MISSION-FOCUSED RISK MAPPING FOR AVALANCHE CONTROL IN GLACIER NATIONAL PARK

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ABSTRACT: Avalanche control for the Trans-Canada Highway (TCH) and Canadian Pacific Kansas City Railway through Rogers Pass in Glacier National Park (GNP) relies on an extensive artillery program using 105 mm howitzers fired from roadside positions, delivered via a partnership between Parks Canada and the Canadian Armed Forces. During control missions, a Parks Canada Mountain Safety Team (MST) forecaster directs artillery fire and observes results from a vehicle on the closed highway, sometimes adjacent to or within the target avalanche path. Since 2011, there have been two incidents where artillery-controlled avalanches have impacted and buried an MST vehicle, fortunately without serious injuries.

Following the most recent incident, Parks Canada requested linear risk mapping to better manage exposure during control missions. This paper summarizes methods used to develop risk mapping for the TCH corridor and gun positions to support MST risk management decisions, and the resulting benefits during operational use. Quantitative risk was classified into four classes based on suggested natural-hazard thresholds in Canada and assigned corresponding risk ratings. Mapping was based on 60 years of avalanche occurrence records to estimate avalanche probability, together with field observations collected at a minimum of 50 m intervals along the highway. Worker vulnerability considered entrained timber and the consequences of steep terrain below the roadway. Results are presented independently for the north and south sides of the valley, allowing the MST forecaster to adjust their position once one side has been controlled.

The mapping is paired with an internally developed avalanche control Risk Level Framework (RLF), which is used to evaluate mission risk for avalanche control operations based on team factors, environmental conditions, and expected avalanche character. Each risk class includes guidance linked to the RLF to support MST forecaster positioning during control operations.

The risk mapping has been used operationally over the past two winters. Key benefits include reduced reliance on visual landmarks and informal heuristics to identify “safe” observation locations, and a more objective basis for managing exposure, particularly during low visibility and nighttime operations.

KEYWORDS: Risk, artillery, avalanche, control, mapping.

1. INTRODUCTION

On January 17, 2022, two Parks Canada vehicles occupied by Forward Observers (FO) were struck by a Size 4 avalanche triggered during artillery avalanche control operations in Glacier National Park (GNP). Both vehicles were destroyed, and fortunately the occupants only sustained minor injuries. This was the second known incident involving burial of an FO vehicle during artillery control operations, after a similar event in 2011.

Following the incident, Parks Canada completed an after-action review to examine the circumstances of the event and identify measures to reduce the risk of a similar occurrence. Recognizing the inherent exposure of the FO role during mobile artillery avalanche control, Parks Canada engaged a consultant to provide updated avalanche path mapping and prepare linear risk mapping along the highway to better manage exposure during control missions.

This paper describes the contributing factors identified through this process, the methods used to complete the risk mapping, the operational application and the benefits to worker safety that have been realized following implementation during mobile artillery avalanche control operations in GNP.

2. BACKGROUND

Glacier National Park (GNP) includes a 43 km section of the Trans-Canada Highway (TCH) and Canadian Pacific Kansas City (CPKC) railway

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where the corridor crosses the Selkirk Range at Rogers Pass (1,330 m a.s.l.). This transportation corridor is exposed to 134 mapped avalanche paths, which affect approximately 26 km, or 63%, of the highway through the park. In several locations, the highway is exposed to avalanche hazard from both sides of the valley.

Rogers Pass is a critical Canadian transportation corridor, with average winter traffic of approximately 4,500 vehicles per day, of which over 50% are commercial vehicles, and 32–34 trains per day. Highway traffic continues to increase at approximately 1-2% annually. The economic cost of disruptions is substantial, with each hour of closure of the corridor impacting the movement of an estimated CAD $4 million in goods (Statistics Canada, 2018).

Avalanche risk is managed through a combination of mobile artillery avalanche control, remote avalanche control systems (RACS), and helicopter control. Approximately 95% of avalanche control in GNP is conducted using 105-mm howitzers operated through a partnership with the Canadian Armed Forces. Artillery is deployed from established gun positions to fire more than 250 avalanche targets distributed throughout the corridor. The principal advantage of artillery is reliability: control can be completed in most weather conditions and at any time of day. RACS installations provide additional control capability, while helicopter control is used for selected terrain and operational circumstances.

