A risk based assessment to rockfall mitigation

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ABSTRACT

The Health and Safety at Work Act (2015) requires companies to provide safe working environments for its staff. In response to this, our client sought to identify effective mitigation solutions for a rockfall hazard above an operational access road. The slope consists of a near vertical, 15 m high, cutting into a steep (~35°) natural slope. Below the cut face there is a single lane access road, with the natural slope continuing below. Groundwater seepage near the top of the cut face has resulted in ongoing rockfall, presenting a hazard to staff using the access road. Previous geotechnical assessments had recommended large scale earthworks to reshape the cutting to remove the hazard. This paper presents an alternative risk management approach developed by Opus, identifying the most appropriate mitigation solution. The current level of risk was evaluated (using the AGS Landslide Risk Management Guidelines), and compared with industry standards to determine an acceptable level of life safety risk. By evaluating the relative cost and risk reduction achieved for feasible mitigation solutions, a proportional cost and acceptable risk based solution was identified. This paper focuses on how the rockfall risk was effectively assessed, managed and communicated with our client.

1 INTRODUCTION

Opus International Consultants Ltd (Opus) were engaged to undertake a site inspection, risk assessment and recommend mitigation options for an active rockfall site on an operational access road near Waipara in North Canterbury (refer to Figure 1).

Figure 1: Site location map (Source: LINZ data service)

The access road was constructed in c.2003, by cutting into a steep (35°) slope. This created a sub-vertical cutting, up to 15 m high along a 100 m section of the road. A 20 m section of the cutting has been prone to ongoing rockfalls, prompting the client to seek specialist advice. A geotechnical appraisal was undertaken at the site in 2015, identifying several possible mitigation options including shotcrete/anchoring, large scale bench/battering of the slope and a local realignment. Until the hazard was appropriately mitigated, a spotter was being used to manage the risk. The client approached Opus in 2016 to review the site and the previous appraisal, and to provide a solution appropriate for the volume of traffic that uses the access road.

2 SITE DETAILS

2.1 Site Geology and Geomorphology

The existing cut batter is near the toe of a steep natural slope that extends a further 50 m upslope. The batter is up to 15 m high and cut at approximately 80° (refer to Figure 2). It is intersected by several gullies over its 100 m length. The site is underlain by Kowai Formation consisting of conglomerates, siltstones, sandstones and mudstones near the base of a local syncline structure (Forsyth et al, 2008). The material exposed in the cut face is interbedded very weak SILTSTONE and SANDSTONE beds, ranging from a few centimetres to up to a metre thick with sub horizontal bedding.

