

State Highway 74 Seismic Rockfall - Predicting Its Impact, Assessing Its Risks and Managing Its Effects

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ABSTRACT

During 2010/2011, the city of Christchurch in New Zealand became 'earthquake central' with large numbers of earthquakes and aftershocks affecting a 350,000 population. This paper investigates the impacts of earthquake induced rockfall on the Lyttelton tunnel, the Lifeline structure connecting Lyttelton port with Christchurch. Structures that were designed to survive direct seismic loadings were also subjected to the indirect impacts of rockfall. Boulders in excess of 10 Tonnes were mobilised by very high ground accelerations, which subsequently rolled down the slopes causing significant devastation and injury. The challenge was to provide immediate, rapidly deployable solutions to maintain operational capacity, then assess the long-term risk, communicate that risk and, where appropriate, provide long-term mitigation measures. Rockfall risk assessment, trajectory analysis and critical asset identification was adopted to enable targeted blasting / scaling, source stabilisation and installation of rockfall barriers making for functional yet innovative and practical solutions.

Introduction

Extensive sections of the New Zealand State Highway network are exposed to hazards related to slope instability (landslides, rockfall and debris flows). Whilst many of these hazards are located in the Southern Alps and along the coastline, State Highway 74 (SH74) that links Lyttelton port to Christchurch city is also at risk from slope instability (rockfall).

Background

During the 1960s a 1.9 km tunnel was constructed to link Christchurch and Lyttelton port through the volcanic deposits of the extinct Lyttelton volcano. Christchurch is the largest city in the South Island and is highly dependent on the port for imports / exports, with major container and coal handling facilities. Whilst the southern portal daylighted into developed township of Lyttelton, the northern portal and approaches traverse rural environments flanked by the steep terrain of the Port Hills with little or no engineering control measures prior to 2010.

Darfield Earthquake

At 0435hrs on 4th September 2010 Canterbury, was shaken by the 7.1 M_w Darfield earthquake. The epicenter was approximately 40 km west of Christchurch, close to the town of Darfield and at a depth estimated to be 10 km. The duration of shaking was in the order of 40 seconds with a maximum perceived intensity of X (Intense) on the Modified Mercalli Intensity (MMI) scale.

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Figure 1. View from *Castle Rock* to northern tunnel portal with ballasted container temporary rockfall protection in place (post 22 February 2011).

Peak Ground Accelerations (PGAs) experienced across the greater Christchurch area were typically in the range of 0.2 – 0.4g. As a result of the seismic activity many buildings, notably unreinforced masonry, were significantly damaged and there was widespread liquefaction. In the Port Hills suburbs to the immediate south of Christchurch there were instances of localized land instability, primarily manifesting as rockfall and cliff collapse.

In the steep slopes to the west of SH74 around the northern portal of the Lyttelton tunnel several large naturally occurring volcanic outcrops became unstable and collapsed, resulting in significant incidents of rockfall. Additional rockfall was also recorded from cut rock batters along sections of the highway.

The impact of these rockfalls on the highway itself was minimal, with only a single (0.5 m³) basalt boulder reaching a trafficked lane. However, the actual occurrence and significant extent of rockfall within relatively close proximity to SH74 necessitated further investigation.

Initial Investigation and Assessment

Following initial incident response actions over the first 24 hours, more detailed geotechnical site inspections were undertaken over the following days to assess the effects of the seismic activity on the rockmass forming the outcrops above and to the west of SH74.

Inspections revealed numerous volcanically derived outcrops with highly dilated defects, collapsed / partially collapsed in limiting equilibrium, which continuing aftershocks or weather events could further destabilize. In order to prioritize sites for appropriate engineering management, a qualitative risk assessment process was undertaken using NZTA's risk assessment methodology.

The method considers the various key elements at risk (e.g. Service Delivery, Health & Safety, Community Sustainability and Financial) in relation to the perceived likelihood of occurrence of

the hazard and corresponding consequences. The method proved to be highly useful in determining where and how much engineering resource was required. Based upon the findings of this qualitative risk assessment three distinct areas of the slopes directly above SH74 were selected for engineering intervention.

