Explicit estimation of rock slope failure likelihood for hazard assessment and safety engineering near Canmore, AB

Renato Macciotta, Chris Grapel, Jason Duxbury & Tim Keegan
Klohn Crippen Berger, Edmonton, AB, Canada
Roger Skirrow
Alberta Transportation, Edmonton, AB, Canada

ABSTRACT
Rock slope instabilities are a common hazard along transportation corridors through the Canadian Cordillera. In 2013, a rock slope instability that developed into a rock fall reached a highway near Canmore, AB; narrowly missing a vehicle and a group of people. This event triggered an investigation of the area and an assessment of potential options to mitigate the risks associated with other potential instabilities at the site. This paper presents an explicit estimation of rock slope failure likelihoods developed for assessing engineering options for rock slope risk mitigation. The engineered options are closely associated with the volumes, likelihood and run out characteristics estimated through the investigation and consider other aspects of the site such as wildlife and recreational activities in the area.

RÉSUMÉ
Les instabilités des talus rocheux sont un danger commun le long des corridors de transport dans la Cordillère canadienne. En 2013, une instabilité de la pente rocheuse qui s'est transformée en une chute rocheuse a atteint une autoroute près de Canmore, AB; manquant de justesse un véhicule et un groupe de personnes. Cet événement a déclenché une enquête sur la zone et une évaluation des options potentielles pour atténuer les risques associés à d'autres instabilités potentielles sur le site. Cet article présente une évaluation quantifiée des dangers développée pour évaluer les options d'ingénierie pour l'atténuation du risque de talus rocheux. Les options d'ingénierie sont étroitement associées aux volumes, aux probabilités et aux distances de rupture estimées au cours de l'enquête et tiennent compte d'autres aspects du site tels que la faune et les activités récréatives dans la région.

1 INTRODUCTION

Rock slope instabilities, in particular rock fall occurrences, are a common hazard along transportation corridors through the Canadian Cordillera (Bunce et al. 1997, Evans and Hungr 1993, Hungr et al. 1999, Lan et al. 2010, Macciotta et al. 2011, 2013, Peckover and Kerr 1977, Piteau 1977). Highway 742 near Canmore, Alberta, is no exception, and on May 20, 2013 a significant rock fall event occurred at the site. The rock fall reached Highway 742, narrowly missing a vehicle and a group of people. The work presented here corresponds to an explicit estimation of rock slope failure likelihoods for hazard assessment and safety engineering performed at the section of highway where the 2013 event occurred. This assessment was performed to define options for rock slope safety engineering, and as a first stage of a quantitative risk assessment of the site. The assessments follow the methodologies presented in Bunce et al. (1997) and Macciotta et al. (2016 and 2017), and are detailed in the following sections. The paper further presents the location and characteristics of the study area and the engineering options considered.

2 LOCATION AND GEOLOGIC CONTEXT

The study area corresponds to a steep rock slope adjacent to a highway near the town of Canmore in AB. This highway is managed by Alberta Transportation (AT) and the rock slope site is known as S042. This section presents the location and its geologic context.

2.1 Location

The S042 site is located on Highway 742 at the entrance to Spray Lakes valley, adjacent to the Spray power canal that conveys water to Whitman's Pond, part of the TransAlta Spray lakes hydro-electric system. The site is approximately 5 km west of Canmore, on the northwest shore of Whiteman's Pond (Figure 1). Figure 2 shows a view of the S042 rock slope.

The proximity of this site to the touristic town of Canmore and the scenery of the area have led to a variety of activities, including wildlife photography, hiking, and rock climbing. This adds a layer of complexity regarding potential engineered structures for rock slope safety.

2.2 Geologic Context

The S042 site corresponds to the southeast end of the Mount Rundle range. Mount Rundle range is oriented southeast-northwest, between Canmore and Banff. Its steep, rocky and bare nature contrasts with the gentle and forested physiography of the Bow valley to the east. The summit of Mount Rundle is at an elevation of 2,948 m, and the Bow valley is between 1,300 m and 1,400 m. The elevation gain is approximately 1,600 m within a horizontal distance of 4 km.

Mount Rundle consists of Paleozoic limestones, dolomitic limestones, dolostones and shales thrusted onto Mesozoic sedimentary rocks outcropping in the Bow valley. The rock units outcropping along the Whiteman's Pond include the Southesk Formation, Alexo Formation and Palliser Formation. Bedding planes are shown to dip at 41° towards the southwest (Price 1970). The peak ground acceleration (PGA) near the site for a 10% probability of exceedance in 50 years is 0.045g (NBCC 2016).