The reliability of mobile artillery control is offset by increased operational complexity and worker exposure. A typical mission requires coordination of gun crews, closure personnel, and other operations personnel, such as snowplow operators, moving along the highway with exposure to avalanche hazard. The FO is central to this process, selecting targets, directing fire, observing avalanche response, coordinating personnel movement, and communicating with external agencies such as CPKP and adjacent highway authorities. These real-time observations directly inform subsequent target selection, sequencing, and control intensity, which are essential to reducing avalanche hazard while minimizing closure duration.

The FO role creates a distinct exposure profile because effective observations often require proximity to avalanche runout zones. The resulting risk is compounded by the need for continuous situational awareness. The FO relies on visual and auditory observations, supplemented by the infrasound and radar detections from the extensive Avalanche Detection Network (ADN), to observe avalanche activity and evaluate control results. Obtaining useful observations can therefore conflict with minimizing exposure, creating an inherent tension between operational effectiveness and worker safety. The associated risk has been demonstrated by the incidents in 2011 and 2022.

This paper describes the worker safety mitigations developed and implemented for FOs in GNP, central to which is the linear risk mapping, and its application within the operational framework for mobile artillery avalanche control.

3. AVALANCHE RISK MAPPING

Linear risk mapping was developed along the TCH to support FO positioning during artillery control operations. Methods included a review of avalanche, landslide and rockfall risk assessment methods, field observations at 50 m intervals (with intermediate points as needed) along the highway, avalanche occurrence data analysis, dynamic modelling of select paths and updated avalanche path mapping completed at a 1:2,500 scale using high resolution imagery and LiDAR-derived terrain data. Quantitative risk was estimated at each field observation point and at each gun position, then classified into four semi-quantitative risk classes for corridor mapping.

3.1 Quantitative Avalanche Risk

Avalanche risk was expressed as the average annual probability of death for an individual positioned at a given location during artillery avalanche control. For FOs, the individual was assumed to be inside a vehicle on the closed highway. For gun positions, where 10 or more personnel may be present and working on foot during control operations, the analysis considered the increased vulnerability of workers on foot. Risk at gun positions was expressed as the probability of one or more fatalities; broader group-risk, including the most likely or maximum number of fatalities, was not evaluated.

Risk was estimated using the following equation:

$$\mathrm{Risk}_j = \Sigma\, \mathrm{P(H)}_i \times \mathrm{P(S|H)}_{i,j} \times \mathrm{P(T|S)}_{i,j} \times \mathrm{V}_{i,j}$$

where Risk_j is the probability of death at location *j*; $\mathrm{P(H)}_i$ is the average annual probability of avalanche scenario *i*; $\mathrm{P(S|H)}_{i,j}$ is the spatial probability that scenario *i* impacts location *j*; $\mathrm{P(T|S)}_{i,j}$ is the temporal probability that the worker is present at location *j* when the avalanche reaches the highway or gun position; and $\mathrm{V}_{i,j}$ is the vulnerability, or probability of fatality, given impact by avalanche scenario *i* (Jamieson, 2018, EGBC, 2023). Temporal probability was assigned a value of 1, since the observer was assumed to be stationary at location (j) when avalanche scenario (i) is triggered by artillery control.

Three avalanche scenarios were chosen based on the Avalanche Hazard Index method (Schaerer, 1989): powder avalanches, light flow avalanches (between 0.3 m and 1 m in depth across the highway) and deep flow avalanches (greater than 1 m in depth across the highway).

Annual probability P(H) is commonly communicated as a return period, which is the reciprocal of the annual probability. Avalanche return period was estimated in a range from 1 to 100 years for this assessment (and up to 300 years for gun positions), based on analysis of avalanche occurrence records, topography and vegetation damage observed in the field or in imagery. Return periods are generalized to an average return period of either 1, 3, 10, 30 or 100 years (and 300 years for gun positions) for each of the three avalanche types (scenarios) considered in this assessment (powder, light and deep flow).

Spatial probability was estimated from the expected likelihood and extent of avalanche impact at each mapped location. Where historical deposit mapping was available, mapped avalanche deposits were reviewed in GIS and the number and extent of overlapping deposits along the highway were used to guide spatial probability estimates (Figure 1). Spatial probability values ranged from 0.1 to 0.8, where a value of 1 would represent a location impacted by all avalanches from the relevant path or scenario.