Initial Engineering Mitigation Works

Due to the ongoing aftershocks following the main earthquake (maximum 5.1 M_w on 8th September 2010) engineering works were organized on an 'emergency works' basis requiring rapid mobilization to site and the use of innovative solutions. In general the removal of the hazardous rock was seen as the most efficient long-term solution as minimal ongoing maintenance would be required.

Two of the three outcrops were identified as necessitating a higher level of control during material removal (as opposed to traditional scaling measures) due the infrastructure and residential areas at risk from potentially works-initiated rockfall. Using techniques developed in the mining industry, it was initially proposed to temporarily rock bolt and 'mesh-entrain' the heavily dilated rock outcrops and then systematically deconstruct the outcrops using targeted drilling and blasting ('rock popping'). Prior to commencing any works on site, additional mitigation measures were completed including the installation of (i) localized spot bolting (top down) and (ii) a temporary catch fence structure below an access track to minimize the rock fall risks posed during the establishment phase.

The third outcrop was a far more significant feature known as *Castle Rock*. During the main earthquake this landmark partially collapsed and caused thousands of cubic meters of rock to fall down towards the northern tunnel portal, including some intact blocks in the order of 500–1,000 Tonnes.

Due to the topography and the soft nature of the ground (end of the southern hemisphere winter) no boulders from this failure directly impacted the highway or supporting infrastructure. In general the likelihood of further catastrophic failure was considered sufficiently low that, despite potentially significant consequences, the overall risk management strategy was one of monitor and have in place contingency and disaster plans.

The mitigation measures therefore considered appropriate for the *Castle Rock* failure were limited to localized drilling and blasting to reduce block sizes with scaling of the material considered sufficiently unstable that it posed a risk from continued aftershock activity or weather events.

All risk mitigation works were undertaken under strict traffic management control to minimize the downslope risks (i.e. travelling and residential public and infrastructure).

Ultimately the rock bolt and mesh-entrapment element of the proposed bluff deconstruction proved to be so successful that the benefits of hazard removal did not outweigh the dis-benefits associated with a complicated deconstruction process in a high risk environment. Based upon this assessment, the rock bolt and mesh solution was upgraded at modest additional expense to provide a longer-term solution.

February 2011 Aftershock

The aftershock sequence following the initial Darfield earthquake continued for some 4–5 months with several aftershocks in the 5.0 M_w region. Typically following an earthquake at least one aftershock of one unit less than the main earthquake can be expected. At 1251hrs on 22nd February 2011 a devastating aftershock of 6.2 M_w occurred at a depth of approximately 5 km, about 2 km west of Lyttelton. PGAs associated with the February shock were significantly higher in Christchurch and the Port Hills than those previously experienced in 2010. Records of both horizontal and vertical accelerations indicated a consistent range of typically 1.0 – 2.0g.

These high PGAs and the pre-conditioning of the general rockmass (primarily as a result of the Darfield earthquake) lead to widespread and significantly damaging rockfall and cliff collapse. Five deaths were attributable to rockfall (all cliff collapse mechanisms) in the wider Port Hills and there were also many recorded incidents of near-misses.

Impacts on Highway Infrastructure

Unlike the initial earthquake, highway infrastructure (notably SH74) was greatly effected by rockfall. However, despite the high PGAs the low probability event of a further catastrophic collapse of *Castle Rock* did not occur (possibly due to the shorter duration of shaking, recorded at approximately 12 seconds). However, several smaller failures occurred and many boulders of typically 1.0 m^3 in size were released.

In contrast to the September 2010 event, the ground conditions (i.e. end of the southern hemisphere summer with very stiff to hard loess deposits) favored high energy rockfall ballistics (e.g. high velocities with correspondingly high bounce heights and energies). The outcome of these various conditions was a far greater number of boulders reaching the highway and supporting infrastructure, resulting in impact damage and elevated levels of Life Safety risk. In addition, previously inactive areas of the Port Hills surrounding the northern tunnel portal became active with respect to rockfall, and this subsequently changed the risk profile further.



