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How differences between snow avalanches and other slope hazards affect mapping and mitigation

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ABSTRACT

Snow avalanches differ from other slope hazards such as debris flows and landslides in ways that affect mapping and mitigation. Snow avalanches start as a result of failure in a bonded granular material in which the bonds are close to the melting point. Periods of instability are often limited to hours or days. In contrast to other slope hazards, explosives are effective triggers of unstable snow, thereby shortening periods of instability and allowing parts of ski areas or transportation corridors to be quickly re-opened. Where snow avalanche occurrences observations are available for a decade or more, this often results in better occurrence and runout records than for other slope hazards. For snow avalanches, hazard mapping thresholds based on a low annual probability (e.g. $Pa \leq 10^{-3}$) are especially uncertain and problematic for hazard mapping.

RÉSUMÉ

Les avalanches de neige diffèrent des autres dangers de pente, comme les coulées de débris et les glissements de terrain, de manière à affecter la cartographie et l'atténuation. Les avalanches de neige commencent à la suite de la rupture d'un matériau granulaire lié dans lequel les liaisons sont proches du point de fusion. Les périodes d'instabilité sont souvent limitées à des heures ou des jours. Contrairement à d'autres dangers de pente, les explosifs sont des déclencheurs efficaces de neige instable, raccourcissant ainsi les périodes d'instabilité et permettant la réouverture rapide de parties de domaines skiables ou de couloirs de transport. Lorsque des observations d'occurrences d'avalanches de neige sont disponibles pour une décennie ou plus, cela se traduit souvent par de meilleurs enregistrements d'occurrence et de ruissellement que pour d'autres dangers de pente. Pour les avalanches de neige, les seuils de cartographie des dangers basés sur une faible probabilité annuelle (par exemple $Pa \leq 10^{-3}$) sont particulièrement incertains et problématiques pour la cartographie des dangers.

1 INTRODUCTION

In this paper, we explain how snow avalanches differ from other slope hazards such as debris flows and landslides and how those differences affect mapping and mitigation.

In particular, we consider why human activities are often located closer to snow avalanche hazards than to other slope hazards. Figure 1 shows the corridor for the Trans-Canada highway through the east side of Glacier National Park in British Columbia, Canada. There are five sheds protecting the highway from snow avalanches. The sheds were constructed where snow avalanches were expected to reach the highway at least once per year. In the storm shortly before the photo was taken, snow avalanches crossed four of the five sheds. This illustrates a key difference between snow avalanches and other slope hazards. If another slope hazard such as debris flows (Figure 2) were crossing the corridor through a mountain pass in multiple places at least once per year, the Trans-Canada highway would not be located through that pass. (Rockfall hazards (Figure 3) are more common and widely distributed than snow avalanches, but in most cases, rockfall is mitigated by scaling, ditches and barriers.)

We explain why low values of the minimum acceptable annual probability $Pa \leq 10^{-3}$ (or maximum acceptable return period $T > 300$ years) are more challenging for avalanches than for other slope hazards.

Figure 1. Photo of Trans-Canada Highway on the east side of Glacier National Park showing five show sheds, four of which have avalanches from the recent storm crossing the highway. Photo: Parks Canada / J. Woods.

Figure 2. Deposit from a 2011 debris flow near Ophir, Colorado, USA. A snow avalanche also reached the site, but the deposit has melted. Photo: C. Wilbur.

2 PHYSICAL DIFFERENCES BETWEEN SNOW AVALANCHE HAZARD AND OTHER SLOPE HAZARDS

There are at least two physical differences between snow avalanches and other slope hazards that affect mapping and mitigation. First, the failures that release snow avalanches occur in a bonded granular material within 10 degrees – often within 5 degrees – of its melting point (Perla, 1977). (This temperature threshold cannot be used to predict avalanche release since most snow in a temperate climate exists in this temperature range. Other avalanche forecasting variables and methods are used to predict unstable conditions. Also, improved data, models and sharing of data result in continuous improvement of avalanche forecasting.)