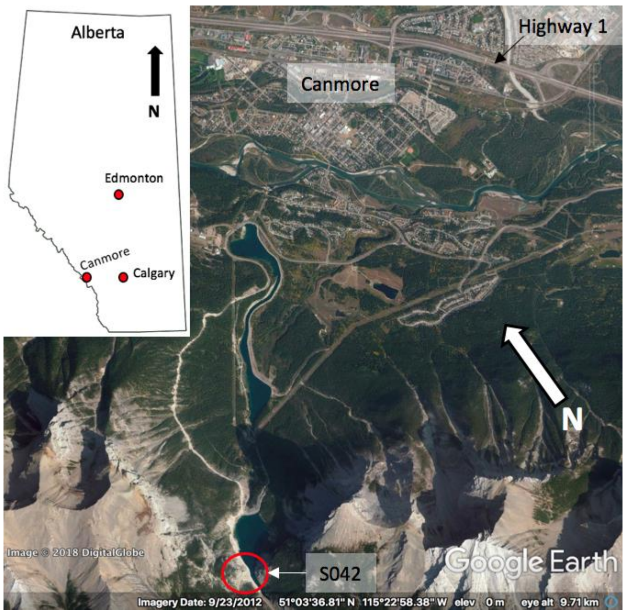

Figure 1. Location of the S042 rock slope (Base image after Google Earth (2018)

2.3 Climate

The climate normals come from a weather station located near Kananaskis, about 29 km to the southeast (Environment Canada 2016). The climate of the area can be characterized as continental subarctic (Figure 3). Based on statistical data collected between 1981 and 2010, the average daily temperature ranges between -6.1°C in January and 14.5°C in July. The average daily maximum (i.e., the average daily maximum within a month) ranges between -1.0°C and 22.1°C, while the average daily minimum ranges between -11.7°C and 6.8°C. Extreme maxima and minima can reach + 34.5°C and – 45.6°C during the summer and winter, respectively.

Monthly precipitation ranges between 18.9 mm in December and 119.4 mm in June. Between October and April, the major amount of precipitation consists of snow.

3 ROCK SLOPE INVESTIGATIONS

3.1 Site investigations

Site investigations in 2016 and 2017 focused on measuring rock mass characteristics and estimating rock fall debris volumes. This was done through observations of the rock slope and debris window mapping at 7 locations (Figure 2). Both conventional and terrestrial photogrammetry mapping were also undertaken. The average volume of the blocks at the base of the talus slope was found to be 0.3 m^3, with a maximum volume of 3.8 m^3.

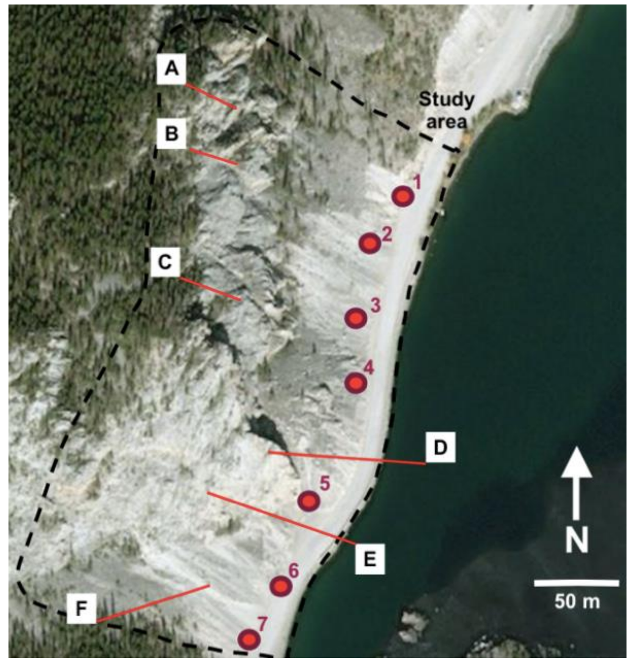

Figure 2. View of the S042 rock slope showing slope sectors A through F for reference through this paper and rock debris window mapping locations 1 through 7

