SELECTION CRITERIA FOR SNOW AVALANCHE MITIGATION MEASURES CONSIDERING OTHER POTENTIAL GEOHAZARDS: EXAMPLES FROM COLORADO AND CANADIAN HIGHWAYS

Dave Gauthier[1]*, Alex Strouth[1], and Mark Vessely[2]

[1]BGC Engineering, Golden, CO, USA
[2]Shannon Wilson, Denver CO, USA

ABSTRACT: While unique in many ways, snow avalanches are one of many potential geologic/natural hazards (geohazards) which threaten transportation and energy corridors, mine sites, etc., across the mountainous regions of the world. However, snow avalanche assessment and mitigation design often occur without consideration for other geohazards that often exist in the same location, and vice versa. Overlapping geohazards may include debris flow, icefall, rock fall, and landslides. Along Colorado highways there are many snow avalanche paths which overlap other recognized geohazards, and a similar set is recognized in Canada. In fact, recent structural mitigation efforts in both countries have encountered this issue. In this paper we consider some scenarios in which different geohazards overlap with snow avalanche in Colorado and Canadian settings, and present a preliminary set of criteria for decision-support in selecting snow avalanche risk mitigation measures, with consideration for other potential geohazards and mitigation options that can either benefit or adversely affect other hazards. We cite examples from Colorado and Canada where mitigation selection would benefit from this sort of decision-support, and lay the groundwork for establishing the value of multi-geohazard mitigation considering risk reduction and life-cycle costs.

KEYWORDS: Mitigation, geohazard, risk

1. INTRODUCTION

While unique in many ways, snow avalanches are one of many potential geohazards which threaten transportation and energy corridors, mine sites, etc., across the mountainous regions of the world. However, snow avalanche assessment and mitigation design often occur without consideration for other geohazards that may exist in the same location, and vice versa. Overlapping geohazards may include debris flow, icefall, rockfall, and landslides, etc. Along Colorado highways there are many snow avalanche paths which overlap other recognized geohazards, and a similar situation is recognized in Canada.

2. OVERLAPPING GEOHAZARDS

Cruden and Varnes (1996) defined the various types of geohazards – including snow avalanche – based on the materials involved and the style of the movement. The materials include earth, debris, rock, snow and ice, etc., and the style of movement includes fall, slide, flow, and avalanche, among others. Of course the majority of these require steep slopes and a ready supply of materials, as well as relevant triggers. Such conditions typically exist in mountainous regions, and in many cases a given location may be exposed to more than one type of geohazard. For example, many large snow avalanche paths are subject to intense and damaging debris flows in the spring and summer, and many open slopes will produce both debris slides and snow avalanches periodically. Rock falls and slides may release from steep avalanche start zones, or may run out into lower elevation avalanche terrain, for example along talus slopes. Kappes et al. (2012) review many of the challenges associated with multi-hazard scenarios; here, we consider avalanche mitigation as a starting point, and examine the practical approach to managing exposure to other geohazards effectively and efficiently at the same location.

With increasing development pressure in mountainous areas, as well as increasing need for network reliability - particularly for energy and transportation corridors – it is becoming much more common to find new projects forced into difficult or hazardous terrain that have been previously avoided. Our focus here is on examples from Canada and Colorado, but of course these scenarios play-out all over the world.

* *Corresponding author address:*
Dave Gauthier, BGC Engineering
Kingston, ON Canada
tel: 613-893-4920
email: dgauthier@bgcengineering.ca

2.1 Canada

The Canadian context for this problem may be best illustrated through an example of a critical component of some linear energy of transportation infrastructure which is under development. Most of the key corridors for power and data transmission, pipelines, highways, and railways are aligned east-west, and therefore must traverse the Canadian Cordilleran ranges across their mostly north-south alignment. This means long ascents and descents in progressively steeper and more exposed valley bottoms. Currently there are a number of pipelines and power lines in various design stages, all of which have issues with multiple overlapping geohazards. Figure 1 is an example of such a place; there is already a highway in this valley, protected by various types of snow avalanche mitigation (berms, walls, sheds, explosives, closures, etc.). New linear infrastructure would have a different set of elements at risk (e.g. travelling public and loss of life, versus pipeline valve and loss of oil containment), and therefore a different approach to avalanche mitigation would be required.

