SLOPE RISK ANALYSIS SUPPORTING POST-DISASTER RECOVERY: THE 2016 KAIKŌURA EARTHQUAKE

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ABSTRACT

On 14 November 2016 a M7.8 earthquake caused significant localised damage to transportation infrastructure around Kaikōura, NZ. The strong earthquake-induced ground motions in the near-source region resulted in substantial rockfall, translational landslides, and channelized debris flows. The closure of SH1, the Inland Kaikōura Road and the Main North Line railway effectively cut off all land routes into Kaikōura.

The North Canterbury Transport Infrastructure Recovery Alliance (NCTIR) was established to rebuild and reopen the coastal routes. To better understand current and future risk to road users, slope risk analyses were carried out following the NSW Roads and Maritime Services 2014 Slope Risk Analysis methodology (NSW RMS SRA 2014). Various risk scenarios were considered reflecting the temporal change in hazards, likelihood, and consequences through the post-disaster recovery process. The core approach of the NSW RMS SRA methodology was applied to consider multiple risk scenarios in order to support the post-disaster activities. A total of ~70 slope risk analyses were carried out over 10km of SH1. Due to the large spatial extent of the slopes and source zones, automation of geospatial analysis of LiDAR derived digital elevation models increased efficiencies in the analysis and documentation.

The application demonstrated that rapid post-disaster risk reduction practices like traffic control and temporary barriers were effective in temporarily reducing risk to acceptable levels. The NSW RMS SRA can be used throughout the post-disaster response and recovery process to understand risk to road users in re-opening the road and optimise the balance of proposed risk mitigation options between risk reduction, costs and impact to road users.

1 INTRODUCTION

On 14 November 2016 a M7.8 earthquake caused significant localised damage to transportation infrastructure around Kaikōura, NZ. The earthquake surface fault rupture cut across State Highway 1 (SH1) generating strong earthquake-induced ground motions in the near-source region, which resulted in substantial rockfall, translational landslides, and channelized debris flows. During the 14 November 2016 M7.8 earthquake peak ground motions were recorded along the alignment at ~1.0g in horizontal and ~2.7g in vertical (QuakeCoRE-GEER-EERI 2016). Landslides and embankment failures caused the most damage and disruption to the transportation infrastructure in the 2016 Kaikōura earthquake (Mason et al. 2017). Failures of low height cut slopes were able to be cleared quickly and only caused short term closure of the road, whereas landslides on high hillslopes extending 50 m to 100 m or more caused extensive damage and prolonged the closure. The unstable nature of the debris and the presence of disrupted rock masses along the slopes above the roadway 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 to clear debris safely.

The closure of SH1, the Inland Kaikōura Road and the Main North Line railway effectively cut off all land routes into Kaikōura. The damage has disrupted the lives of those who live along the highway and who rely on the road and rail networks to access their homes, farms and businesses and the movement of goods to market.

The geomorphology of the coastal slopes north and south of Kaikōura suggests that large scale landslips/debris flows were common in geologic history. Tension cracks are ubiquitous on the upper slopes. Large quantities of loose debris and rocks are on left on failed slopes, which have reactivated with time under rainfall events. Following the earthquake, the changed hazard conditions and urgency to re-open the road required a dynamic and flexible risk analysis framework to better support informed recovery, optioneering and design. One of many challenges is keeping drivers safe and the roads open, while clearing, repairing and rebuilding.

The North Canterbury Transport Infrastructure Recovery Alliance (NCTIR) has been set-up by the government under the Hurunui/Kaikōura Earthquakes Recovery Act 2016 to repair the road and rail networks for re-opening by the end of 2017. Road access was restored to Kaikōura before Christmas 2016, via the Inland Route 70. State Highway 1 south of the seaside town has been open with restrictions. The work by NCTIR includes repairing and rebuilding the networks to be more resilient and safer, helping keep the South Island community better connected in the future.

To better understand current and future risk to road users, slope risk analyses were carried out on SH1 following the methodology outlined in the New South Wales Roads and Maritime Services (RMS) Guide to Slope Risk Analysis V4.0

2014 (NSW RMS SRA). This paper presents the application of the NSW RMS SRA in a post-disaster environment following the Kaikōura earthquake.

