastructure

The earthquake caused widespread damage across the northeast of the South Island. In particular, fault rupture, strong ground shaking, and co-seismic landslides severely damaged road networks, including SH1 between Ward and Cheviot and local roads in the Hurunui, Kaikōura and Marlborough districts. Landslides and embankment failures caused the most damage and disruption to the transportation infrastructure in the earthquake (Mason and Brabhaharan, 2019). Failures of low height cut slopes and cracking/displacement of fill embankments were able to be repaired quickly to provide at least limited access, and only caused short term closure of the road. Landslides on high hillslopes extending 50 m to 100 m or more above the transport corridor led to large volumes of landslide debris and rockfall that inundated the transport corridors and prolonged closures, due to the unstable nature of the debris and the presence of disrupted rock masses along the slopes above the roadway. These made reconstruction efforts more difficult and involved a much longer duration for clearing of debris with sluicing, roped access scaling and careful formation of access tracks required before debris could be cleared safely. Therefore, the outage periods were much longer, such as the along the coastal section of SH1 north of Kaikōura, which was closed for 13 months.

3.2 Recovery

The North Canterbury Transport Infrastructure Recovery alliance (NCTIR) was set up by the government under the Hurunui/Kaikōura Earthquakes Recovery Act 2016. NCTIR consisted of an alliance between NZTA, the Asset Owner for the state highways, KiwiRail, the rail Asset Owner, and New Zealand's four largest infrastructure contractors. Several engineering consultants engaged by the alliance provided the technical capability to investigate, assess, develop and design the measures to restore functionality and enhance resilience. NCTIR's immediate purpose was to repair and re-open the earthquake-damaged road and rail networks on the Kaikōura Coast and the inland road (SH70). The Asset Owner outcome requirements for the NCTIR programme were to achieve an acceptable level of safety and service for day to day operations. Two key outcomes were required from the NCTIR programme:

1. Risk to Life: Target risk levels were determined separately by both Asset Owners, with As Low As Reasonably Practicable (ALARP) principles applying for risks lower than these levels. The risk estimation for the state highway was completed using the New South Wales Roads and Maritime Services (NSW RMS) Guide to Slope Risk Analysis (Version 4, 2014). Slope risk adjacent to the rail corridor was assessed using KiwiRail's in-house slope hazard rating (SHR) system as a proxy.

2. Level of Service: KiwiRail and NZTA specified acceptable duration outages for different return periods, expressed as an Annual Recurrence Interval (ARI). The outages ranged from a few hours for frequent events, to over 120 days outage for events in excess of 100-year ARI.

At any one site, mitigation work involved implementation of one or more solutions that addressed the two outcome areas above. In general, the mitigation solutions involved engineered stabilisation and protection works. However, non-engineered works, such as operational controls in response to earthquakes or rainfall, were considered as part of the suite of mitigation measures. The mitigation measures and strategies for enhancing resilience are described in more detail in the discussion below.

4 RESILIENCE ASSESSMENTS AND PERFORMANCE

4.1 Comparison of resilience in the Kaikōura earthquake with prior resilience assessments

The resilience of the coastal state highway corridor through Kaikōura has been assessed and mapped in two separate studies: as a pilot study as part of the 2000-2001 research into resilience (Brabhaharan *et al*., 2001), and then as part of the national state highway resilience study in 2016 (Mason and Brabhaharan, 2017), which was completed before the Kaikōura earthquake. The damage caused by the earthquake allows comparison of the observed performance with that anticipated from the resilience studies. This is illustrated in Figure 3, which shows the corridor-level study carried out in 2000-2001 and the observed performance in the 2016 earthquake. The observed performance was mapped using the observations during the post-earthquake response in November 2016 and post-earthquake LiDAR imagery and maps, captured using the same metrics as the resilience study (Brabhaharan *et al*., 2017).