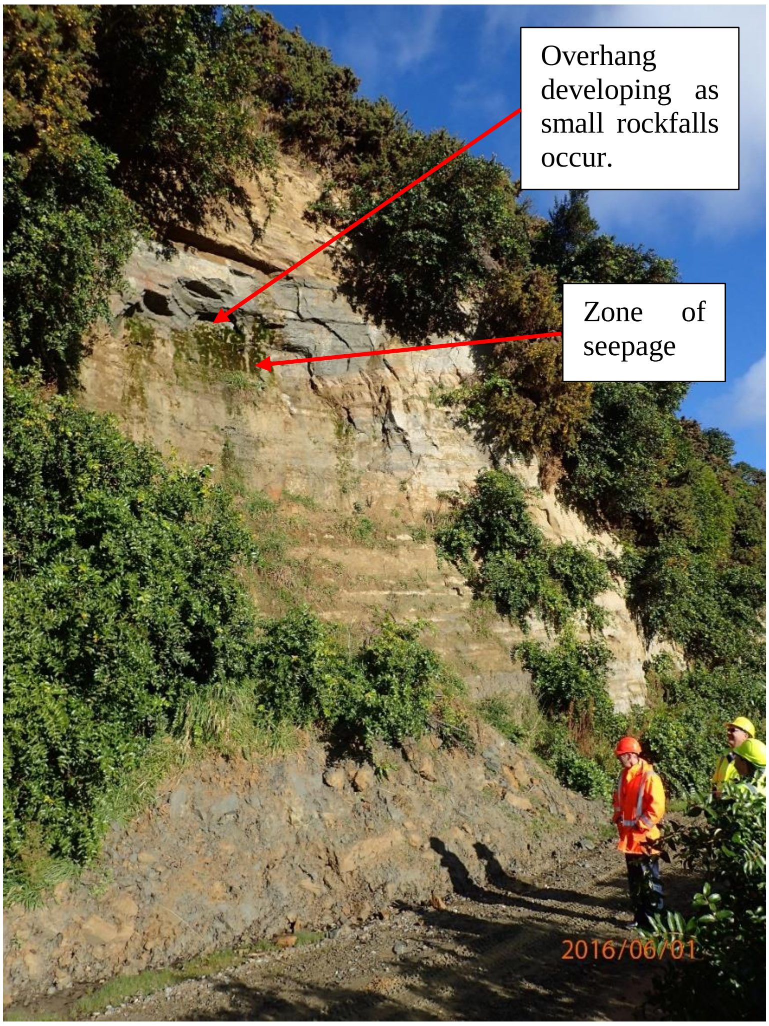

Figure 2: Cut face as inspected in 2016

2.2 Failure History

The full length of the cutting is prone to isolated rockfalls, however a section of cut approximately 20 m in length has a higher frequency of rockfalls, and occasional larger batter failures. The client indicated that small rockfalls (< 2 m^3 in volume) occur 1 – 2 times per annum. A larger event occurred in 2010 which inundated the full width of the access road (refer to Figure 3).

2.3 Site observations

The current area of cut batter instability is approximately 20 m in length. At the base of the cut, the access road is single lane and is approximately 4 m in width. Any available catch zone (approximately 1 to 1.5 m wide) has been inundated with rockfall debris (refer to Figure 2). On the downhill (north) side of the road, there is a berm of fill material (up to 2 m high) that is likely stockpiled rockfall debris from historical events.

Individual rock blocks of typically 100 mm to 200 mm size were observed at the base of the slope. Thicker bedding further up the slope will likely result in larger blocks being dislodged (as is evident in Figure 3).

Seepage was observed at several points in the lower 10 m of the cut face. The source of seepage was not identified during the walkover inspection.

Figure 3: Slip in 2010, debris extending over the access road

3 FAILURE MECHANISM

Weathering of material at the face being exacerbated by seepage is the inferred mechanism for small rockfalls. Subsequent undermining of upper portions of the slope then eventually results in a larger failure (refer Figure 3). The face is expected to continue unravelling via regular small rockfalls and intermittent larger rockfalls.

4 RISK ASSESSMENT

Risk to life is assessed by estimating the probability of an event occurring (i.e. rockfall), the probability that someone is present when it occurs and the expected consequence. There is no worldwide standard for tolerable risk limits, which vary depending on the country and risk context. Australian Geomechanics Society Landslide Risk Management Guidelines (AGS, 2007d) suggest the upper limit for tolerable loss of life risk for the Person Most At Risk (PMAR) is 1×10^{-4} per annum (i.e. greater than 1 death every 10,000 years). Where the assessed risk of loss of life is greater, mitigation is required to reduce the risk to below this level. Below this threshold, the risk falls into an ALARP (As Low As Reasonably Practicable) zone, whereby steps should be implemented to reduce the risk where it is practical to do so. Christchurch City Council adopted similar levels for tolerable risk when assessing risk to life from rockfall following the Canterbury Earthquakes.

A semi-quantitative risk assessment was initially undertaken for the site using the New South Wales (NSW) Roads and Maritime Services Slope Risk Analysis methodology (Roads and Maritime Services, 2014). This method analyses the risk for a potential failure at the site using a series of ratings which are then combined through a matrix to determine an ARL (Assessed Risk Level) for each failure type. The highest ranking that can be achieved is an ARL1, which requires mitigation works to be undertaken to reduce the risk. ARL2 rankings are placed on a priority remediation list. The lowest ranking is an ARL5 which is associated with negligible risk (AGS, 2007d).

Using the NSW methodology, the following parameters/assumptions were used to assess the risk rankings for our site:

- The AADT for the road is 4 vehicles per day;
- The vehicle operational speed is approximately 40 km/h;
- A large rockfall (similar to the 2010 event) is expected approximately once every 5 to 10 years;
- A medium sized rockfall (maximum dimension 0.5 m, volume < 2 m^3) occurs annually; and,
- A small rockfall (individual blocks up to 0.3 m diameter) occurs annually.

