Uncertainty in snow avalanche risk assessments

Bruce Jamieson
University of Calgary, Calgary, Alberta, Canada
Canadian Avalanche Association, Revelstoke, BC, Canada
Pascal Haegeli
Avisualanche Consulting, Vancouver, BC, Canada
Grant Statham
Alpine Specialists, Canmore, Alberta, Canada

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ABSTRACT
Snow avalanche risk assessments are applied in planning for residential areas, energy corridors, transportation corridors, industrial sites, ski area expansions, as well as for operational decisions for work sites, ski areas and commercial backcountry recreation. While many of these assessments are qualitative, some are quantitative. Increasingly, uncertainty has become an explicit part of snow avalanche risk assessments. Sources of uncertainty in snow avalanche risk assessments include weather, climate, snowpack, vegetation, terrain, as well as the exposure of people and things of value. We review strategies for reducing uncertainty in the assessment process including the use of independent predictive methods as well as reviews. To reduce the frequency of death and damage from snow avalanches, analytical methods such as non-exceedance probabilities can ensure that much of the uncertainty lies below the applicable threshold of acceptable risk. Finally, we summarize strategies for communicating uncertainty about avalanches to the risk owner.

RÉSUMÉ
L'évaluation des risques d'avalanche de neige sont appliqués dans la planification pour les zones résidentielles, les couloirs de l'énergie, des corridors de transport, des sites industriels, des expansions de stations de ski, ainsi que pour les décisions opérationnelles pour les sites de travail, les domaines skiables et les loisirs de montagne commerciale. Alors que beaucoup de ces évaluations sont qualitatifs, certains sont quantitative. De plus en plus, l'incertitude est devenue une partie explicite de l'évaluation des risques d'avalanche de neige. Les sources d'incertitude dans les évaluations de risque d'avalanche de neige dont les conditions météorologiques, le climat, le manteau neigeux, la végétation, le terrain, ainsi que l'exposition des personnes et des choses de valeur. Nous passons en revue des stratégies pour réduire l'incertitude dans le processus d'évaluation, y compris l'utilisation des méthodes de prévision indépendants ainsi que des examens. Pour réduire la fréquence de la mort et les dommages causés par les avalanches de neige, les méthodes d'analyse telles que les probabilités non-dépassement peuvent veiller à ce que la majeure partie de l'incertitude se situe en dessous du seuil applicable de risque acceptable. Enfin, nous résumons les stratégies de communication de l'incertitude sur les avalanches au propriétaire du risque.

1 INTRODUCTION

The International Standards organization defines uncertainty as “the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood.” (ISO Guide 73 2009). Uncertainty is an inherent part of snow avalanche risk management and cannot be eliminated, only reduced. It is present at all stages of the risk management process, including data gathering, analysis, assessment and decision making (Morgan and Henrion 1990; Vick 2002). Accommodating uncertainty begins by first acknowledging its existence, then reducing it when practical, communicating the irreducible uncertainty and accommodating it in decisions.

The objective of this paper is to provide a brief overview of the sources of uncertainties encountered in avalanche hazard and risk assessments and to discuss the most commonly used strategies for handling it.

2 SOURCES OF UNCERTAINTY

Avalanche risk results from the diverse and multi-scale interactions of weather and climate, terrain, snowpack and people or property. Each of these domains contribute their own set of uncertainties to the avalanche hazard or risk assessment process. In this section we briefly discuss examples of sources of uncertainty from each of these domains.

2.1 Weather and climate

Short-term avalanche forecasting depends heavily on forecasted weather, which involves uncertainty. Uncertainty increases with the lead time of the weather forecast. The range in a weather parameter also becomes wider as greater spatial areas are considered. For example, if 10 cm of snow is forecast overnight, the range of expected precipitation is narrower for a small ski resort than for a forecast region of 30,000 km^2.

Changes in climate are causing changes to the snowpack in mountain areas of the northern hemisphere (e.g., Bellaire et al. 2013; Eckert et al. 2013). Records from the last 40 to 70 years show the length of the snow season in some alpine regions is shortening and snow heights are decreasing, especially at lower elevations. When run for the next 35 to 85 years, combined climate and snowpack models suggest these trends will continue (e.g. Castebrunet et al. 2014).

In the Alps of France, Eckert et al. (2013) show that there are trends towards more wet avalanches and shorter runout distances towards valley bottoms. However, winters with extreme avalanches running long distances remain possible. Canadian studies of trends over the last 40 to 50 years (Bellaire et al. 2013; Sinickas et al. 2015) do not show a convincing decrease in the frequency or runout of avalanches threatening infrastructure in the valley bottom. Other than a trend towards shallower snowpack with more melt-freeze crusts, little is known about snowpack and avalanche trends at the elevations currently popular for winter recreation.

It is important that anyone involved in avalanche planning stay informed regarding climate change and any observed or predicted trends in avalanches, and consider the associated uncertainty in their reports. Such uncertainty could affect any results or conclusions that have been derived using contemporary methods based on historical records.