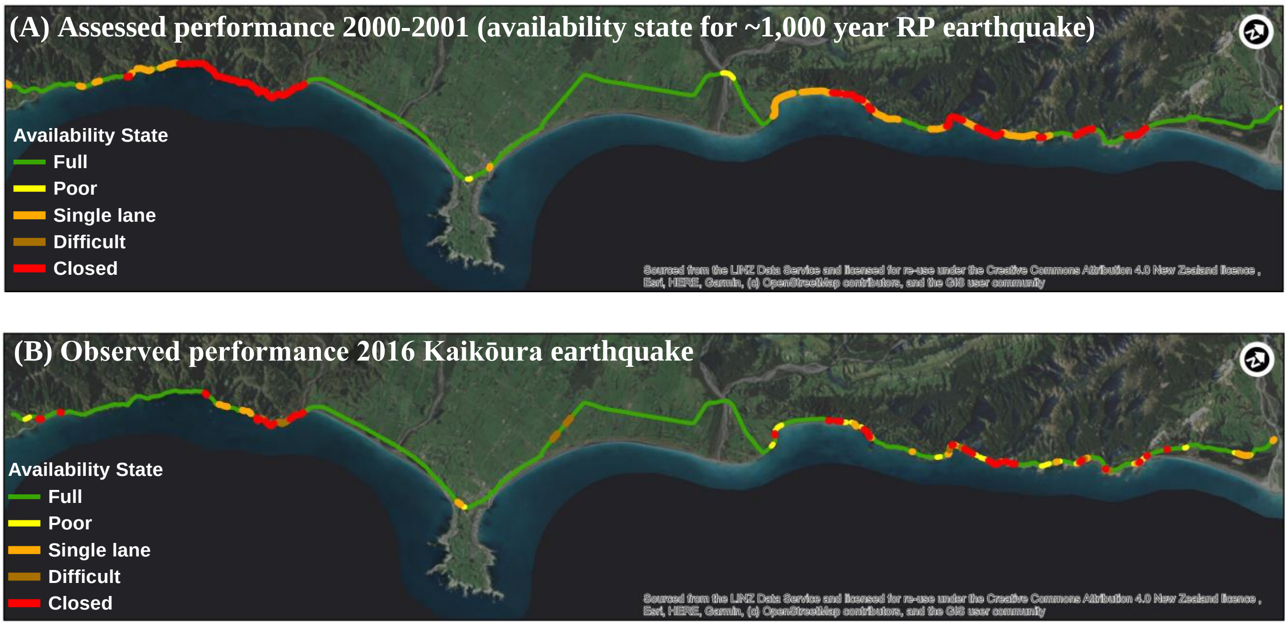

Figure 3: Comparison of the mapped resilience of the coastal section of State Highway 1 through Kaikōura with the actual performance of the corridor in the 2016 Kaikōura earthquake

Generally, the observed availability of the state highway ties in with that assessed based on the 2001 study, and the route was closed over most of the coastal sections of the highway, as predicted in the 2001 resilience study as well as the 2016 national state highway resilience study. Whilst not every section assessed as vulnerable to damage got closed in that particular earthquake event, the vulnerabilities were distinctively demonstrated, with fault rupture, strong ground shaking and co-seismic landslides severely damaging the corridor. In some long sections assessed as being vulnerable to closure or reduction to single lane, the full length has not failed, and failure of the full section would not be expected in any one event.

Overall, the resilience of the corridor assessed before the 2016 earthquake was largely realised in that event, confirming the value of resilience assessments to anticipate potential hazard impacts and enable planning of interventions and response to enhance resilience to hazard events.

4.2 Post-earthquake impacts and assessment of future resilience

Many areas of hillside and ridge cracking occurred during the earthquake without causing landslides. In other areas, landslides were initiated but the debris was retained on the hillslopes or in gullies above the transport corridor. Following the earthquake, a number of failures developed in response to heavy rainstorms, including re-mobilisation of existing landslide debris fans into debris flows, and landslides or debris flows from slopes that had been cracked or damaged in the earthquake. This matches overseas experience, which has shown that large earthquakes not only trigger extensive landslides but also increase the number and severity of subsequent rainfall-induced landslides (Lin et al., 2006; Zhang et al., 2014). This 'slope weakening' can persist in the landscape for many years to decades (e.g. Hovius et al., 2011; Parker et al., 2015). The rates of slope failures along the Kaikōura coastal transport corridor are therefore expected to be significantly elevated for a period of many years to decades following the earthquake, highlighting the reduced resilience of the corridor compared to its pre-earthquake condition.