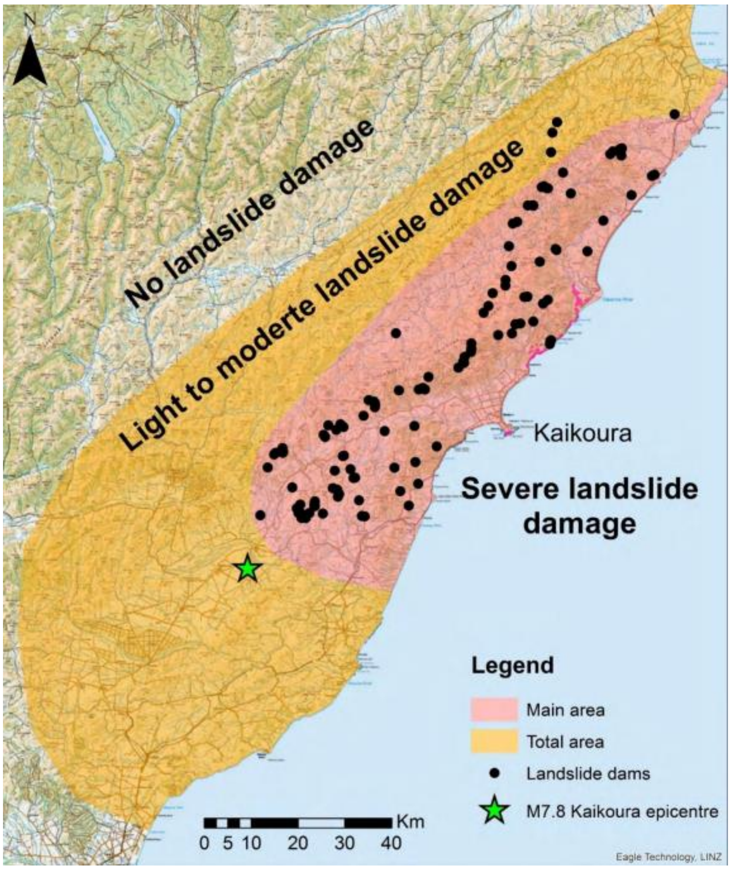

Figure 1: Landslide Area (data sourced from GNS)

2 KAIKŌURA SLOPE RISK ANALYSIS APPLICATION METHODOLOGY

The NSW RMS SRA guidelines were developed to analyse risk associated with cut and fill slopes to the highway network in New South Wales, Australia (Stewart et al. 2002). The procedure is based on visual assessment and provides the basis for management and setting out priorities for investigation, monitoring, and remediation of slopes. The NSW RMS SRA methodology is based on the risk analysis approach in Landslide Risk Management Concepts and Guidelines (AGS 2007). It is intended for use by experienced Geotechnical Practitioners who have successfully completed a specialised training program. The NSW RMS SRA does not address acceptance of risk, safety response, or policy for slope mitigation.

The methodology follows the basic steps of risk management:

- Slope Definition
- Hazard Identification
- Hazard Likelihood Analysis
- Consequence Analysis
- Evaluate Risk (Hazard Likelihood × Consequence)

Application of NSW RMS SRA, as intended, assesses a slope in its current conditions. The assessed components of risk: hazard likelihood, vulnerability and consequence are considered constants (until the next inspection), whereas in a post-disaster scenario they will potentially change in orders of magnitude within a short time frame. For example the temporal variability in likelihood of an aftershock earthquake trigger or increased susceptibility to rainfall (i.e. lower triggering thresholds) triggering failure of earthquake damaged slopes in the short-term. Post-disaster activities, such as temporary traffic speed reduction and temporary bunds, can also change the risk by orders of magnitude.

To support the post-disaster recovery process at Kaikōura different risk scenarios were analysed reflecting temporal changes in hazards, likelihood, and consequences. The core risk methodology of the NSW RMS SRA was not changed, rather it was applied to consider multiple risk scenarios in different temporal states to support the post-disaster environment.

NSW RMS SRA does not provide guidance on risk mitigation actions, but can provide the risk analysis framework and basis to support optioneering, decision making and planning on subsequent mitigation works. The NSW RMS SRA can be used throughout the mitigation process to optimise the balance between risk reduction, costs and impact to road users.