Figure 2. Shelterbelt to immediate west of tunnel northern portal with broken limb of tree indicating extreme bounce heights (post 22nd February 2011).

Seismic Performance of Pre-Existing Engineered Mitigation Measures

As a result of the damage to SH74 and the threat of further rockfall, the highway was closed and then opened with restrictions utilizing a “permit” system. Within 24 hours of the damaging quake the three main areas treated post-September 2010 were re-inspected.

The *Castle Rock* feature had deteriorated further, with many more areas of highly dilated rockmass visible and the relic head-scarp itself had clearly provided a significant source of material resulting in rockfall at highway level. However, there were no immediate indications of catastrophic failure that would substantially impact SH74 below.

The two outcrops that had been bolted and meshed had performed at a level beyond their design criteria. One of the outcrops was qualitatively assessed as continuing to operate at between its Serviceability Limit State (SLS) and its Ultimate Limit State (ULS) - with some minor localized displacement noted, whilst the more significant of the two features had exceeded the ULS with deformations in the 200–300 mm range, but without resulting in collapse or localized release of material. The performance of these two rockfall protection structures almost certainly resulted in reduced damage and service interruption over this section of the highway, and is highly likely to have prevented serious injury and/or fatalities.

Additional Engineering Mitigation Measures

Review of the outcomes of February 2011 aftershock provided a greater level of understanding of rockfall dynamics, potential boulder run-out paths and the elevated risks associated with an ever changing seismic environment. Of particular interest were the high variations, both vertically and laterally, of trajectories (largely due to hard ground conditions and angular basalt boulder shapes). To address these risks and maintain operational Lifeline infrastructure, further geotechnical assessment and engineering inputs were required.

Due to the much wider distribution of active rockfall sources following the February 2011 aftershock and the urgent nature of intervention required, a philosophy of passive protection around key infrastructure (i.e. catch structures) as opposed to active containment at source (i.e. bolting and meshing) were adopted.

As an immediate risk mitigation strategy, infrastructure at the highest levels of risk were either avoided (e.g. Heathcote Valley underpass closed and traffic diverted) or protected (e.g. main portal) by the strategic placement of ballasted shipping containers. Whilst these immediate actions permitted the re-opening of SH74 and the Lyttelton tunnel, the level of service was severely compromised and required significant levels of traffic management to ensure smooth and safe operation.

Once the immediate risks had been managed to appropriate levels, further engineering resource was applied to provide medium-term solutions. This enabled the restricted operational capacity to be lifted (i.e. removal of the majority of the shipping containers, lifting of speed restrictions and the re-opening of the Heathcote Valley underpass).

Utilizing a benched access track around the northern tunnel portal, the rapid construction of a temporary, low-energy 4 m high catch fence was achieved. In total the catch fence was 450 m in length and was completed within a month. The temporary nature of the structure provided a medium-term solution yet reflected the uncertainty of the longer-term future.

In addition to the installation of temporary catch fences, the outcrop that had displaced causing the bolt and mesh system to exceed its ULS was deconstructed using targeted drill and blast techniques. This was undertaken following the completion of the catch fences. During the scaling phase at least one boulder of 0.5 m³ was arrested by the temporary catch fence providing an indication of its likely capacity and also its value.



Figure 3. Part-complete temporary rockfall protection structures (post 22 February 2011).

Ongoing Aftershock Performance

Over the remaining 10 months of 2011 numerous aftershocks caused further widespread rockfall in the Port Hills areas. The most notable aftershocks were 16th April 2011, 5.0 M_w; 13th June 2011, 5.9 M_w; and, 23rd December 2011, 6.0 M_w.

Throughout this period no further rockfall reached SH74. During the June 2011 aftershock further boulders were released from *Castle Rock* resulting in significant impacts to the catch fence, with one boulder impact at full height (3.5-4.0 m) causing the sacrificial supporting timber posts to fracture resulting loss in effective height. The boulder was arrested within a short distance of the catch fence.