5 ENHANCING RESILIENCE DURING RECOVERY

5.1 Resilience assessments during recovery

Recognising this increased vulnerability, the future resilience of the coastal transport corridor was assessed by NCTIR against the level of service targets set by the road and rail asset owners (Mason *et al*., 2018). The objective was to identify critical sections of the corridor that are priorities for engineering works that help enhance or restore resilience. The resilience was assessed by subdividing the rail and road corridors into 150 m-long segments and estimating the potential outage should there be a slope failure in that segment for a range of potential trigger events (consisting of small to large storm and earthquake events). The assessment was done for several time periods, being target dates for reopening of the rail and road corridors as well as a nominal end date for the NCTIR programme. This helped identify the potential improvement in resilience due to the completion of engineering works and reduction in aftershock hazard, but also identify if resilience will significantly decrease following the completion of the NCTIR programme of works given the consequent reduction in availability of plant and personnel to respond quickly to slips or other outages. Figure 4 shows the interpreted resilience profiles ('heat maps') representing the results of the assessment.

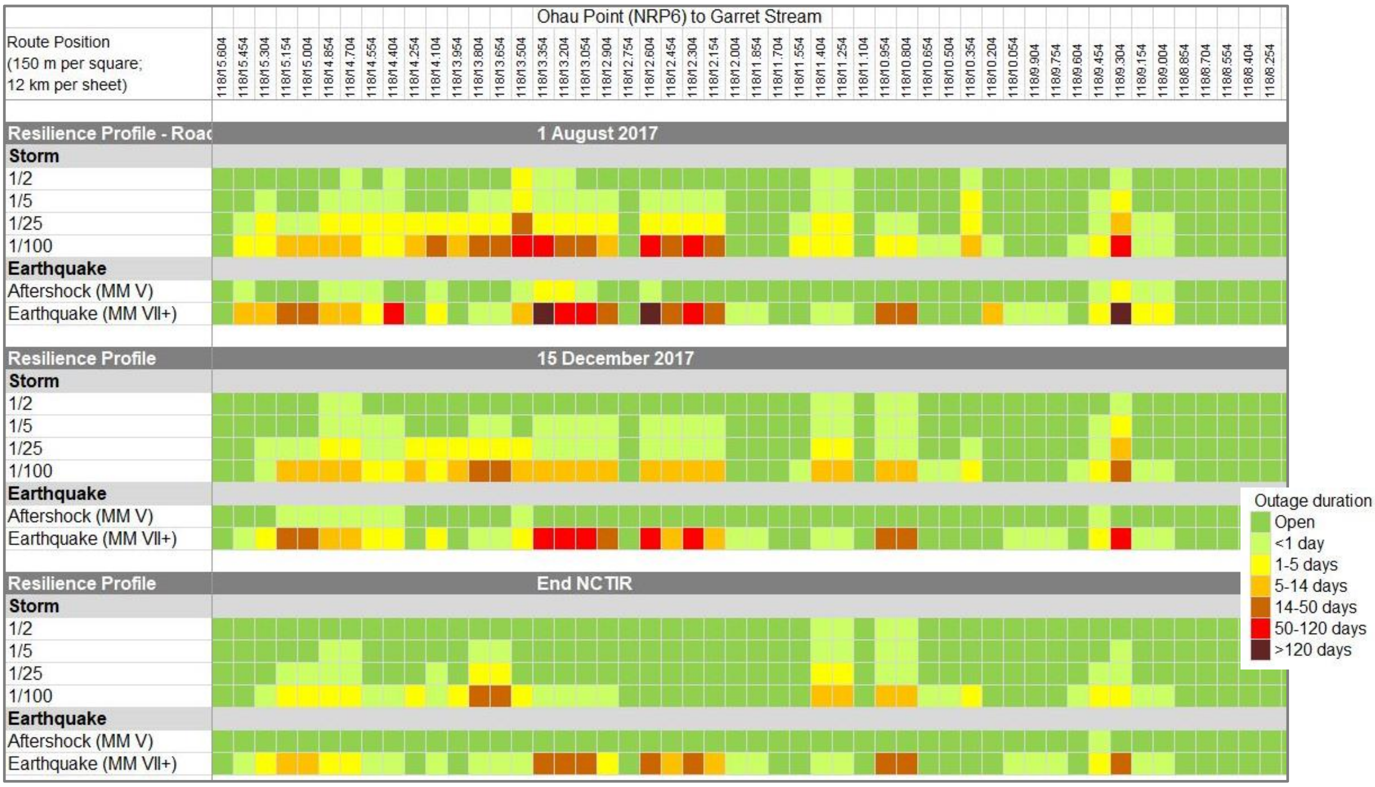

Figure 4: Extract from interpreted resilience profiles for SH1. Each cell represents 150 m length corridor.

The resilience assessment showed that significant clusters of potential long duration outage occur at the steep hillside sections along the coastal corridor, particularly around the areas of heavy damage from the Kaikōura earthquake. These slopes show a range of behaviours depending on the size and type of the hazard scenario, with failure of some slopes and initiation of debris flows likely to occur under relatively small, high frequency rainfall events.

5.2 Strategies for resilience enhancement in recovery operations

The assessment of future resilience provided the basis for estimating outages of the transport corridor for given hazard events. This enabled the asset owners to identify critical sections of the corridor that are priorities for engineering works as well as helping establish response priorities for future events to minimise the impact of outages in those critical sections. The resilience study considered robustness, redundancy and response as components of the corridor resilience. Initiatives that strengthen each of these aspects will therefore contribute to overall improvement of the resilience.

5.2.1 Robustness