The risk assessment evaluated both the risk of a fatality from (i) a vehicle hitting the fallen debris and (ii) a vehicle being hit by falling debris. The various scenarios evaluated to a maximum ARL3 rating. Work by Opus to assign a quantitative minimum, maximum and average values to each ARL band in the NSW Risk methodology (Likelihood, Temporal, Vulnerability and Consequence) indicates that the annualised risk level for each ARL3 event sits between 1×10^{-7} and 1×10^{-4}

The assessed risk was further verified using published quantitative methods (Bunce et al, 1997) which indicated an annualised risk of 2×10^{-6} for an individual rockfall event.

In order to determine the total annual risk for the site, the risks for each scenario were summed. The total risk for loss of life from rockfall to the PMAR is estimated to be in the order of 1×10^{-5} (which equates to 1 death per 100,000 years). This falls below the threshold of unacceptable risk, but remains within the ALARP zone. A summary of the assessed risk is presented in Table 1.

Rockfall Scenario		NSW Method	Bunce Methodology
Large	**Car Hits Debris**	ARL4	4.2×10^{-07}
	Debris Hits Car	ARL3	4.5×10^{-06}
Medium	**Car Hits Debris**	ARL3	1.0×10^{-07}
	Debris Hits Car	ARL3	2.3×10^{-06}
Small	**Car Hits Debris**	ARL3	1.0×10^{-07}
	Debris Hits Car	ARL3	2.3E x 10^{-06}
TOTAL			$\mathbf{9.6 \times 10^{-06}}$

Table 1: Evaluated risk for loss of life from rockfall

It is important to note that the economic consequences of rockfall (e.g. road closures) were deemed to be insignificant by the client and were not further evaluated.

5 MITIGATION EVALUATION

Several mitigation options were considered to reduce the rockfall risk, including those in the earlier appraisal and options suggested by the client. The client's preferred solution was a minor road realignment, as these works could be undertaken without specialised plant. Other options evaluated were: the use of a spotter (current practice); regular slope monitoring and risk management; low cost improvements such as installing horizontal drains or trimming the batter face and higher cost improvements such as installing a mesh drape or earthworks to remove the hazard.

In order to determine if the mitigation cost is warranted given the level of risk, the capital cost vs reduction in risk were evaluated for each option. This information was used to determine the Cost Effectiveness (with respect to life saved) and Disproportionality Ratios (using simplified methodology from Bowles, 2003).

Cost Effectiveness is a measure of life safety risk reduction (or cost per statistical life saved, CSLS) which is the equal to the annualised cost of the risk reduction measure divided by the annualised risk reduction achieved by the measure. Bowles proposed an Adjusted CSLS (ACSLS) for ALARP evaluations which also considers the economic benefit for each risk reduction measure (refer to equation 1).

$$ACSLS = (c - b_E)/r_L \quad (1)$$

Where:

c = Annualised Cost of Risk Reduction Measures

b_E = Annualised Economic Benefit of Risk Reduction Measures
= Economic Loss x Reduction in Probability of Loss of Life

r_L = Annualised Life Safety Risk Reduction for Risk Reduction Measure
= Estimated Number of Fatalities x Reduction in Probability of Loss of Life

The Disproportionality Ratio is a method proposed by HSE (Health and Safety Executive) to estimate the degree of disproportionality for a risk reduction measure in line with ALARP principles (Bowles, 2003). The ratio considers ACSLS and the Value of Preventing a Fatality (VPF) (refer to equation 2). Typically ratios of between 1 and 10 are considered to be at appropriate levels for ALARP principles (refer to Figure from Bowles (2003) in Appendix).

$$\text{Disproportionality Ratio, } R = ACSLS/VPF \quad (2)$$

For each mitigation measure Cost Effectiveness and Disproportionality was determined and compared against guideline values (refer to Table in Appendix) to determine the level of justification. For this assessment VPF was set at $4.1M which is similar to the Ministry of Transport's Value of Statistical Life (Ministry of Transport, 2015).

The evaluation identified that the current measure of risk reduction (using a spotter to observe traffic under the cutting) is associated with a high annual cost and minimal risk reduction. The cost effectiveness corresponds to a "Poor" ALARP justification rating and a disproportionality ratio greater than 50. Even low cost capital improvements (Options 3 to 5, $10,000 - $30,000) with an order of magnitude risk reduction (including the clients preferred solution) had "Moderate" ALARP justification rating and disproportionality ratios greater than 30.