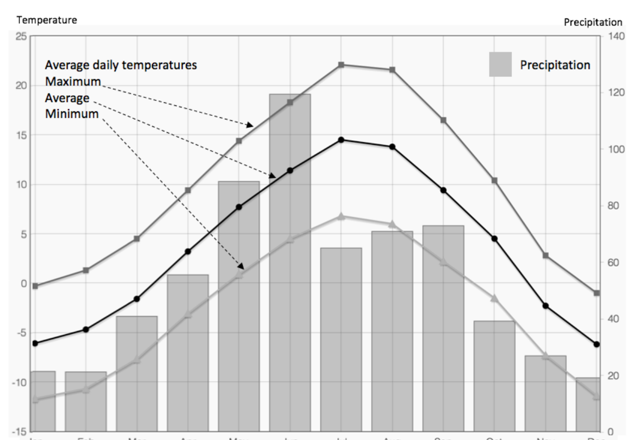

Figure 3. Average monthly precipitation and daily temperatures (maximum, average and minimum) at the Kananaskis weather station between 1981 and 2010 (Environment Canada 2016)

Large blocks were observed at the base of the rock fall event in 2013, adjacent to the highway (Figure 4b). However, at other locations, large blocks generally do not reach the base of the talus slope. It was assessed that large blocks falling individually would fragment upon impact on the talus slope or would not be able to bounce due to their heavy weight. Consequently, they would likely slide on the talus slope and stop uphill from the highway (Figure 4a). Based on this observation, it was estimated that the volume of 0.3 m^3 could an adequate characteristic size for individual rock falls reaching the road.

Spacing of discontinuities obtained through conventional structural mapping of the slope are shown in Table 1. An estimate of the order of magnitude of potential rock fall volumes can be estimated through combination of discontinuity spacing (Macciotta and Martin 2015). Direct combination of maximum spacing for J1, J2 and S0 renders a volume of 2.7 m^3, and an average volume of 0.15 m^3, Values somewhat smaller than those observed but consistent with their order of magnitude, thus increasing confidence for using them for analysis.

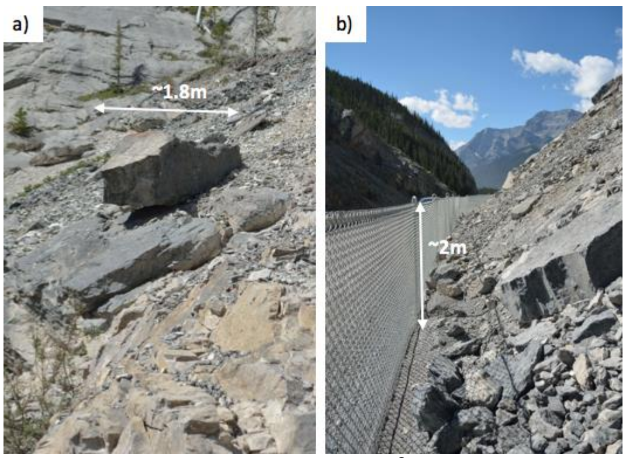

Figure 4. Rock blocks larger than 1 m^3 contained within the talus slope at sector C in Figure 2 (a) and adjacent to the road at sector D (b)

Kinematic analyses based on the characteristics shown in Table 1 indicated that:

- Planar sliding is marginally possible on East facing rock slopes, possible along Northeast facing rock slopes, and marginally possible on southwest facing rock slopes.
- Wedge failure is possible.
- Flexural toppling is marginally possible on northeast facing rock slopes but unlikely to happen because a required joint set is not ubiquitous with close spacing.

None of the failure mechanisms highlighted above were observed at the S042 site. One reason is likely that some of the highlighted mechanisms involve minor joint sets, which are relatively infrequent. Planar sliding and wedge failure are possible on northeast facing rock slopes, however these we also not observed. This suggests that small rock detachments require cohesion loss to make the block movement kinematicly feasible. Mechanisms associated with these degradation processes and detachment events include chemical weathering, precipitation events, strong winds, anthropogenic activities, seismic events, freeze-thaw cycles, ice jacking, and wildlife activity.

Table 1. Discontinuity characteristics at S042

Disc. Set	Type	Dip (°)	Dip Direction (°)
J1	Joint	80	149
J2	Joint	59	25
J2b	Joint	46	77
J4	Shear	58	248
S0	Bedding	38	252
Disc. Set	Trace length (m)		
	Min.	Max.	Mean
J1	0.4	3.0	1.1
J2	0.3	3.0	1.1
J2b	0.5	1.3	0.9
J4	0.4	2.5	0.8
So	Continuous		
Disc. Set	Spacing (m)		
	Min.	Max.	Mean
J1	0.1	2.4	0.5
J2	0.1	2.8	1.0
J2b	0.04	0.2	0.1
J4	N/A		
So	0.1	0.4	0.3