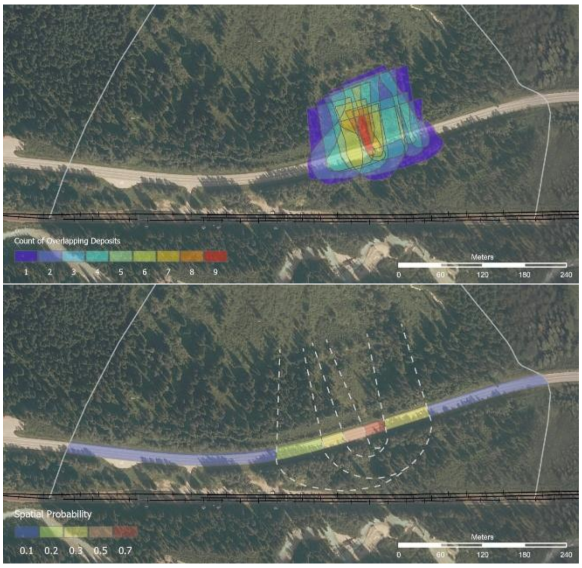

Figure 1. Historical avalanche deposit mapping with sum of overlapping deposits. Colour scale shows low values (dark blue) to high values (red). A total of 12 deposits were mapped in this example, with a minimum of 1 deposit to a maximum of 9 overlapping deposits, implying a range of spatial probability P(S|H) of 0.08 (1/12) to 0.75 (9/12).

Vulnerability values were assigned for each avalanche scenario based on published values summarized by Jamieson (2018), with separate values for a person inside a vehicle and a person on foot (Table 1). Vulnerability was lowest for powder avalanche impacts and highest for deep dense-flow avalanche impacts. Two additional site-specific factors were incorporated for deep flow avalanches: woody debris and steep slopes below the roadway. Woody debris can increase impact severity and complicate rescue excavation, while steep slopes or creeks below the highway can increase burial depth and rescue time if a vehicle or worker is pushed off the road. Each factor was rated using a four-class scale and applied as a multiplier (Table 2) to the deep-flow vulnerability value. These multipliers were not applied to light flow avalanches, which are less likely to entrain hazardous woody debris or displace a vehicle from the roadway. Powder avalanche vulnerability was considered to already account for debris impact potential.

Table 1. Vulnerability values for powder, light and deep avalanche flow.

Avalanche Scenario	***Vulnerability***	
	In Vehicle	***On Foot***
Powder flow	0.03	0.05
Light flow	0.10	0.19
Deep flow	0.23	0.43

Table 2. Vulnerability multipliers for woody debris and steep slopes.

Description (Forest Cover / Steep Slope)	***Vulnerability Multiplier***
No forest cover / Flat	1.0
Sparse forest cover or small trees / Short steep slope (e.g., fill slope)	1.1
Intermediate density, some large trees / Long steep slope, or creek/river at base	1.3
Dense, mature forest High consequence steep slope (e.g., bridge, long slope)	1.45

3.2 Risk Guidelines, Acceptable Risk and Risk Classification

Calculated risk values were classified into four risk classes using suggested Canadian natural-hazard thresholds and workplace risk as guidance, including criteria discussed by Porter and Morgenstern (2013), APT (2014), Strouth and McDougall (2020), WorkSafeBC (2021), and EGBC (2023). Because forward observing is a skilled, voluntary occupational activity, thresholds were adapted from those used for involuntary public exposure. A PDI of 1×10^{-4} was selected as the upper threshold for negligible risk, while a PDI greater than 1 × 10^{-2} was classified as high risk. The intermediate range was divided into low and medium risk classes, representing conditions where risk may be tolerable if reduced to as low as reasonably practicable (ALARP).

Each mapped risk class was assigned a corresponding qualitative rating and operational guidance phrase (

Table 3). The risk classes were also linked to the avalanche control Risk Level Framework (RLF), a tool internally developed by Parks Canada to evaluate mission risk based on team factors, environmental conditions, and expected avalanche character. This linear risk mapping, when paired with the RLF, provides a direct connection between the spatial distribution of avalanche risk and the operational mitigations associated with each risk level. Together, the mapping and RLF provide an objective basis for FO positioning during artillery control and allow positions to be adjusted as control progresses, including separate consideration of avalanche exposure from the north and south sides of the valley (Figure 2).

Table 3. Risk thresholds and qualitative ratings applied for Forward Observer avalanche risk mapping.