Strategies to strengthen the robustness of road and rail assets help reduce the potential for reduction in the level of service after a significant hazard event. Options to improve the robustness of the corridor include realigning the road and rail away from the steep hillsides, engineered works to reduce the potential for slope failure, and engineered works to reduce the potential for inundation of the corridor. Specific measures are discussed in the sections below.

5.2.2 Redundancy

Planning new alternative routes or enhancing the resilience of existing alternative routes to the existing vulnerable transportation links improves resilience through enhancing redundancy within the network. There are few options to improve redundancy for the rail as the MNL is the sole rail route between Canterbury and Marlborough. For the road network, redundancy was enhanced by repairing and upgrading the inland route (SH70) between Waiau and Kaikōura and strengthening key vulnerabilities on the alternative Nelson-Marlborough and Lewis Pass state highway route between Blenheim and Waipara (SH63-SH6-SH65-SH7).

5.2.3 Response

Emergency response preparedness reduces the outage period and helps bring the transport link back into normal service quickly. The NCTIR alliance provided KiwiRail and NZTA with the ability to react quickly in the event of a hazard event. For the post-NCTIR period, the following measures enhance organisational response for management and maintenance of the network:

- Installation of tripwire fences with remote monitoring sensors to notify when rock falls or slips occur;
- Monitoring of unstable slopes with GPS sensors and ground surveys to provide a forewarning of slope failure;
- Rainfall Trigger Action Response Plans (TARPs);
- Implementation of streamlined response plans for hazard events, such that personnel and plant can be mobilised quickly in the event of failure.

5.3 Robustness - Stabilisation and protection works implemented

At any one site, repair and mitigation work involved implementation of solutions to achieve the life safety and level of service targets. In general, the mitigation solutions involved engineered stabilisation and protection works. However, non-engineered works, such as operational controls in response to earthquakes or rainfall, were also implemented on a corridor-wide basis.

Engineered risk mitigation solutions can be considered as either reducing the likelihood (active mitigation) or consequence of failure (passive). Active solutions typically included:

- Scaling, boulder removal and sluicing;

- Bulk earthworks to re-profile slopes at risk of further failure (Figure 5A);
- Slope stabilisation with rock bolts and mesh;
- Anchored rock fall netting (Figure 5B);
- Installation of drainage measures to relieve groundwater pressures or control surface water runoff.