3.2 Field Observations

Blocks at the toe of the *talus* slope varied from weathered, sub-angular blocks to fresh (no to imperceptible weathering), angular blocks. These fresh, angular blocks were considered to have detached from the rock face within the last 3 to 5 years. Some angular, fresh blocks, equal and less than 0.3 m in equivalent diameter were found adjacent to the highway (between the roadway and the talus slope and east of the road, adjacent to the barrier at the lake side - Figure 5). A subset of these blocks could be blocks that have been encountered on the road and have been moved to the side of the road. Between 40 and 60 rock blocks (estimated) with equivalent diameters between 0.3 m and 0.6 m were found to have been contained by the existing 2m high catch fence (downslope sectors D and E – Figure 6). These blocks would have travelled downslope to the road surface if not for the catch fence.

The potential for failure of large slope volumes (up to 1000 m^3) would require more complex mechanisms that those analyzed through kinematic analyses (planar sliding, wedge failure or flexural toppling). Field observations evidenced the potential development of complex daylighting failure surfaces along a combination of bedding planes, fractures, joint families, and other discontinuities; through progressive failure mechanisms (Figure 7). Some indications include differential weathering, increased rock mass disaggregation, presence of opened discontinuities.

3.3 Window mapping of debris

Window mapping of rock block volumes was performed in 7 locations along the toe of the talus slope (red points in Figure 2). The window mapping allowed better understanding the volume - frequency distribution of blocks that reach and can potentially obstruct the highway, without considerations of blocks that stopped at higher locations within the talus slope. The number of blocks surveyed and the area surveyed for each window is shown in Table 2. Figure 8 shows the histogram of surveyed block volumes along the toe of the talus slope of S042, for all 7 windows in Figure 2.

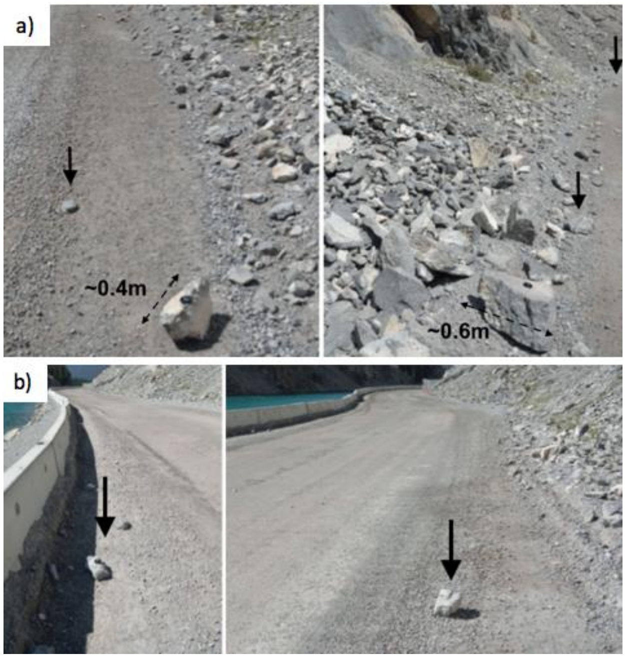

Figure 5. Fallen blocks found adjacent to the highway at the toe of the talus slope in sector F (a) and east of the road, adjacent to the barrier at the lake side (b)

Figure 6. accumulation of rock debris contained by existing 2m-high fence at sector D and E in Figure 2

Table 2 confirms that most blocks that reach the highway are equal or smaller than 0.3 m^3, which is consistent with previous observations. Larger blocks are typically found at higher locations within the talus slope, and their likelihood for reaching the highway is substantially lower. However, these larger blocks could likely reach and block the highway following larger slope instabilities.

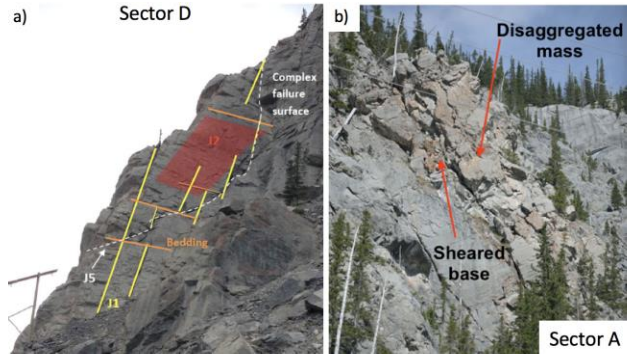

Figure 7. Evidence of progressive failure mechanisms that can lead to larger failure volumes