Fig 1: Hypothetical example from Canada, showing the proposed permanent location of an element of critical infrastructure, with exposure to several geohazards.

2.2 Colorado

The Colorado Department of Transportation (CDOT) has started evaluating avalanche sites for active hazard reduction such as remote detonation systems and structural elements. At some of these sites there also is a documented history of impact from hazards including rockfall and debris flows. For example, Figure 2 presents the location of a scarp from debris flow above U.S. 40 on Berthoud Pass that is also located in an area where avalanches occur due to the steep, poorly vegetated cut slope. Additionally, this site also generates rockfall from the scarp area. In response to the debris and rockfall hazard, a low energy rockfall fence was installed in 2010 to reduce the potential for rock to reach the road. However, the fence was not effective at reducing the avalanche hazard and not capable of accommodating avalanche loads, which was not the original intent (Figure 3). As a result, CDOT is evaluating future hazard mitigation projects to consider improvements or adverse impacts to other hazard types. For example, anchored slope mesh has been considered for the subject site on U.S. 40; however, there are concerns that this could increase the avalanche hazard due to sliding along the mesh interface. As a result, other mitigation approaches may be installed to maximize the hazard reduction for both snow and earth slope hazards.

Fig. 2: Debris flow site located on U.S. 40 in an area with a hazard from bank slope avalanches.

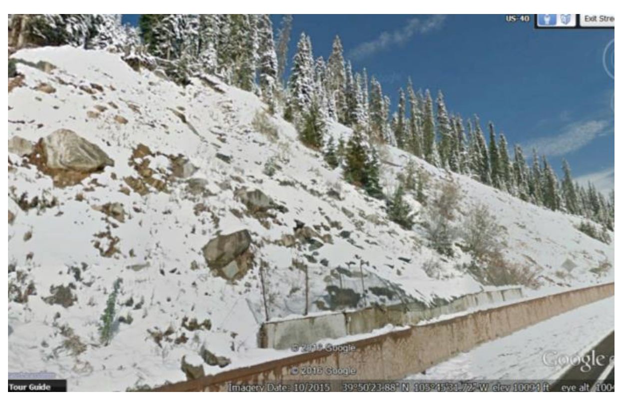

Fig. 3: Damaged rockfall fencing installed at subject site in Figure 2.

3. MITIGATION OPTIONS

Mitigation measures intended to reduce risk to a given piece of infrastructure (e.g. a power-transmission pylon or pipeline valve station), including infrastructure exposed to snow avalanche hazards, can be grouped into one of three broad categories:

- Avoidance, where the element at risk is placed out of the reach of the hazard
- Stabilization or removal of the hazard, to reduce the likelihood that it will occur
- Protection of the elements at risk, to reduce the consequences of the hazard on the element

Figure 4 highlights more specifically some of the common types of mitigation measures and their potential impact on the hazard associated with rock fall, debris slide, and debris flow. This is not a thorough treatment, and is mostly intended to illustrate the idea that a given mitigation that may be effective for avalanche (e.g. gas exploder) may actually generate a more serious hazard of another type (e.g. rock fall, through disturbance of the rockmass). Figure 4 would look different for every actual scenario.

In some cases, the avalanche mitigation measure may be only partly effective for a different hazard. As an example, a rolling or bouncing rock may sometimes be stopped when it encounters an avalanche catch net; however, a rock fall catch net would often be designed to resist much higher local stresses (or energy), which means that some rock falls would penetrate or destroy an avalanche net designed for relatively low energy impacts (e.g. Gleirscher and Fischer, 2014; Brändle et al., 2014). The reverse may also be true, in cases where the high impact energy resistance of a rockfall catch net is not optimized for the high stresses and flow depths possible in snow avalanche impacts (e.g. Margreth and Roth, 2008).

Any owner interested in reducing avalanche hazard to a particular location or piece of infrastructure would also seek to reduce, if possible, the other geohazards, and, more importantly, would be unlikely to move ahead with work that would generate a net increase in the total hazard or risk due to exacerbation of one or more other hazards.