3 POST-DISASTER APPLICATION

Following the event, post-disaster response teams worked to clear the road and open access to Kaikōura. Activities included clearing, scaling, sluicing, earthworks, temporary barriers, and traffic controls.

The immediate application of the NSW RMS SRA looked at three risk scenarios to better understand the risk of the slopes with respect to post-disaster activities. This activity also helped support decision making on mitigation measures. The scenarios captured the temporal states of post-disaster response and recovery in Kaikōura:

No traffic management/temporary works, with increased earthquake aftershock likelihood. This was the current risk level to road users, if nothing was done beyond clearing the road. This was particularly applicable to the sections of the road where public access was available shortly after the earthquake.

Traffic management/temporary works, with increased earthquake aftershock likelihood. This scenario assessed the risk level during the immediate recovery and mitigation works, nominally in the first one to two years after the November 17 2016 mainshock and considered an increased probability of an aftershock triggering slope instability.

Without traffic management/temporary works, post aftershock period: This risk scenario considered hazard likelihoods at the pre-November 2016 probability, if no mitigation was completed. The risk was generally higher than the pre-November 2016 level as the slopes were considered to be unstable immediately following the earthquake.

Application of analysis steps from the NSW RMS SRA in the post-disaster context are presented below.

3.1 SLOPE DEFINITION

In order to define the slope risk over 10km of SH1, individual slopes needed to be discretised into manageable sections or sites with consistent characteristics and risk rating. Due to the large spatial extent of the study area, geospatial analysis of LiDAR derived digital elevation models supported the slope definition. Sites were classified into two categories: "primary" sites, where significant landslide debris had already blocked the road and "secondary" sites, generally slopes in-between the primary sites that had failed, but where debris had not blocked the road. Construction activities were already underway to re-open to road at the time of assessment. The secondary sites had a reasonable potential to impact the road in a future event. Sub-division of secondary sites was based on geology, geomorphology, height, angle, aspect, and relation to infrastructure along the toe. A total of ~70 slopes were identified.

A geographic information system (GIS) was implemented to automate components of the analysis and increase efficiency. GIS layers included pre- and post-earthquake LiDAR, pre- and post-earthquake aerial photography, road and rail alignments, and recent site mapping. The GIS provided an analytical platform that allowed calculation of slope angle, crest line (based on pre-earthquake LiDAR), toe line (based on pre-earthquake LiDAR), distance of toe from infrastructure (road or rail), and the coastline. The post-earthquake LiDAR recorded the tectonic shift the topography and required a correction to align pre- and post- surfaces. Efficiencies in analysis and documentation were realised through automated map production including aerials, slope shade, and cross-sections with relative location of the road and rail (Figure 2).