Option 2 consisting of Slope Monitoring and Risk Management has an associated "Strong" ALARP Justification rating and disproportionality ratio of 10.

The earthworks option to bench and batter the slope has a "Poor" ALARP justification and very high disproportionality ratio. A summary of the options considered and associated Cost Effectiveness and Disproportionality is presented in Table 2.

	Option	Cost Estimate	Risk Reduction	Cost Effectiveness ($/life)	Disproportionality Ratio
1	Current practice – use of a spotter	~$18k	0.5 an order of magnitude	210M Poor Justification	52
2	Slope Monitoring and Management	~4k	0.5 an order of magnitude	40M Strong Justification	10
3	Install slope drainage	~$13k	1 order of magnitude	150M Moderate Justification	37
4	Trim the overhang	~$15k	1 order of magnitude	175M Moderate Justification	43
5	Minor road realignment	~$30k	1 order of magnitude	195M Moderate Justification	48
6	Install a mesh drape to slope	~$80k	1 order of magnitude	530M Poor Justification	129
7	Bench and Batter slope	~$300k	2 orders of magnitude	1800M Poor Justification	442

Table 2: Summary of Mitigation Option Evaluation

6 RISK MANAGEMENT

Findings were presented to the client, with a follow up meeting to further discuss the potential risk mitigation options. Based on the risk assessment and mitigation option evaluation, the client adopted Option 2 for the site, engaging our help to develop an appropriate monitoring and risk management plan for the site. This included:

- A sign in/sign out process for vehicles using the road;
- Visual inspection of the rockfall site prior to passing underneath;
- Maintaining a record of rockfalls;
- Monthly photograph of the site and review;
- Annual review of site changes and associated risk level; and
- Engage a specialist for review should any significant change occur.

7 CONCLUSIONS

An earlier geotechnical appraisal at a known rockfall site identified that road realignment or large scale earthworks to bench and batter the slope would provide rockfall risk reduction by either eliminating the hazard or minimising the probability of debris reaching the access road. Opus were engaged to review the site and previous appraisal, and recommend a solution appropriate for the traffic volume on the road.

Using NSW Slope Risk Analysis methodology a risk rating of ARL3 was determined for the site. This was further verified using quantitative methods which estimated the total annualised risk for loss of life from rockfall to be 1×10^{-5} for the PMAR. This sits below the threshold of unacceptable risk and in the ALARP zone.

To order to determine an appropriate mitigation solution for the level of risk, Cost Effectiveness and Disproportionality Ratios were calculated for each mitigation option. This identified that a low cost solution such as *slope monitoring and risk management* was appropriate an in line with ALARP principles for risk mitigation. This option was adopted by the client.

This method is considered applicable for assessing ALARP measures with respect to life safety and may not be applicable where there are significant other consequences from rockfall (e.g. closure of critical routes).

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APPENDIX

Extract from
Bowles, D.S. (2003) *ALARP Evaluation: Using Cost Effectiveness and Disproportionality to Justify Risk Reduction.* ANCOLD 2003 Conference on Dams.

Table 2. ALARP Justification Ratings (Illustrative Example Only) (Bowles and Anderson 2003)

ALARP Justification Rating	Range of Cost-per-statistical-life saved (AU$M/life)	
	Greater than or equal to	Less than
Very Strong		5
Strong	5	50
Moderate	50	200
Poor	200	

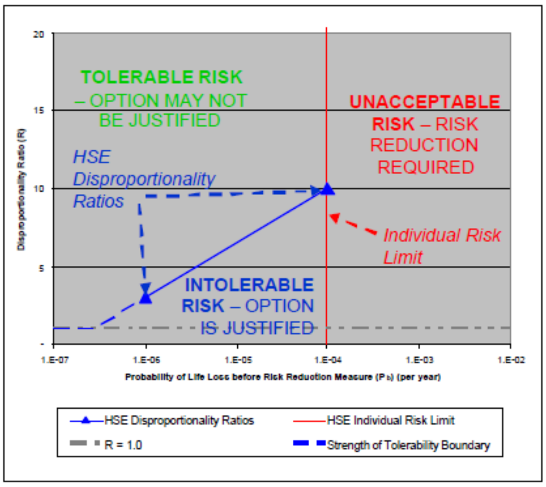

Figure 1. Plot of HSE Guidance for Evaluation of Disproportionality Ratio