Avalanche Mitigation type	Av.	Rock fall	Debris slide	Debris flow
Avoidance				
Minor changes	green	yellow	green	yellow
Removal				
Typically N/A	green	red	red	yellow
Stabilization				
SZ Support	green	green	yellow	green
Gas exploder	green	red	yellow	yellow
Hand charges	green	red	yellow	yellow
Launcher	green	red	yellow	yellow
Artillery	green	red	yellow	yellow
Protection				
Shed/gallery	green	yellow	green	green
Bench/catchment	green	green	green	green
Berm	green	green	green	green
Wall	green	yellow	green	yellow
Splitter	green	green	green	yellow
Mounds	green	green	green	yellow
Nets	green	yellow	green	yellow

Fig. 4: Comparison of mutually beneficial (green), deleterious (red), and neutral (yellow) avalanche mitigation measures, relative to rock fall, debris slide, and debris flow.

4. SELECTION CRITERIA

4.1 *Basic criteria*

At this point the selection criteria may be self-evident, but in any case are summarized below:

- The mitigation measure must reduce the avalanche hazard
- The mitigation measure should not cause another geohazard to become more hazardous
- Given a choice, the measure which reduces the total overlapping hazard the most should be selected

Selection of potential snow avalanche mitigation measures typically requires site specific assessment, and the specific factor(s) that is most important at each site typically varies based on project details. Selection criteria that should be considered include:

- Total risk reduction
- Economics
- Execution
- Environmental impacts

Total risk reduction considers how the measure reduces risk for all hazard types that are present at the site. Hazard types can include debris flow, rockfall, and other slope hazards mentioned in this paper, but for example in roadway projects, can include driving hazards related to lane width, shoulder width, driver distraction, and decision sight distance. Additionally, the measure should consider the estimated magnitude and frequency of the different hazard types, and be designed for a consistent frequency of event across the hazard types (e.g. it is not rational to design a catchment fence for a 30-year rockfall that would be destroyed by a 2-year snow avalanche). The selection process should consider the potential for, and attempt to avoid, transfer of risk from one element to other adjacent elements. Risk transfer most commonly occurs when "protection" elements, such as berms, walls, or sheds, deflect or direct avalanches, rockfalls, or flows from one element toward an adjacent element. Another common scenario is where some active measure like blasting to remove rockfall sources, or to trigger avalanches, generates new avalanche terrain, or rockfall sources.

Economic considerations include capital cost related to mitigation design and construction, in addition to operation and maintenance costs. Ideally, the total life-cycle cost of the mitigation measure would be considered. This is more relevant to snow avalanche mitigation than many other geohazard types because active monitoring and control (i.e. operation and maintenance cost) is a common, highly effective mitigation option that must be compared with other options that have high capital costs, but relatively low maintenance costs (e.g. protection options, gas exploders).

Execution refers to the practicalities of designing, permitting, and constructing the mitigation measures. Mitigation measure designs should seek to maximize confidence that the design will function as intended despite the wide ranging uncertainties that are prevalent in geohazard assessment. Similarly, designs should seek to maximize flexibility to adapt to different conditions that are encountered during construction and operation. Permitting and schedule constraints also commonly have a large influence on designs, and in some cases can dictate design selection.

Environmental impacts refer to a variety of considerations including social license to modify the landscape, aesthetic impacts, and impacts to vegetation, water resources and wildlife habitat. Environmental approval typically depends on the perceived environmental and social value of the area in relation to the perceived risk. Environmental factors can have a large influence on designs, particularly when the hazard site is located in a national park or other protected area.

4.2 *Mitigation selection framework*

Figure 5 illustrates a basic logical framework for comparison and selection of snow avalanche mitigation measures based on the criteria described above. The example is a hypothetical scenario involving an overlapping avalanche and rockfall hazard. Three snow avalanche / rockfall mitigation measures are compared, including a snow / rock shed, catchment berm / wall, and gas exploder. The snow / rock shed is ruled out because the capital cost exceeds the project budget. The gas exploder is ruled out because it potentially increases rockfall risk, and a catchment berm / wall is identified as the preferred option.