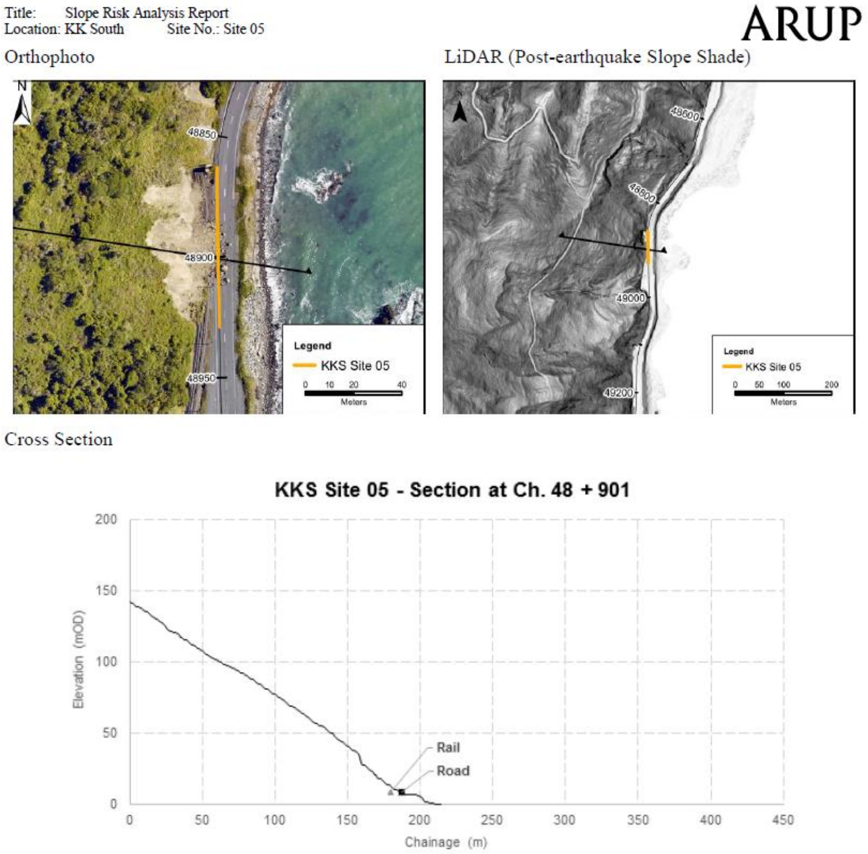

Figure 2: Example of automated plan, slope shade, and cross-section generation from GIS.

3.2 HAZARD IDENTIFICAITON

The first step in risk analysis is hazard identification, where all of the main potential failure mechanisms are recognised. At Kaikōura, the immediate focus was on impact from slope instability above the road, as this was the dominant ground damage that caused closure of the roads (Mason et al. 2017). Hazard types included rockfall, colluvium landslides, debris avalanche and debris flows.

Hazard identification combined site geologic mapping of slope failures and sources zones supplemented by GIS-based desk studies. The primary slopes where slope debris had reached the road served as an analogue for the potential failure of the secondary slopes. The hazard identification also included consideration of first-time failure of slopes exhibiting tension cracks or other signs of deformation, but where complete failure had not yet occurred.

Source zone extents, maximum block size, and tension cracks were captured in the GIS. Definition of the design hazard size for each slope was completed through mapped fallen boulders and review of source areas.

The GIS also assisted in identifying slope deformation through analysis of pre- and post-earthquake LiDAR profiles. Figure 3 shows earthquake induced slope deformation comparing pre and post-earthquake digital terrain models. The red is volume loss, green is volume gain.

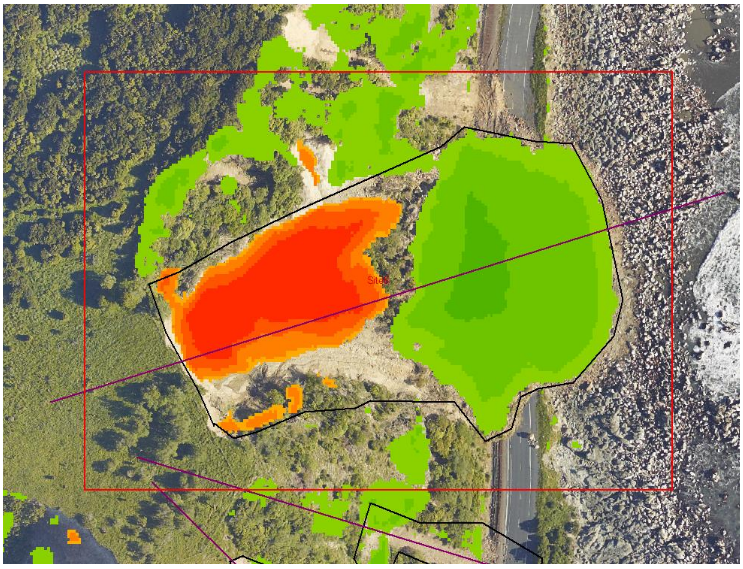

Figure 3: Earthquake induced slope deformation comparing pre and post-earthquake digital terrain models. The red is volume loss, green is volume gain.

3.3 HAZARD LIKELIHOOD ANALYSIS

Hazard likelihood refers to the probability of a hazard triggering on a defined slope. The NSW RMS SRA defines the likelihood that debris reaches the element at risk (e.g. the road) by the product of probability of detachment (P_d) and probability of transport (P_t). P_d is the probability that the material is detached from the slope and starts to move. P_t is the probability that, once dislodged, the debris will travel as far as the road.