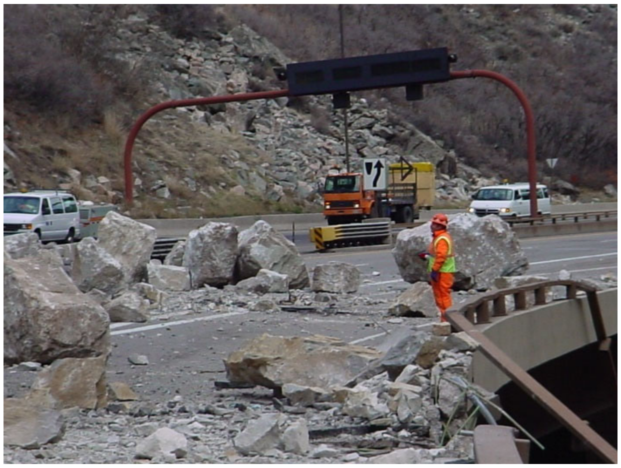

Figure 3. Rockfall on I-70 highway through Glenwood canyon in Colorado, USA. Photo: Colorado Department of Transportation.

Second, as shown in Figure 4 of a fracture in a weak layer of buried surface hoar (i.e. frost), the samples are too fragile to be transported to the lab. (The only reason the detached slab on the left side of the photo did not slide is because the frictional force under the slab was greater than the component of gravity pulling the slab downslope.)

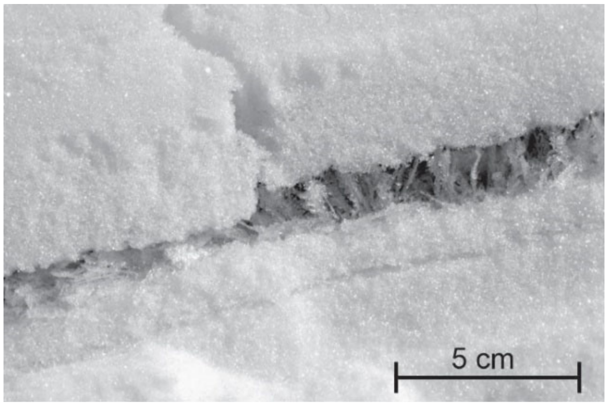

Figure 4. Photo of a fracture in a buried weak layer of surface hoar (frost). Potential failure layers, such as this one, are too fragile to be transported to a cold lab for mechanical testing. Photo: UCalgary.ca/asarc.

3 FREQUENCY OF OCCURRENCES AND RUNOUT RECORDS

In temperate zones, snow avalanches are common, likely more common than other slope hazards, although records for small landslides and small snow avalanches are incomplete. Schaerer (1984) estimated that in western Canada an average of approximately 1.5 million avalanches capable of injuring or killing a person (Size class D2 or larger according to McClung and Schaerer (2006)) occur each winter. However, he estimated only 2 to 5% of these occurred near settled areas, transportation routes or backcountry-use areas. More recently, Stitzinger et al. (2000) estimated that at least 300,000 size D2 or larger avalanches occurred in BC annually.

From October 1996 to 2007, there were 151 deaths in 105 fatal snow avalanches, an average of 14 deaths and 9.5 fatal avalanches per year (Jamieson et al. 2010). However, most of these occurred during recreation, which is voluntary risk.

Thousands of landslides occur every year in Canada (nrcan.gc.ca, retrieved 15 May 2020). Blais-Stevens et al. (2018) report 767 deaths in 150 fatal landslides from 1771 to 2018, an average of 3 deaths and 0.6 fatal landslides per year. Although the observation period is much longer than cited for snow avalanches, this suggests that fatal snow avalanches are more common than fatal landslides.

Partly because many snow avalanches run into, across or near highways, ski areas or popular areas of parks, records of avalanche occurrences, including runout distance, are kept by the operations that manage the avalanche risk in these areas. These runout records are one of several sources that are used to associate return periods with runout distances.

4 VEGETATION DAMAGE AND DENDROCHRONOLOGY

Compared to other slope hazards, the frequency of snow avalanches more often provides a useful record of snow avalanche runout distance. Sources of runouts for snow avalanches include written records (as noted in the previous section), vegetation damage (Figure 5) and, increasingly, deposits detected after snowstorms by satellite or UAV.

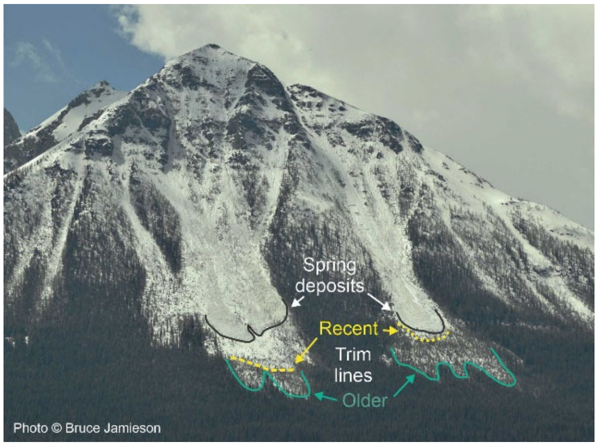

Figure 5. In this photo, two trim lines are visible. The age of vegetation just upslope of trim lines such as these comprise one of several methods used to estimate the return period. Photo: B. Jamieson.