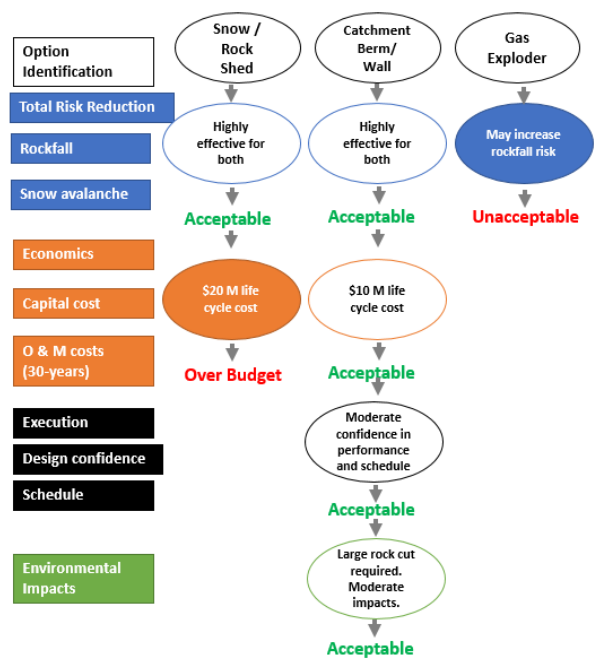

Fig. 5: Example multi-geohazard mitigation option comparison framework.

4.3 *Worked example – risk reduction and economics*

This section describes a method for economic evaluation of multi-geohazard mitigation options. This type of analysis can be used to evaluate the "Economic" selection criterion described in the previous section and in Figure 5. This analysis would be combined with assessment of the other (typically more subjective) selection criteria presented in the previous section.

Figure 6 is a worked example of a probabilistic risk reduction analysis for a single site, which is exposed to avalanche, rockfall, debris flow, and debris slide hazards. First, we estimate the total economic risk associated with all of the hazards, given an unmitigated case, as follows:

- Estimate the cost impact of total destruction of the element at risk, for example a pipeline valve station (e.g. Fig. 1)
- Consider the encounter probability over the design life (e.g. 30-year period) for a destructive snow avalanche (and each of the other hazards)
- Consider the 'vulnerability' of the element to each hazard, i.e. what proportion of events reaching it will result in its destruction?
- Multiply the encounter probability, vulnerability, and cost impact for each hazard to estimate partial risk associated with each hazard
- Sum the partial risk values associated with each hazard to estimate the total risk.

This sum represents the normalized exposure of the element to the geohazards over the life of the project, i.e. there is a 23.4% chance of a $10 million impact over thirty years. This is really a partial-risk approach, and follows the general approach of geohazard risk assessment guidelines (e.g. Porter and Morgenstern, 2013), and previous efforts in avalanche risk assessment (e.g. Schaerer, 1989; Barbolini et al, 2004).

Next, we repeat this analysis accounting for geohazard mitigation, including two important additions for each type of mitigation:

No Mitigation	Avalanche	Rock fall	Debris flow	Debris slide
Total cost associated with destruction of an element at risk, including replacement and any impacts, i.e. consequences	$10,000,000	$10,000,000	$10,000,000	$10,000,000
Encounter probability for a destructive geohazard event in 30-year life of the project, i.e. 1:100 year avalanche or 1:1000 year rock fall	26%	3%	0.26	0.26
The vulnerability of the element to the geohazard event, or chance of destuction in a direct hit	90%	100%	100%	100%
Total exposure (chance of event x vulnerability x cost of destruction)	**$2,340,000**	**$300,000**	**$2,600,000**	**$2,600,000**
			Total for no mitigation:	**$7,840,000**

Gas Exploders	Avalanche	Rock fall	Debris flow	Debris slide
Total cost associated with destruction of an element at risk, including replacement and any impacts, i.e. consequences	$10,000,000	$10,000,000	$10,000,000	$10,000,000
Total cost of mitigation (gas exploders):	$1,000,000	$0	$0	$0
Encounter probability for a destructive geohazard event in 30-year life of the project with mitigation in place	10%	26%	60%	60%
The vulnerability of the element to the geohazard event, or chance of destuction in a direct hit	90%	100%	100%	100%
Total exposure (cost of mitigation + (chance of event x vulnerability x cost of destruction))	**$1,900,000**	**$2,600,000**	**$6,000,000**	**$6,000,000**
			Total for gas exploders:	**$16,500,000**