2.2 Terrain

When estimating the extreme runout from a particular path or the risk to a skier descending a path, the terrain is fixed. However, there is variability and hence uncertainty when considering the avalanche terrain for a backcountry skier during a day. For example, the severity of the terrain varies along a route rated Complex according to the avalanche terrain exposure scale (ATES; Statham et al. 2006). Also, when planning a transportation corridor, the risk will vary between the centre and sides of a path where it crosses the corridor (Schaerer 1989). Hence, uncertainty increases when greater ranges of time or space are considered.

2.3 Snowpack

Snowpack properties and hence the probability of triggering vary strongly over terrain (Schweizer et al. 2008; Figure 1). For example, triggering often becomes more likely where a slab is relatively thin (over a weak layer). Also, thicker slabs often release wider avalanches, resulting in larger and more destructive avalanches. Further, the properties of the weak layers that release the slabs also vary over terrain, and can vary critically within several metres (e.g. Campbell and Jamieson 2007; Schweizer et al. 2008). These are just three examples illustrating that the snowpack is a major source of uncertainty for avalanche forecasting and for backcountry risk assessments while travelling over snow in avalanche terrain.

Figure 1. The crown height and bed surface for this slab avalanche are variable and hence illustrate uncertainty in snowpack properties within a single avalanche start zone. B. Jamieson photo.

For land-use planning, the snowpack properties can also be a source of uncertainty. This can be illustrated by a fatal avalanche accident that occurred along BC Highway 16 about 45 km west of Terrace, BC (Stethem and Schaerer 1979, p. 89-92). A café had been built 60 metres west of an obvious course taken through coniferous forest by slower wet avalanches. On 22 January 1974, a fast dry avalanche took a different course through the coniferous forest and killed seven people in the café. The accident investigation revealed that the course of fast dry avalanches had a return period of 15 years, but was unknown to the initial planners.

2.4 People

At the time of an avalanche, people may be in unexpected places. For example, people may be in closed zones of ski areas, stopped in no stopping zones on roads, or skiing where a guide directed them not to go.

Also, people’s perception of the relevant environmental factors including terrain, their assessment of the conditions (McClung 2002; McCammon 2002), and subsequent actions are sources of uncertainty.

While some of these sources of uncertainty such as weather are external to an avalanche safety operation, the uncertainty associated with the movement of people within an operational area can be internal. Reducing the uncertainty associated with human perception in decision-making often requires considerable effort.

3 TYPES OF UNCERTAINTY

To discuss how the various approaches used in avalanche hazard and risk assessments deal with uncertainty, it is useful to distinguish between aleatoric and epistemic uncertainty. Following Der Kiureghian and Ditlevsen (2009) and Ang (2011), we define the two types of uncertainty as follows:

Aleatoric uncertainty refers to the uncertainty that is due to the natural variability or randomness of a complex system that are beyond the current scientific understanding of the phenomenon. The outcome of a coin toss, which can only be predicted probabilistically, is a classic example of aleatoric uncertainty. Examples of aleatoric uncertainty in avalanche risk assessments include small scale variations of weather and snowpack characteristics over mountainous terrain (e.g., Schweizer et al. 2008). Aleatoric uncertainty cannot be reduced, but needs to be incorporated in avalanche hazard and risk assessments by using a probabilistic assessment framework.

Epistemic uncertainty arises from lack of knowledge that is within the current scientific understanding of the phenomenon. In other words, this type of uncertainty is due to aspects of the system that could be known in principle, but are unknown due to limitations in assessment methods or resources. Examples of sources of epistemic uncertainty are observations of limited extent or detail and assessment methods that knowingly neglect the effects of certain contributing factors or combine factors in a way that does not accurately represent reality (Morgan and Henrion 1990, p. 67-69). If operationally feasible, epistemic uncertainty can potentially be reduced by gathering more data or refining models (Der Kiureghian and Ditlevsen 2009).

Vick (2002 p. 38) proposes that in quantitative assessments, epistemic uncertainty can be included as a subjective term for the prior probability. An avalanche hazard assessment can, for example, include epistemic uncertainty due to snowpack observations of limited depth that did not capture the presence of a critical weak layer at the base of a deep snowpack. However, this approach fails in assessments that do not recognize key characteristics of the hazard or risk. Because scenarios or important elements of a hazard situation might be missed, epistemic uncertainty has the potential to fundamentally affect the choice of appropriate mitigation measures (Ang 2011).

In qualitative assessments, epistemic uncertainty can only be rated qualitatively. For example, avalanche professionals commonly describe their perception of how well their observations and resulting hazard assessment represent the existing situation with qualitative confidence ratings such as low, moderate or high (Fischhoff and Kadvany, 2011, p. 126-127).

While there are other ways to partition uncertainty into different types (e.g., Spiegelhalter and Riesch 2011) and there is debate about the precise distinction between aleatoric and epistemic uncertainty (e.g., Der Kiureghian and Ditlevsen 2009; Vick 2002), we believe that the classification outlined above offers a valuable framework for systematically addressing uncertainty in avalanche hazard and risk assessments.