Risk Threshold (PDI)		***Risk Term***	***Color Code***	***Guidance Phrase***	***Avalanche Control Risk Level***
≤ $1x10^{-4}$	≤ 1:10,000	Negligible	Green	FO is generally appropriate in all conditions.	Use at Risk Levels 1-3 appropriate.
>$1x10^{-4}$ to ≤ $1x10^{-3}$	>1:10,000 to ≤ 1:1,000	Low	Yellow	FO is not recommended during times of unpredictable avalanche character (e.g., unexpected natural events, long-return period natural and artillery-controlled events).	Use at Risk Level 1 and 2 appropriate. Use not recommended at Risk Level 3.
>$1x10^{-3}$ to ≤ $1x10^{-2}$	>1:1,000 to ≤ 1:100	Medium	Orange	FO not recommended during times of unpredictable avalanche character and/or in areas without previous hazard reduction.	Use at Risk Level 1 appropriate. Use at Risk Level 2 requires site-specific evaluation. Use not recommended at Risk Level 3.
> $1x10^{-2}$	> 1:100	High	Red	FO is not recommended at any time.	Use not recommended at any Risk Level.

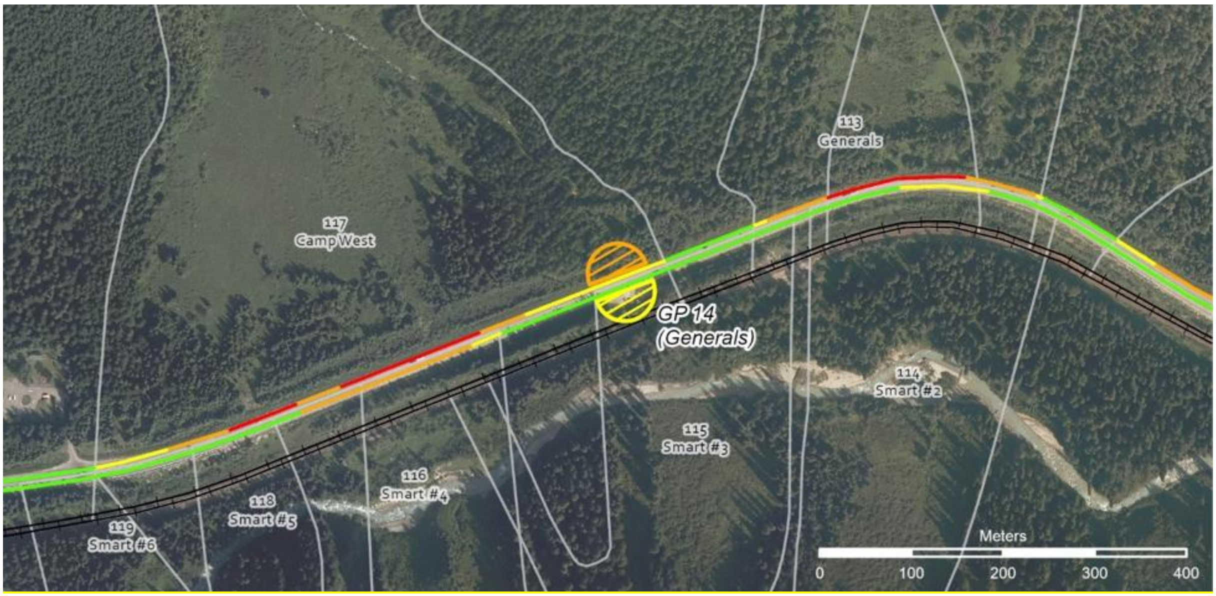

Figure 2. Example of the Forward Observer avalanche risk mapping.

4. OPERATIONAL APPLICATION AND RISK LEVEL FRAMEWORK

Historically, worker safety during avalanche control relied primarily on the experience and judgment of individual avalanche forecasters. This approach allowed experienced personnel to adapt effectively to changing conditions and operational demands; however, it depended heavily on tacit knowledge and on each forecaster's ability to recognize, interpret, and integrate multiple sources of information in real time. As a result, the approach was not consistently applied within teams with varying levels of experience. It was also subject to degradation when situational awareness was challenged by distractions, competing operational priorities, prolonged missions, fatigue, rapidly changing conditions, or cognitive bias.