Large Berm	Avalanche	Rock fall	Debris flow	Debris slide
Total cost associated with destruction of an element at risk, including replacement and any impacts, i.e. consequences	$10,000,000	$10,000,000	$10,000,000	$10,000,000
Total cost of mitigation (a large berm):	$2,000,000	$0	$0	$0
Encounter probability for a destructive geohazard event in 30-year life of the project with mitigation in place	6%	0.60%	3%	3%
The vulnerability of the element to the geohazard event, or chance of destuction in a direct hit	50%	100%	100%	100%
Total exposure (cost of mitigation + (chance of event x vulnerability x cost of destruction))	**$2,300,000**	**$60,000**	**$300,000**	**$300,000**
			Total for large berm:	**$2,960,000**

Fig 6: Hypothetical economic evaluation of potential mitigation options that address multiple geohazards. Here the objective is to find the lowest combined cost of mitigation and exposure after mitigation. Note the impact that the mitigation has on the encounter probability may differ between options and geohazards.

- Include the upfront capital and maintenance cost of the mitigation (with 100% encounter probability)
- Reduce the encounter probabilities for each hazard based on the design or assumed effectiveness of the mitigation.

In cases where a particular mitigation reduces the exposure to one hazard (e.g. snow avalanche) but drastically increases the exposure to another (e.g. rockfall), such as would be the case with a gas exploder in some locations (Fig. 6), it is clear that this option should not be selected. For a different type of mitigation, the exposure to all geohazards may be reduced substantially, but such a mitigation measure may be so expensive as to outweigh the benefit, relative to the unmitigated case. This approach allows for at least a basic analysis and comparison of these factors, often in terms that are easily understood by owners (e.g. 26% chance of spending $10,000 versus some other chance of spending a different amount).

5. CONCLUSIONS

In this paper we briefly described a logical framework to select avalanche mitigation at locations exposed to other geohazards. The overarching concept is that a particular mitigation should not result in a net increase in overall geohazard risk, and, as possible, should be optimized for mitigation cost versus economic risk reduction across all geohazards. Additionally, a framework is presented to compare other factors that can influence or control geohazard mitigation selection, including design confidence, schedule, environmental and aesthetic concerns, and risk perceptions and risk tolerance of stakeholders.

CONFLICT OF INTEREST

The creation of this document was not supported financially or materially by the ISSW. None of the authors benefit financially from the production or sale of ISSW proceedings nor have they received any related grants or patents.

ACKNOWLEDGEMENTS

Thanks to Ty Ortiz and Tyler Weldon of CDoT, and Ethan Greene of the CAIC, for sharing ideas, information, and insights.

REFERENCES

Barbolini, M., Cappabianca, F. and Sailer, R., 2004. Empirical estimate of vulnerability relations for use in snow avalanche risk assessment. WIT Transactions on Ecology and the Environment, 77.

Brändle, R., Gröner, E., Margreth, S. and Geobrugg, A.G., 2014. Avalanche Barriers in the starting zone exposed to rock fall: Range of capacity and 1: 1 rock fall tests with flexible snow net. ISSW 2014, Grenoble, France.

Cruden, DM, and Varnes, DJ. 1996. Landslide Types and Processes. Chapter 3 of Landslides: Investigation and Mitigation. Transportation Research Board, National Academy of Sciences, 247:36-75.

Gleirscher, E. and Fischer, J.T., 2014. Retarding avalanches in motion with net structures. Cold Regions Science and Technology, 97, pp.159-169.

Kappes, M.S., Keiler, M., von Elverfeldt, K. and Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. Natural Hazards, 64(2), pp.1925-1958.

Margreth, S. and Roth, A., 2008. Interaction of flexible rockfall barriers with avalanches and snow pressure. Cold regions science and technology, 51(2), pp.168-177.

Porter, M., & Morgenstern, N. (2013). Landslide Risk Evaluation – Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction. Geological Survey of Canada, Open File 7312, 21 p. DOI:10.4095/292234

Schaerer P (1989) The avalanche-hazard index. Ann Glaciol 13:241–247