Dendrochronological records of snow avalanches are limited. Since most trees in temperate and boreal forests near avalanche runout zones do not live much longer than 100 years, dendrochronological records of avalanches from more than 100 years previously are rare (Figure 6).

5 EXPLOSIVE TRIGGERING

Snow avalanches are commonly triggered by explosives to remove unstable snow from avalanche start zones at skis areas and highways. Explosive triggering for other slope hazards is very rare. (The 1978 quick clay landslide in Rissa, Norway is a notable exception). The effectiveness of explosive triggering for removing unstable snow is one reason parts of transportation corridors and ski areas are located in avalanche runout zones.

Figure 6. This 2019 snow avalanche at Ophir Pass in Colorado, USA has swept up the opposite slope destroying the forest. The dendrochronological record of this avalanche will last ~100 years. Photo: C. Wilbur.

Partly because the bonds between snow grains are close to the melting point of ice, the timing is critical. During and soon after a storm, the window of instability during which explosives are effective can be as short as an hour.

6 GEOMORPHOLOGY

Geomorphic evidence for snow avalanches is very limited and difficult to assess. Only for the largest – and hence rarest – snow avalanches, does Perla (1980) mention "could gouge the landscape". Gardner (1983) mentions erosion from large wet snow avalanches is inconsistent. In contrast, most other slope hazards rely on landforms and surface features for mapping since these mass movements have shaped the landscape. Deposits shaped by avulsions of debris flows are just one example. Debris/alluvial fans often have material transported by debris flows and – much less frequently – by snow avalanches. Geologic evaluation of the source areas/start zones can help determine the relative contributions of the different mass movements. In contrast to landslides and debris flows, geomorphic evidence from avalanches is not relied upon for mapping and assessments.

7 SUBSURFACE SAMPLING

Figure 7 shows the Frank Slide in southwestern Alberta, Canada. The peripheral shape of the deposit is similar to snow avalanche deposits. In fact, some of the flow models for landslides are also used for snow avalanches (e.g. Hungr 1995, Jordan et al. 2016). The slide occurred over 100 years ago. One hundred or a thousand years after such mass movements, subsurface sampling or GPR will be able to identify the extent of the deposit. However, almost all snow avalanche deposits melt in the following summer, so the extent of historical runouts cannot be detected by subsurface sampling years, decades or centuries later.

Figure 7. Areal photo of the Frank Slide in south Alberta. S Alberta MDs and Counties image, Google Earth 2011.

8 DIFFERENT ACCEPTABILITY THRESHOLDS FOR DIFFERENT SLOPE HAZARDS?

This section focuses on the acceptability threshold for avalanches and other slope hazards. These hazard thresholds are based on return period (or annual frequency) and, for some slope hazards, a threshold intensity (i.e. magnitude) is also specified. (The few Canadian jurisdictions that use acceptable risk criteria (van Dine et al. 2018) rather than hazard thresholds are excluded from this comparison.)

Traditionally, the annual probability was defined as the limiting value of annual frequency over a long observation period. However, since an acceptable annual frequency such as 1:10,000 would require an impossible observation period (even with subsurface sampling), we interpret annual probability separately from an observable annual frequency. Specifically, the Pleistocene epoch (ice age) ended about 11,700 years ago, so subsurface sampling (which is not possible for snow avalanche deposits) cannot detect more than one runout with a frequency of 1:10,000 years.

In many jurisdictions, the thresholds for acceptability vary with the slope hazard. In most jurisdictions in British Columbia, the thresholds vary from 1:200 year events for floods, 1:300 year events for snow avalanches to 1:10,000 year events for landslides (MoTI 2015, EGBC 2010, 2012, CAA 2018). However, for new subdivisions the Fraser Valley Regional District requires an annual probability of < 1:10,000 years for snow avalanches, debris flows and landslides and < 1:200 years for flood inundation (FVRD 2017). This follows from Cave (1992/93) which proposed that the differences be based on the effects of the hazards (i.e. landslides are more deadly than floods) and not on a strict geotechnical classification.