This series of impacts validated construction of the temporary catch fence during a period of elevated seismic activity whilst a longer-term hazard management plan was established. Furthermore, the effectively ‘full scale field testing’ provided valuable information as to the likely capacity of the catch fence that could be taken forward into more detailed assessment throughout 2012.



Figure 4. Impacted and damaged temporary rockfall protection structures (post 22 February 2011).

Quantitative Risk Assessment and Long-Term Risk Management

Later, Christchurch City Council (CCC), in conjunction with GNS Science (GNS) and numerous consultants and academic institutes (collectively known as the Port Hills Geotechnical Group, PHGG), embarked upon a risk assessment and management process to understand the risks posed by land instability in the Port Hills. The risk assessment process was quantitative and based upon the AGS 2007 publication *Landslide Risk Management*. Detailed GPS location of rockfall endpoints, mapping of trajectory trails, identification of likely rockfall sources, banding of trigger events, association of rockfall frequencies to trigger events, back analysis of rockfall ballistics, consideration of spatial / temporal probabilities and variable vulnerabilities permitted a detailed and robust quantitative risk assessment to be completed.

As a result of this study the full length of SH74 within the rockfall hazard zone was mapped and a quantified risk level determined. However, the risk metric was specifically applicable for negative impacts in terms of residential usage and was therefore likely to be misleading to those operating public infrastructure, such as a highway network.

An in-depth understanding of the entire quantitative landslide risk assessment process applied in the Port Hills by CCC provided the capability to disaggregate the CCC quantitative risk assessment results and re-compile in a metric that was more appropriate to the element at risk (i.e. highway users).

Findings of the Revised Quantitative Risk Assessment

The key elements of the quantitative risk assessment were the number of boulders estimated as being released under differing triggers with respective frequencies of occurrence. Main adjustments included:

- Allowance for the spatial distribution vehicles;
- Adjustment for the variable nature of temporal occupancy of the highway by vehicles; and,
- Variation in vulnerability depending upon the vehicle type and travel speed.

To determine the most relevant risk metric several scenarios had to be considered, which included:

- Operational shift staff;
- The *Person Most At Risk* (PMAR); and,
- Societal risk using f(N) Pairs and F(N) Plots.

Based upon risk estimates corresponding to these specific metrics, together with the demonstrable performance of the rockfall protection structures installed to date, it was determined that:

- Risks from rockfall to road users in the rockfall hazard zones were controlled to *Tolerable* levels and broadly in accordance with the ALARP (*As Low As Reasonably Practicable*) principle; and,
- Removal of rockfall protection structures would (in the short to medium-term) increase the rockfall risk levels to *Unacceptable* levels.

By comparison, the risks posed to occupants of residential dwellings (if hypothetically located at the same location of the highway) would not have fallen within the same ALARP principle band but would have been *Unacceptable*. This demonstrates the importance of correctly understanding the metrics of quantitative risk assessments to ensure that appropriate risk based decisions are taken.

Long-term Actions Derived from the Revised Quantitative Risk Assessment

Following discussion and review of the initial quantitative rockfall assessment results and confirmation of the appropriateness of the temporary mitigation measures, a longer-term risk management strategy is currently under development. Due to the predicted seismic decay indicated by GNS for the greater Christchurch region a diminishing risk profile can be considered. In essence this means that the frequency of seismically induced rockfall events is predicted to diminish over time.

In time the risks are likely to reach a level such that the requirement for rockfall protection structures is greatly reduced and the overall protection measures surrounding SH74 can be rationalized, thus providing a more efficient and reduced impact on future maintenance budgets. It is anticipated that this period will be in the years 10–15 years.

A further benefit of the longer-term planning is the development of an appropriate response system to future seismic activity that resets the CSHM, potentially significantly altering the rockfall risk profile. This will enable a more rapid and robust deployment of temporary protection measures and a quantified assessment as to when those measures can be removed.