Table 2. Area and number of blocks surveyed per window in Figure 2

Window	Area (m^2)	No. of blocks surveyed
1	50	17
2	44	12
3	62	23
4	Linear scan	76
5	40	33
6	80	14
7	80	20
Total	-	195

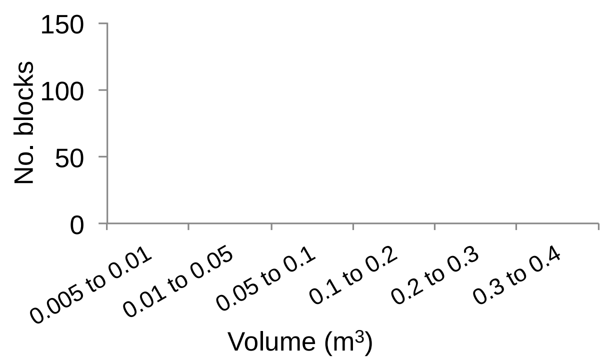

Figure 8. Histogram of surveyed block volumes along the toe of the talus slope of S042, for all 7 windows in Figure 2

3.4 Highway maintenance observations

AT's maintenance observations regarding debris that are found blocking the road were provided through two communications by their local maintenance contractor. These were qualitative in nature, but evidenced a peak on rock fall activity during the winter and spring months, and into June. Weather for the region (summarized in Figure 3) shows maximum and minimum temperatures variation through the year and indicates that the potential for freeze-thaw cycles is greater in February to April and October to November, May and June presenting the most precipitation, and the thawing period would occur sometime between April and early June. According to previous studies in the Canadian Cordillera (Macciotta et al. 2015) precipitation, freeze-thaw cycles and thawing; are all rock fall triggering mechanisms. Therefore, climate trends in the area would suggest that the periods of most rock fall activity would be the months of February to June, followed by the months of October and December, with less activity on the months of July through September and January. All these are generally consistent with the road maintenance communications provided by AT.

Maintenance communications further provide insight into volumes and frequency of fallen blocks into the road. Crews reported one hour of material removal every day between February and June, mostly removed by a grader or by hand. This suggests a relatively small amount of debris. Considering that the S042 site is only a section of the larger area from which the data reported by maintenance (no locations are recorded) has been collected, and that laborers are reported to remove the material; the upper limit for individual rock falls of 0.3 m^3 at site S042 can be further considered representative. Further, it would appear conservative to assume that blocks reaching the highway can be a daily occurrence between the months of February to June. few occurrences would happen during the other months of the year according to maintenance crews.

4 SLOPE HAZARD ASSESSMENT AND MITIGATION STRATEGIES

4.1 Rock slope failure volume-frequency relationships

Information summarized in the previous sections included rock block volume data and qualitative observations of rock slope stability conditions, block locations relative to the talus slope and highway, and maintenance effort to clear the road from debris. These were used to assess volume-frequency relationships of blocks that can potentially reach and block the highway as well as the potential for larger events.

Plots of cumulative frequency vs. rock slope failure volume are commonly used for assessing failure frequencies and derive their probabilities (Hungr, et al. 1999). Figure 9 presents the relative cumulative frequency of surveyed blocks at the toe of the talus slope and on the highway's cleared area. This plot is relative to the number of surveyed blocks, and therefore not representative of rock fall frequency. Moreover, the data was focused to those blocks that have reached the highway (or adjacent to the highway), therefore discriminates for the larger blocks found embedded in the talus slope at higher elevations.

The relationship between volume and relative frequency shown in Figure 9 can be scaled to represent the annual frequency of rock falls reaching the highway. Highway maintenance experience suggests that road cleanup occurs daily between February and June and sporadically the rest of the year. It is a conservative assumption that rock blocks reach the highway almost daily at the S042 between February and June, with a few occurrences (once or twice a month) the rest of the year. This would equate to approximately 100 blocks equal or smaller than 0.3 m^3 each year reaching and potentially blocking the highway at Site S042. This information was used to produce the cumulative frequency plot of rock falls reaching the highway (Figure 10).