In addition to a minimum frequency/probability (or maximum return period), some acceptable hazard thresholds include an intensity threshold (e.g. impact pressure ≤ 1 kPa for snow avalanches (CAA 2018)). Jakob et al. (2011) proposed that the intensity for debris flows be based on maximum flow height and the square of maximum velocity.

Such low acceptable probability thresholds for slope hazards are challenging for the practitioner contracted to draw a hazard line for a residential or other development. Jakob et al. (2018) show that stationarity must be assumed for non-stationary processes such as landslides.

In many snow avalanche paths, including those where colluvium in the runout zone favors an approximately parabolic profile, the difference in runout distance for Pa ~1:300 years and Pa ~1:10,000 years may be small (Figure 8). Hence, the uncertainty in the runout distance may – potentially – be small as shown in Figure 8. The authorities that set the acceptability thresholds for jurisdictions are likely striving to locate residential developments beyond the maximum credible runout distance.

For snow avalanches, such low probabilities present greater challenges than for landslides and debris flows because:

- Large snow avalanches are sensitive to precipitation/snowfall amounts over a few days (arguably more sensitive than debris flows). Due to change in the snow climate, the trends in multi-day precipitation intensity are non-stationary and uncertain.
- Wide benches in the runout zone on which avalanches are certain to decelerate (slope angle < 15°) followed by slopes on where avalanches will accelerate (> 24°)

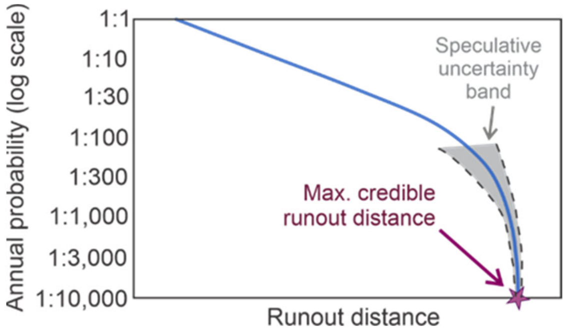

Figure 8. Concept of a maximum credible runout distance beyond which decreased annual probability has negligible effect on runout distance. The gray uncertainty band is speculative but may be indicative of assumptions by some jurisdictions.

- Channelized paths with the potential to overflow laterally, i.e. how deep must a gully be to contain a 1:10,000 year snow avalanche?
- The powder component of large dry snow avalanches runs past the stopping position of the dense flow and can run 100s of meters across level ground or upslope with decreasing impact pressure. Figure 9 shows a powder avalanche running up a slope where it did not damage the forest. Many planning guidelines specify an impact pressure, e.g. 1 or 3 kPa, beyond which the minor damage to structures is considered acceptable.

Figure 9. Photo of a powder avalanche running up the opposite side of a valley. Such avalanches run far past the farthest damage to forests, etc. Photo: J. Kuper.

Hence, for Pa ≤ 10^{-3}, uncertainty in the runout distance in specific paths or tracks can increase for snow avalanches and decrease for other slope hazards. For snow avalanches, uncertainties related to low probabilities can result in large discrepancies in hazard mapping, even among experienced and qualified practitioners.

9 SUMMARY

In a specific path or track, snow avalanches are usually much more frequent than most other slope hazards. In many avalanche paths in North America, vegetation damage provides a record of avalanche runout in the preceding 50 to 100 years. Boundaries in vegetation called trim lines and historical records, combined with statistical techniques, often allow the snow avalanche specialist to confidently draw hazard lines for return periods up to about 100 years (Pa ~0.01). However, for Pa ≤ 10^{-3}, the snow avalanche specialist often has difficulty confidently drawing hazards lines partly because the deposits melt and subsurface methods do not work.

Fortunately for transportation corridors and ski areas, explosive triggering can be quite effective. However, because the failures that release snow avalanches occur within about 10 degrees of the melting point for the ice bonds, the timing can be quite critical. Sometimes the window for intentional triggering is as short as an hour.

Because of the lower flow density of snow avalanches, the impact forces are often lower than from other mass movements. This factor combined with the "triggerability" of snow avalanches are two of the reasons why human activities are often closer to snow avalanches than other slope hazards.

In Canada and elsewhere, different acceptability criteria exist for different slope hazards. These vary by annual probability (or frequency or return period) and by the intensity variable (e.g. impact pressure for snow avalanches). For snow avalanches, thresholds based on a low annual probability (e.g. Pa ≤ 10-3) are especially uncertain and problematic for hazard mapping.

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