At Kaikōura the determination of P_d triggers were predominantly earthquake and rainfall, while P_t considered the ability for the rockfall or landslide to reach the road constrained by site slope geometry, run-out mechanics, and interplay of road and rail infrastructure at the toe.

Probability of Detachment (P_d**)**

Earthquakes Triggers

The estimation of P_d from earthquakes considered ground motions from two temporal states; long-term seismic hazard and an increased aftershock state.

The long-term rate is derived from the probability of rockfall inducing ground motions as estimated by the NZ National Seismic Hazard Model (Stirling et al. 2010). This model provides estimates of ground motion for reference annual probabilities of exceedance. For example, there is 10% in 50 years probability or annual likelihood of 0.002 for peak ground accelerations to exceed ~0.7g annual for shallow soil sites at Kaikōura.

At Kaikōura given the location of the main shock, there is an increased probability that an aftershock will occur within a short time and distance to the site. Considering aftershock decay models, the probability of an earthquake trigger rockfall from aftershock within a few years was considered an order of magnitude higher than pre-earthquake likelihood. There is uncertainty in the potential for aftershock estimation. A simplified methodology was developed to calculate the probability of a future damaging aftershock over a specified time interval (Mote 2016). It is important to note that the aftershock period is not constant as occurrence of a large aftershock proximal to the site will reset the aftershock window and extend this heightened likelihood.

Rainfall Triggers

Similar to earthquake triggers, rainfall triggering likelihood varies with time and therefore requires estimation for multiple temporal states.

The historic record of rainfall triggered rockfall on SH1 from NZTA was used to develop a baseline frequency of past slope instability events. This was considered the long-term landslide instability likelihood, if climate change is ignored. This is the rate on a landscape that was approaching a meta-stable state, where the previous significant earthquake was >50 years earlier and the slopes have been exposed to numerous wet seasons and significant cyclonic rainfall events.

The current slope conditions, following the earthquake, are unstable and will take time to reach the prior meta-stable state. For example remnant rainfall from Cyclone Debbie with 100mm of rain in 36 hours caused a debris flow that pushed ballast-filled containers onto the road. Observations from the many recent rainfall events that have triggered slope instability, show that, at least in the first season, loose material is impacted by rainfall.

The significant question is how many wet seasons or significant storms (e.g. > 1 in 5year) it will take for a slope to shift from unstable to meta-stable. The mitigation activity of sluicing the slopes from helicopters is an effort to quicken this process. Understanding the change from an unstable slope to meta-stable is one of the challenges in understanding the long-term risk. At the present, thresholds for rainfall-induced instability are much lower than prior to the earthquake, and consequently there is a greatly increased hazard from slope failure due to rainfall.

Probability of Transport (P_t)

P_t considers the ability for debris to reach the road constrained by site slope geometry and run-out mechanics. Derivation of P_t was based on an assessment of the observed rockfall/debris run-out and rockfall modelling.

For primary sites where debris had demonstrably reached the road, P_t was equal to 1.0. The assumption was that subsequent rockfall would reach the road again. For secondary slopes, where the debris had not reached the road, the estimation of P_t was a critical part of the risk analysis.

During the post-disaster recovery and subsequent construction temporary debris barriers were constructed providing a significant reduction of P_t..

P_t was estimated for two temporal states: with temporary barriers and without. Subsequent slope regrading or permanent barriers will also require estimates of P_t.

Across the study area, as hazard sources are ubiquitous and triggers are likely, one of the few instances where risk was at an acceptable level, was through a low P_t.

Site mapping

Existing debris observed from the site mapping provided a baseline of run-out, including boulder size and distance from source. Site mapping showed where debris had stopped and how it had been stopped (e.g. by trees or naturally come to rest). An important observation was the spatial relationship between the railroad and SH1, as the railroad in many places creates a rockfall catch bench that reduces P_t (Figure 3).

One of the key findings from the site mapping was that the relationship between the railroad and SH1 was not always captured realistically from the LiDAR and aerial photos flown after the event. The LiDAR was gridded with 1m resolution, which missed many of the smaller features. This emphasised the need for the site mapping to ground truth the model.