Current Rockfall Risk (due to EQ) - Plotted F,N cumulative risk

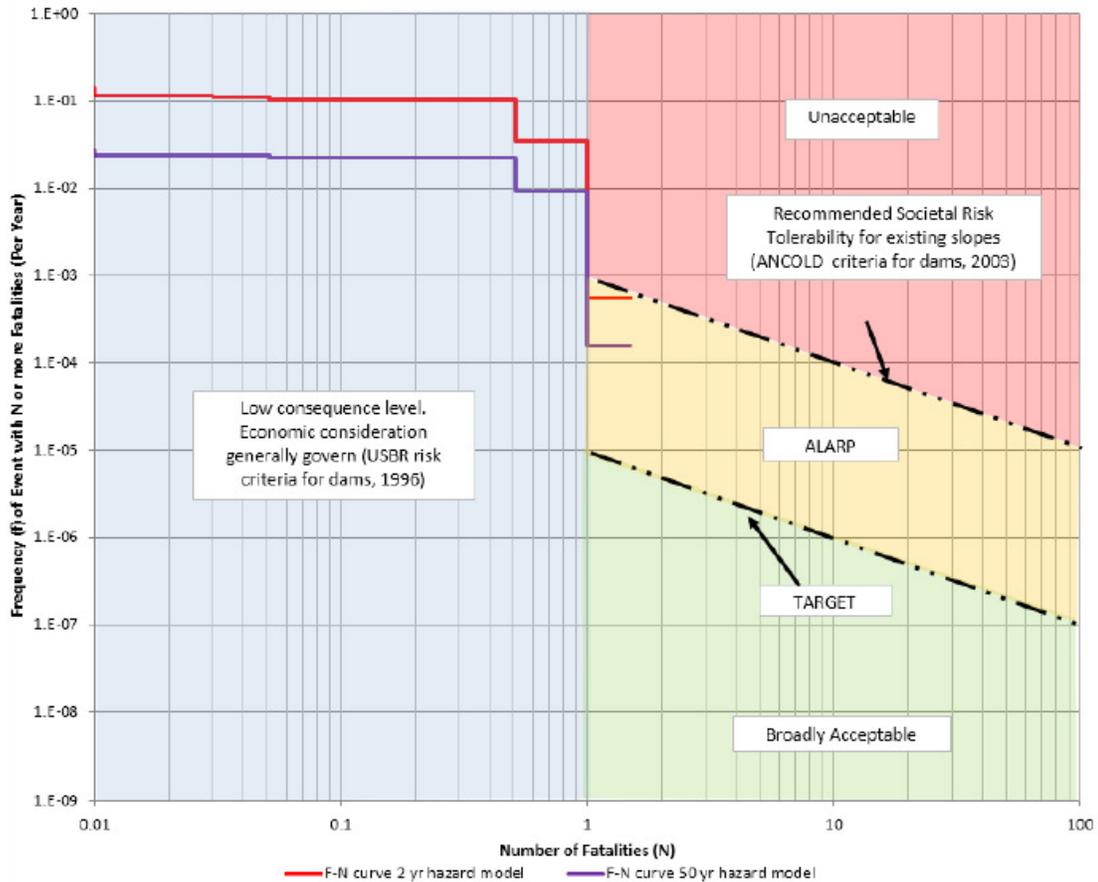


Figure 5. F(N) Plot and ALARP regions for quantitative rockfall risk (2 and 50 Year CSHM curves presented).

Conclusions

Through the use of both qualitative and quantitative risk assessment processes the rockfall risks levels along SH74 in the Port Hills to the south of Christchurch city have been adequately managed.

Occurrence of rockfall onto either SH74 has not occurred since the installation of all temporary rockfall protection structures and there has been no further operational impacts due to rockfall.

Rebuild of the damaged control building has been completed based upon selection of a site that is exposed to a *Tolerable* level of risk managed in accordance with the ALARP principle.

Further assessment and works are currently underway to provide a long-term strategy for disaster response and recovery.

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