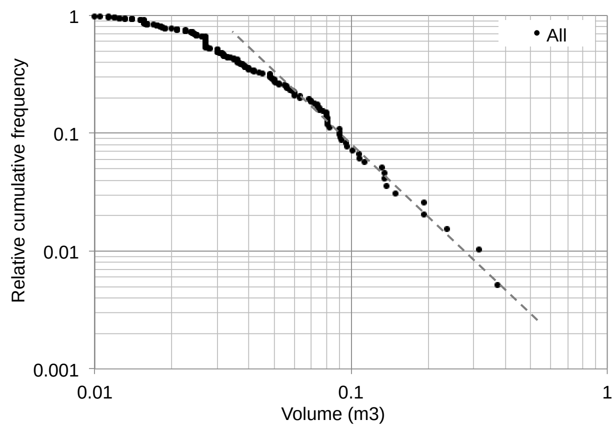

Figure 9. Relative cumulative frequency of surveyed blocks at the toe of the S042 rock slope

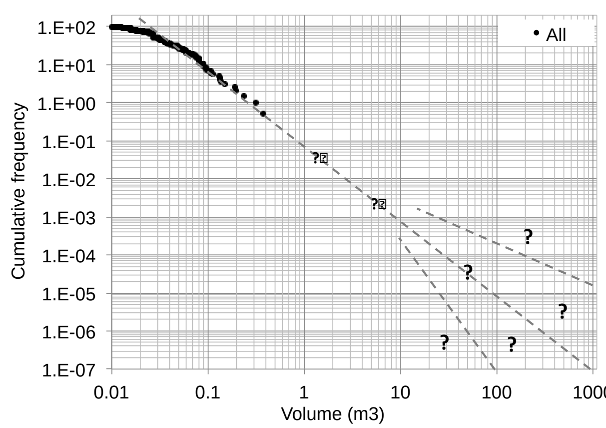

Figure 10. Cumulative frequency of blocks reaching the highway

There is much uncertainty regarding extrapolation of the best fit lines in Figure 10 to volumes over 10 and 100 m^3. There are less than a handful of blocks visible at the S042 site that suggests failures larger than 100 m^3. It can be argued that this is representative of the post-glacial activity of the slope (approximately 10,000 years), which would correspond to a frequency of 10^{-4} per year. These frequencies are only crude estimates of past activity, and current slope deformation processes and level of rock mass disaggregation need to be considered for estimating the likelihood of failures larger than 100 m^3. This information, the field observations described and the frequencies in Figure 10 were used to elicit failure likelihoods and estimate probabilities for different ranges of rock slope failure volumes reaching and potentially blocking the highway. These are summarized in Table 3. Likelihoods for rock fall volume ranges are calculated from Figure 10 by subtracting the cumulative frequency of the upper volume boundary from the cumulative frequency of the lower volume boundary. Table 3 includes the rationale behind the selected frequencies.

Table 3. Estimated and elicited frequencies of block volumes that can potentially reach the highway

Block volume (m^3)	Estimated frequency (per year) of blocks reaching the highway	Justification	Observations
Less than 0.1 m^3	90	Relative cumulative frequency scaled to estimated number of blocks reaching the highway.	Data driven.
0.1 to 0.5 m^3	10	Relative cumulative frequency scaled to estimated number of blocks reaching the highway. Surveyed data extrapolated to 1 m^3.	Data driven.
0.5 to 1 m^3	0.2	Relative cumulative frequency scaled to estimated number of blocks reaching the highway. Surveyed data extrapolated to 1 m^3.	Data driven and minor extrapolation.
1 to 10 m^3	About 0.1 (one block every 10 years)	Relative cumulative frequency scaled to estimated number of blocks reaching the highway, extrapolated surveyed data and experienced opinion.	equivalent to one 1 m^3 to 2.15 m^3 block. Based on extrapolation and experienced opinion (similar contexts). frequency can be conservative given the history of the site (one occurrence in recent history).
10 to 100 m^3	closer to 0.01 (one every 100 years) or less	Relative cumulative frequency scaled to estimated number of blocks reaching the highway, extrapolated surveyed data and experienced opinion.	Much uncertainty associated with this estimate. Large blocks embedded on talus suggest disaggregated blocks from large failures would tend to stop before reaching the highway and minimize the volume with the potential to block it.
Larger slope instabilities (up to 1000 m^3)	Uncertain. Up to 0.01 annual probability for risk assessment purposes.	Experienced opinion, large blocks embedded on talus.	Much uncertainty associated with this estimate. Large blocks embedded on talus suggest disaggregated blocks from large failures would tend to stop before reaching the highway and minimize the volume with the potential to block it. Probability adopted for risk assessment purposes correspond to levels of disaggregation of some large blocks in zones A, B and D. Extrapolating the survey data is not considered adequate for these volumes.

4.2 Runout distance

Rock fall trajectory simulations in 2 dimensions were used to estimate the run-out distance, bouncing height and kinetic energy generated by falling, bouncing and rolling blocks. The software RocFall (Rocscience Inc., 2013) was used for these analyses. The software models free fall of boulders along parabolic trajectories, the impact of boulders with the ground and the subsequent rebound, and rolling of the boulders. The simulations were done for six representative sections along the S042 rock face (Figure 11).