Passive structures included:

- Catch-ditch earthworks;
- Rock fall and debris catch fences/attenuators (Figure 5C);
- Shallow landslide barriers;
- Earth bunds and hybrid bunds/fences;
- Construction of new bridges to allow debris flows to pass beneath the transport corridor;
- Seaward realignment of the rail and road corridors away from the hazardous hillslopes (Figure 5D);
- Rock fall and debris avalanche shelters;
- Remote monitoring, such as tripwire fences, extensometers, and GPS sensors.

Figure 5: Examples of NCTIR recovery works. (A) Slope re-profiling and bulk earthworks. (B) Anchored rock fall netting. (C) Rock fall fences. (D) Realignment of the transport corridor.

5.4 Response - Corridor management

Establishment of temporary weather stations throughout the NCTIR works area enabled data to be collected on the depth, intensity and spatial variation of rainfall events along the corridor. Observations of post-earthquake slope failures by NCTIR geologists and construction personnel were instrumental in understanding the frequency and magnitude of slope failures in response to these rainfall events. This was fundamental to the development of operational measures to ensure safety of construction personnel while allowing the recovery operations to proceed in the context of enhanced risk associated with storm events and potential aftershocks.

Rainfall Trigger Action Response Plans (TARPs) were developed for the road and rail corridors, with probabilistic thresholds established based on rainfall-slope failure relationships that were determined for the

Kaikōura area from the records of slope failures following the earthquake (Justice *et al*., 2018). Based on forecast rainfall, the TARPs enabled assessment of potential slope risks for construction activities, freight trains, and public traffic on SH1, hence predicting when pre-emptive closures of the routes may be needed.

The corridor resilience could be further developed following the completion of the NCTIR recovery programme by development of an integrated, network level asset management strategy for the transport corridor. This would allow asset management and resilience enhancement to be considered in an integrated manner alongside maintenance, safety improvements and capacity improvements.

5.5 Research

Further understanding of the earthquake effects of the Kaikoura earthquake and its effect on the landscape, landslide, runout and debris cascade mechanisms and the performance of earthworks will help understand the resilience of transport corridors including the Kaikoura corridor to earthquakes and storms in future hazard events, and enhance our resilience assessment, design and management measures. A current 5-year research funded by MBIE's Endeavour Programme led by GNS Science and supported by other organisations will lead to a better understanding. The performance of earthquakes and the impact on the resilience of transport and other infrastructure is being carried out by the authors, and the results will be shared in the coming years.

6 CONCLUSIONS

Experience from the November 2016 Kaikōura earthquake shows the need to understand the resilience of existing infrastructure in earthquakes. The earthquake caused widespread damage and severe disruption to the road and rail networks across the northeast of the South Island. State Highway 1 through Kaikōura was closed for 13 months by earthquake-induced slope failures and the rail corridor for 9 months. Assessments of the resilience of the State Highway 1 corridor to potential earthquakes made before the 2016 earthquake were largely realised in that event, confirming the value of resilience assessments to anticipate potential natural hazard effects and enable planning of interventions and response to enhance resilience to hazard events.

An alliance of road and rail asset owners and contractors was formed after the earthquake and was supported by a range of engineering consultants, which helped develop and implement a programme of engineered and non-engineered recovery works to reopen the road and rail network. Post-earthquake landslides and debris flows in rain events showed the earthquake-damaged slopes are much more vulnerable to future failures, and experience from overseas shows this condition will persist for years to decades. The post-earthquake resilience of the transport corridor to future storm and earthquake events was assessed to help quantify the increased vulnerability of the corridor. This assessment enabled development of strategies to enhance resilience as part of the recovery works. This included engineered measures to strengthen the corridor to reduce the potential loss of service, monitoring and response plans to improve response and recovery time, and operational controls to allow proactive management of the safety risks along the corridor for construction activities and public traffic.

The long outage of this nationally important transportation corridor highlights the need for prior planning to understand the resilience of our infrastructure, identify resilience gaps and to plan for event response and/or invest in strengthening key vulnerabilities. It also highlights the need to improve our understanding of the performance of infrastructure in earthquakes. This understanding will help develop appropriate design and resilience management responses to future earthquakes that are underpinned by the resilience context.

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