Reliance on operational experience also presents a particular challenge when considering low-frequency, high-consequence events. Avalanche events with return periods of 30 years or more often fall outside the direct experience of even the most experienced forecasters. In these circumstances, historical records alone provide a limited reference for anticipating the spatial extent and potential consequences of rare avalanche events. A framework was therefore developed to support decision-making beyond the limits of individual operational experience.

The RLF was developed to provide a common structure for assessing and communicating risk during avalanche control operations. It supports four primary functions: (1) assigning an operational hazard level to each avalanche control mission; (2) communicating the hazard level to personnel involved in the mission; (3) identifying when the hazard level is changing during an operation; and (4) selecting appropriate mitigations to maintain operations within the defined operational risk band. A simplified example of the RLF is shown in Table 4.

Each risk level considers a combination of environmental, human and operational factors, and expected avalanche activity. Environmental factors may include avalanche hazard, weather, visibility, snowpack conditions, and the potential for avalanche activity in areas occupied or traversed by personnel (such as uncontrolled sections of the highway). Human and operational factors include personnel experience, fatigue, transportation requirements, mission duration, competing priorities, and the ability of personnel to respond to changing conditions. Each risk level is associated with actions to mitigate risk, either by reducing the probability of exposure or the potential consequences of an avalanche event.

The RLF is designed as a decision-support tool rather than a prescriptive set of rules. It does not replace the professional judgment of the avalanche forecaster or FO, nor does it prescribe a single operational response to a particular set of conditions. Instead, it provides a shared mental model and common language for recognizing changes in risk, selecting appropriate controls. This is particularly important where conditions are evolving rapidly or where competing operational objectives must be balanced. The framework allows experienced personnel to apply their judgment while providing less-experienced forecasters with a structured basis for decision-making.

Table 4. A simplified example of the avalanche control Risk Level Framework (RLF), a tool internally developed by Parks Canada to evaluate mission risk based on team factors, environmental conditions, and expected avalanche character

Risk	***Protocol***	***Triggers***	***Actions***
1	Basic	Daytime; low weather input; low snow volume; rested staff; avalanches stop well above highway.	Local closures appropriate. Maintenance unrestricted. Training permitted.
2	Advanced	Limited visibility/night; active weather; seasonal snow volume; limited staffing reserve; high traffic; avalanches reach runout/dust highway.	Revelstoke–Golden closure. Vehicle tracking. Restrict uncontrolled travel. Standard two-gun procedure. Control before stationary work. Plan staffing for next operational period.
3	Extreme	Continued loading or rapid wet avalanche transition; second operational period <48 hours; poor visibility/night; high snow volumes; wind masking sound; unexpected naturals; avalanches reach highway; long-return period events; vehicle or rescue involvement.	Revelstoke–Golden closure. No uncontrolled travel. Essential personnel only. Vehicle tracking. Single gun procedure. Defensive positions. Control before rescue or stationary work. Plan staffing for next operational period.
4	Full Closure	Extreme weather; unsafe travel; conditions beyond team experience; multiple climax avalanches.	Suspend operations. Keep all personnel in safe areas. Plan staffing for next operational period.

Prior to a mission, the RLF is used to assess the anticipated level of risk and identify appropriate mitigations. The resulting risk level and associated controls are then communicated to personnel during the mission briefing. Risk mapping provides the spatial component of this assessment, allowing personnel to identify areas of greater or lesser exposure and to consider this information when planning personnel movements and FO locations.

The risk mapping is loaded onto tablets used by Forward Observers in the field (Figure 3). This allows FOs to view their position relative to mapped avalanche hazards and refine their operating locations as conditions evolve. The spatial information is particularly valuable during nighttime operations and storm conditions, when visibility may be severely reduced, and visual identification of avalanche paths and runout zones is difficult. In these circumstances, the digital risk map provides an additional source of situational awareness that is independent of visual cues.

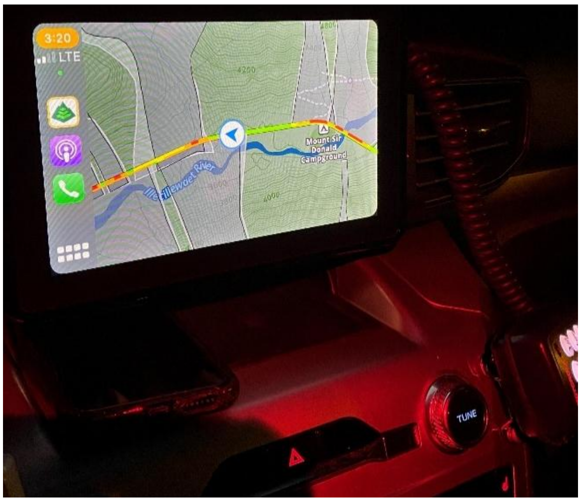

Figure 3. Nighttime control operations with risk and avalanche path mapping and the FO location shown on the dashboard mounted table in the FO vehicle.