Rock fall initiation was selected at different heights of the rock face with an initial horizontal velocity of 0.1 m/s. Surface parameters could not be calibrated due to the lack of reliable field evidence of block runout distances. Consequently, typical values from the literature (Macciotta et al. 2011) were used (Table 4). Friction angles of 15° and 20° were used for hard rock surfaces and talus surfaces, respectively, in order to account for the angularity of observed blocks and the micro-topographic not accounted for because of the resolution of the photogrammetry model. These parameters were considered representative of the trajectory that the blocks with representative volume of 0.3 m^3 would follow.

A typical section (cross section 3 in Figure 11) with the results of the trajectory model output for existing conditions is shown in Figure 12. This figure clearly indicates the potential for blocks (0.3 m^3) reaching the road at various heights (and velocities), which is consistent with observations discussed earlier.

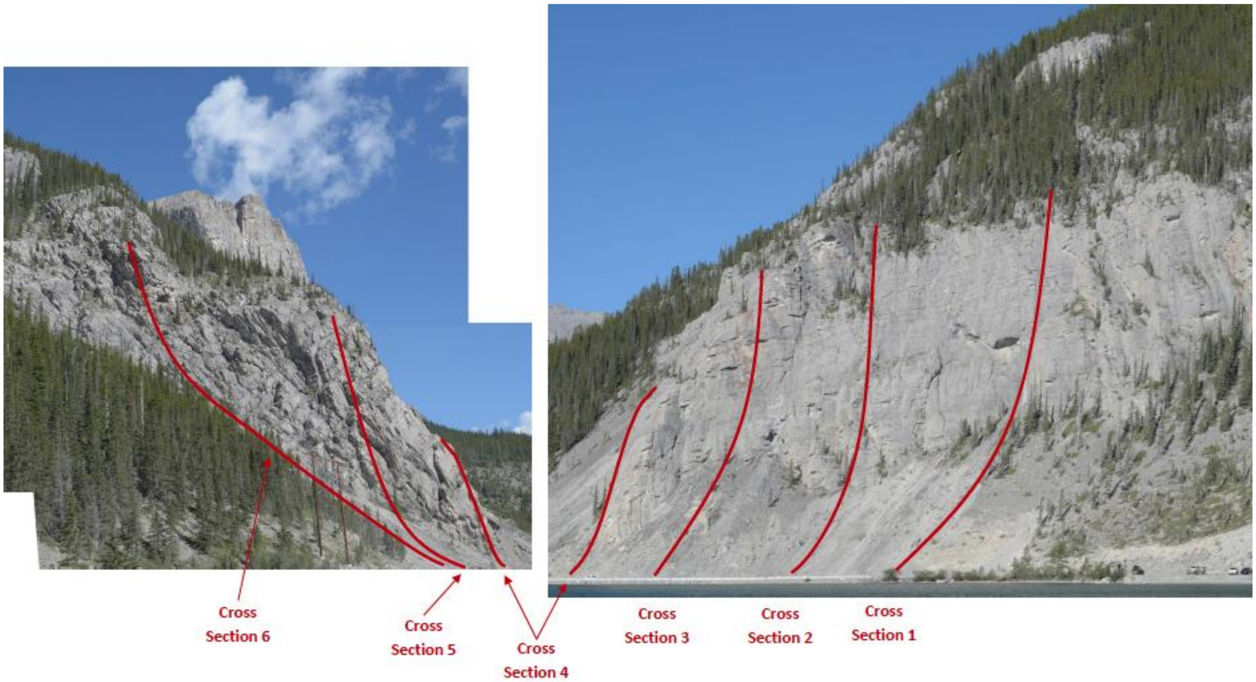

Figure 11. Cross sections selected for run out analysis of fallen debris

Table 4. Input surface parameters used for the 2-dimensional trajectory simulations

Input Parameter	Hard Rock Surface		Talus Surface	
	Mean	Standard Deviation	Mean	Standard Deviation
Normal Coefficient of Restitution, Rn	0.40	0.04	0.30	0.04
Tangential Coefficient of Restitution, Rt	0.85	0.04	0.70	0.04
Friction Angle	15	2	20	2