Figure 3: Railroad acting as a catch bench for rockfall

Video Observations

Video observations of the slope behaviour during sluicing allowed ground truthing of P_t. Relevant observations included:

- The general shattering of larger rock sources into smaller boulders.
- Varying travel times from the source to the road.
- Bounce height at the toe of the slope did not appear to exceed the height of the temporary protection (shipping container) ~3.0m in height.
- Some rocks had significant bounce heights when they launched off of rock outcrops protruding from the slope. These bounce heights exceeded 5m.

Temporary Mitigation

Temporary mitigation included shipping containers and un-engineered debris berms at the toe of high risk slopes (Figure 4). The presence of temporary barriers demonstrated a significant reduction in P_t.

Figure 4: Temporary Rock Bunds. Note recent boulder fall.

Back-analysis rockfall modelling

Rockfall models were established to support estimation of P_t and subsequent mitigation design. A thorough back-analysis was completed to support derivation and verification of rockfall model parameters.

GIS allowed automation production of rockfall modelling input files for all sites, including cross-sections with relative location of the road and rail as analysis points.

3.4 CONSEQUENCE ANALYSIS

Consequence analysis identifies the effects of the hazards, by considering the exposure and the vulnerability of elements at risk. Consequence analysis can be expressed separately for loss of life, damage to property and consequential loss (e.g. road repair, infrastructure damage, and indirect consequential costs). During the post-disaster recovery stage the consequence analysis was mainly focused on loss of life to road users. During mitigation the analysis will include direct and indirect costs to all elements at risk.

The probability for loss of life is defined by the temporal probability (T) that the road user is present and the vulnerability of that road user (V). At Kaikōura, the scale of hazards required analysis of a number of consequences with respect to the identified hazards. For example the consequence to a vehicle impacting rockfall on the road will have a different temporary probability and vulnerability, than a rockfall directly impacting a moving vehicle under a cliff line.

Temporal Probability (T)

The exposure of road users or T was based on the average annual daily traffic (AADT) provided by NZTA and guidance in the NSW RMS SRA. Although traffic was likely reduced immediately following the earthquake, the AADT was kept the same for the risk analysis. This provided some conservatism in the immediate post-disaster risk scenario, with the goal to return safe traffic to normal levels as soon as possible.

Interactions between vehicles and landslide debris are complex and many factors need to be considered including road geometry, debris volume/velocity, number of lanes impacted, difference between day and night, and the potential for debris to enter the vehicles at window height. NSW RMS SRA provides guidance on modifying T for direct impact from rockfall and large scale failure. Depending the posted speed and size of failure T is either increased or decreased.

Vulnerability (V)

Vulnerability refers to the probability of the event causing death assuming that the person is in the zone of influence. NSW RMS SRA provides guidance on vulnerability of vehicle-debris impact. Vulnerability was estimated based on hazard size or volume from site mapping and the posted speed limit.

Vulnerability was estimated for two temporal states. One for normal posted speed limits and one for traffic control. Traffic control included a combination of reduced speed limits (typically <30km/hr) and limited opening time (daylight hours only) increasing stopping distance visibility.

3.5 ASSESSED RISK LEVELS

NSW RMS SRA combines Hazard Likelihood (P_d x P_t) and Consequence (T x V) to provide an Assessed Risk Level (ARL) from ARL1 (highest risk) to ARL5 (lowest risk). At Kaikōura, ARLs for the three risk scenarios reflecting the temporal states of post-disaster recovery were generated for each hazard for a specific slope site.

The ARL provides a risk level, but ultimately risk acceptance criteria is up to NCTIR/NZTA.

One challenge in setting a broad acceptance criteria is that many of the slopes and existing high cliff cuts along SH1 likely had a high risk level pre-earthquake. Reasonable and practical risk mitigation may return the risk to pre-earthquake levels, but the risk may only be tolerable.

4 INPUT INTO RISK MITIGATION

Application of the NSW RMS SRA supports risk mitigation optioneering by quantifying the hazard and consequence in the various states of post-disaster recovery process. Mitigation optioneering explores ways to reduce risk through reducing one or more of the hazard and consequence inputs. For example:

- Eliminate risk by hazard removal,
- Scaling or sluicing loose material to reduce the probability of detachment,
- Reduce probability that debris hits the road through re-grading slope, constructing barriers, or realigning the road away from the slope, and
- Reduce the consequence, through reduction of vulnerability through effective speed reduction.