The ADN provides a further source of real-time information to support FO decision-making. Automated avalanche detections can alert the operational team to avalanche activity that may not be immediately visible or audible from the FO location. Combined with direct observations, the ADN provides information that can be used to reassess the evolving hazard, inform subsequent target selection, and determine whether personnel can safely move through or occupy avalanche paths.

The integration of the RLF, risk mapping, and real-time avalanche detection via the ADN creates a layered decision-support system. The RLF provides a common framework for assessing and communicating operational risk; risk mapping provides spatial context for that risk; and the ADN provides real-time information on avalanche activity. Together, these tools support the FO in maintaining situational awareness, adapting operational mitigations as conditions change, and, ultimately, reducing avalanche risk to the FO and other operational personnel. Importantly, they are intended to augment, not replace, the experience, judgment, and continuous reassessment required for safe mobile artillery avalanche control.

5. DISCUSSION

The development and implementation of the avalanche risk mapping and the RLF provide a more structured approach to managing worker exposure during mobile artillery avalanche control. The tools make elements of tacit knowledge more explicit and accessible to the broader operational team. Risk mapping provides spatial information to support FO positioning where safe locations are limited, while the RLF provides a common framework for assessing changing conditions and identifying appropriate mitigations. Together, they improve risk communication, decision making and provide less-experienced personnel with a consistent basis for decision-making without replacing professional judgment.

This approach also helps address risks beyond the experience of individual forecasters. The risk mapping incorporates long-return-period avalanche scenarios, prompting explicit consideration of low-frequency, high-consequence events. Integration of the mapping with the RLF allows spatial exposure and changing operational conditions to be considered together, particularly during prolonged missions, nighttime operations, and storms when visibility and situational awareness may be reduced. Tablet-based mapping and real-time information from the ADN provide additional sources of information to support reassessment of FO positioning and personnel movement.

The primary value of the system is not eliminating operational risk, which is not feasible, but providing multiple layers of decision support to reduce worker exposure. Quantitative risk assessment provides the basis for risk classification, while the risk mapping and RLF translate this information into practical operational tools. The framework remains intentionally non-prescriptive, allowing professional judgment and adaptation to conditions that cannot be fully captured by a model. The experience in GNP demonstrates that quantitative risk assessment can be translated into practical tools that improve the consistency of worker-safety decisions while maintaining the effectiveness of mobile artillery avalanche control.

6. CONCLUSION

The FO role during mobile artillery avalanche control presents an inherent challenge: FOs must maintain sufficient proximity to avalanche terrain to support effective, real-time control while minimizing their own exposure to the hazard. Past incidents demonstrated the consequences of this exposure and highlighted the need for a systematic approach to FO safety.

The combination of quantitative risk assessment, linear risk mapping, and the RLF provides a practical means of incorporating spatial and operational risk into avalanche control planning, decision-making and execution. The tools support the selection of lower-exposure FO locations based on the overall risk profile of the control mission, they provide a framework for adapting mitigations as conditions evolve, while retaining the professional judgment required for complex avalanche control operations.

The experience in GNP demonstrates that risk assessment can be translated into practical field tools that support worker safety without compromising the reliability and effectiveness of mobile artillery avalanche control. Continued evaluation of operational experience, incidents, and near misses will be important to refine the framework and ensure that mitigations remain appropriate as operational practices and technology evolve. This approach may also have application to other avalanche programs where workers must operate within or in close proximity to avalanche terrain while supporting transportation corridors, critical infrastructure and public safety.

7. ACKNOWLEDGEMENTS

The authors would like to thank Alan Jones (Dynamic Avalanche Consulting) who provided senior review of the risk mapping project, Jaime Sanderson (Project Manager - McElhanney), and the Mountain Safety Team in Glacier National Park for their candor and thoughtful reflection, which contributed to the development of the Risk Level Framework and continues to drive program improvements.

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