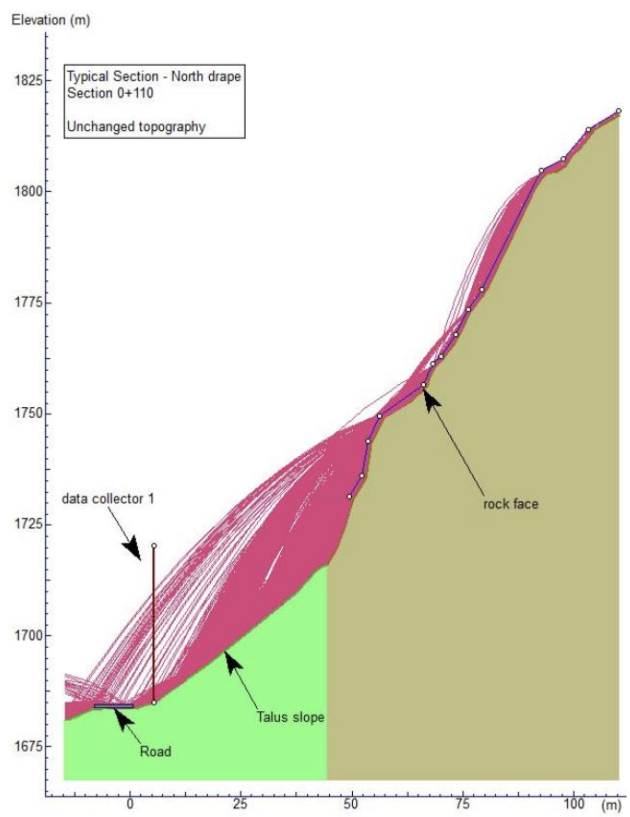

Figure 12. rock fall trajectory model output for existing conditions.

4.3 Hazard Levels

Based on the characterization and analysis presented in the previous sections, two rock slope related hazards are predominant: falling of individual blocks with an average volume of 0.3 m^3, and rock mass failures with volumes up to several thousands of cubic meters, sliding along complex failure surfaces. Based on the estimated failure volume-frequency relationships and the trajectory model heights and paths, hazard levels can be estimated for the different volume scenarios (Table 5).

4.4 Mitigation options and evaluation

The proposed mitigation options and their evaluation consider: 1) the perceived hazard level in Table 5, 2) the potential for larger slope failures, and 3) wildlife and recreational activities. The options for rock slope mitigation and their evaluation are presented in Table 6.

Table 5. Perceived hazard levels for rock slope failure volumes at S042

Block volume (m^3)	Perceived hazard level	Justification
Less than 0.1 m^3	Medium	High frequency, small blocks can injure people
0.1 to 0.5 m^3	High	High frequency, can injure (severely) people inside large vehicles
0.5 to 1 m^3	Medium	Lower frequency, can injure (severely) people inside large vehicles
1 to 10 m^3	Medium to low	Low frequency
10 to 100 m^3	Low	Low frequency, will likely disaggregate in smaller blocks. Provide indication of failure before release
Larger slope instabilities (up to 1000 m^3)	Very Low	Very low frequency, will disaggregate in smaller blocks. Provide indication of failure before release

Table 6. Proposed mitigation strategies

Strategy	Evaluation
Scaling/spot bolting	Suitable and effective for blocks 1 to 10's of m^3 in volume. Would reduce likelihood.
Catchment ditch	Effective however limited area between highway and talus slope. Could require stabilized cut in talus.
Barrier	Effective option at toe of talus. Can reach up to 5000 kJ in energy dissipation for large failures that disaggregate in multiple blocks (if addressing the large volume, lower hazard levels is required).
Hanging drapery and attenuators	Would be required to limit falling block heights (blocks up to 0.5 m^3 could gain lateral momentum and overcome barrier height). Placement should balance the areas requiring channeling blocks towards the toe of the slope and wildlife activity as well as recreational activities.
Monitoring	Required to provide insight into the state of activity of the larger disaggregated masses observed.
Increased awareness	Clear signaling for increased awareness of road users, hikers, climbers, etc. in the area

5 CONCLUSIONS

This paper presented an explicit estimation of rock slope failure likelihood for hazard assessment and safety engineering near Canmore, AB. The likelihood estimation was based on field observations, kinematic analyses, field surveys and personnel experience. These, together with insights into the runout characteristics of the fallen material, provided a means to evaluate the hazards associated with different slope failure volumes. This paper described these procedures in detail. Based on the hazard assessment and the known wildlife and recreational activities at the site, safety engineering options were evaluated for further consideration. The work presented here is the first stage in a risk-based approach for rock slope safety engineering at site S042, currently being developed.

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