To support the process, GIS was used to automate generic slope cross-sections. Figure 5 shows an example pre- and post-earthquake slope profile with a pre-earthquake linear profile from the toe back to crest (dashed) and a mitigated profile (yellow). This allows the volume of material in the source area and the debris has been quantified. The proposed mitigated slope profile is then able to be directly imported into a rockfall analysis packages to allow iteration of design options.

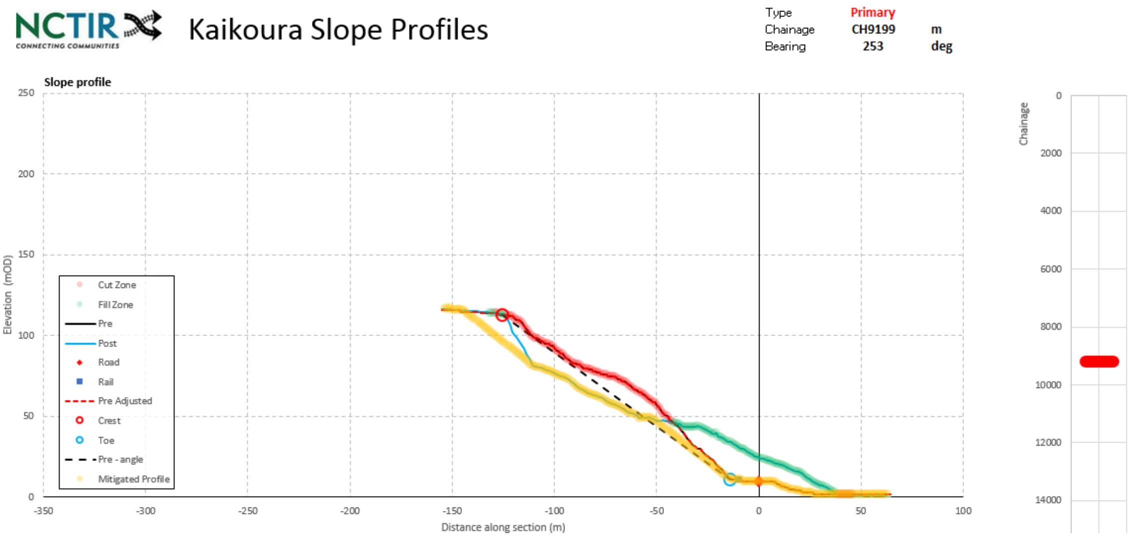

Figure 5: Automaed grading cross-sections showing pre- and post- slope profiles and initial regrading profiles.

5 CONCLUSIONS

At Kaikōura, analyses of risk scenarios reflecting the various states of post-disaster recovery across 70 slopes were carried out to support the post-disaster response and recovery. The application demonstrated and documented that rapid post-disaster risk reduction practice like traffic management or temporary bunds were effective in temporarily reducing risk.

Innovative integration of GIS data supplemented the analyses throughout the process. The GIS supported slope geometry definition and hazard characterisation, and automated cross-section generation efficiently supported mitigation optioneering. The baseline hazard and consequence data will be used to support further mitigation design to open SH1. GIS LiDAR analysis provided automation and many efficiencies, but the site mapping was essential in capturing the spatial relationship between the rail and the road.

The resilience of a community can be directly related to the performance of its infrastructure. Transport infrastructure is designed to be robust in the face of major disasters, but the resultant scale and cumulative effect of damage still can cause significant disruption and impact to our transport infrastructure. The challenge is in repairing and rebuilding the networks to be more resilient and safer, helping keep everyone better connected in the future.

Better understanding of the potential for aftershocks is essential to resilient seismic design and the ability of a community to recover quicker. The 2016 Kaikōura earthquake demonstrated that the NSW RMS SRA can be used throughout the post-disaster recovery process to understand existing risk to road users in re-opening the road and optimise the balance of proposed risk mitigation options between risk reduction, costs and impact to road users.

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