4 STRATEGIES FOR REDUCING EPISTEMIC UNCERTAINTY

Avalanche hazard and risk assessment and some aspects of mitigation involve reducing epistemic uncertainty. Specifically, McClung and Schaerer (2006 p. 149) define the goal of avalanche forecasting in terms of minimizing uncertainty about the instability of the snowpack and include methods for reducing uncertainty. General strategies for reducing the epistemic uncertainty in both short and long term hazard and risk assessments include:

1. Identifying knowledge gaps early in the assessment process and seeking specific information to reduce the gaps.
2. Applying independent methods in the same assessment.
3. Seeking independent expert opinions of hazard or risk such as peer reviews or guidance from other processes such as decision aids (McCammon and Haegeli 2007).

The estimates or opinions from the different methods (2) and different experts (3) can be combined with greater weight assigned to methods or opinions with less uncertainty. Using runout estimation as an example, Jamieson and Sinickas (2015) argue that in some North American avalanche paths, vegetation boundaries (trim lines) have less uncertainty than estimates from dynamic models, and therefore trim lines should be assigned more weight in the estimation of runout.

5 STRATEGIES FOR CONSIDERING UNCERTAINTY IN ASSESSMENTS

This section summarizes strategies for considering uncertainty and reaching appropriately conservative decisions and designs.

5.1 Safety factor

The safety factor is the ratio of structural capacity to the allowable load (e.g., Beer and Johnston 1981, p. 23). It is widely used in geotechnical assessments of slope stability. Higher ratios are safer in that they allow for greater uncertainty in the load including variations over time and space. While safety factors based on slope failures and laboratory tests have been published in design codes for soil and rock slopes, they have not been published for snow slopes likely because snowpack properties vary more strongly over space and time.

Safety factors for snow pressure and avalanche impact on structures are needed, but few have been published (e.g., WSL-SLF 2007, p. 54). In some cases, a high value for a variable such as flow density (or low value for a variable such as friction) is used “for safety”. For example, Jóhannesson et al. (2008) propose a flow density of 300 kg m^{-3} for large dry avalanches in the runout zone. Often, the avalanche consultant and structural engineer (or geotechnical engineer for earthworks) must decide on a safety factor based on their knowledge of the uncertainty, especially for the loads applied by the design avalanches.

5.2 Non-exceedance probabilities

When the statistical distribution of a random variable used in risk or hazard assessment is modeled, 50 % of its values will be less than or equal to the median (which is close to the mean for approximately symmetric distributions). Hence, the median has a non-exceedance probability of 0.5. In some avalanche assessments, it advantageous to apply a higher non-exceedance probability to a particular variable. For example, a non-exceedance probability of 0.8 may be applied for statistical runout estimation, which means that only 20 % of the paths in the range have relatively longer extreme runouts (e.g. McClung and Mears 1991). When risk or hazard can be modeled as a statistical distribution, a higher non-exceedance probability implies lower hazard or risk to the elements of value, i.e. greater safety.

In Figure 2, a Monte Carlo simulation is used to display the quantitative uncertainty of a truck being hit on a hypothetical haul road. The figure also shows the risk for a non-exceedance probability of 0.90, which could be used for evaluating whether the risk is acceptable.

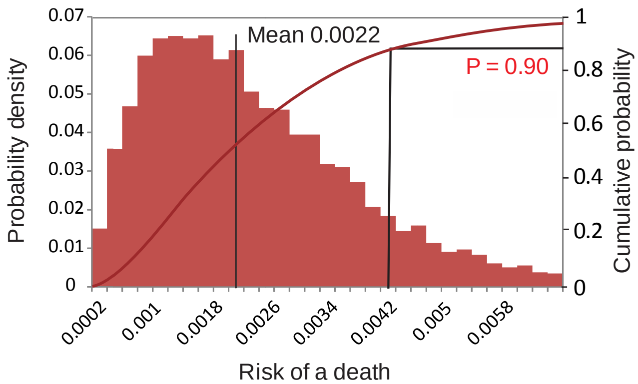

Figure 2. Monte Carlo simulation of risk of death to logging truck drivers on a hypothetical haul road for a mine (Jamieson and Jones, in preparation). The risk is the product of the simulated probability of a truck being hit (triangular distribution with mean 0.024) times the simulated vulnerability of the drivers (beta-PERT distribution with mean 0.09). The Monte Carlo method allows quantitative uncertainty to be displayed, and used to calculate an acceptable risk in terms of a non-exceedance probability greater than 0.5.

5.3 Margin of safety

While the margin of safety also has a qualitative definition in engineering (e.g., Beer and Johnston 1981, p. 23), its typical use in operational avalanche risk assessments is more qualitative and refers to the additional caution due to uncertainty that lies beyond the expected avalanche hazard or risk. For example, when the snowpack variability increases uncertainty in the triggering probability and hence avalanche risk, a greater margin of safety is used to select terrain for human activity such as recreation. Since the uncertainty cannot be fully known or quantified, it is sometimes managed by adding a margin of safety, which can decrease the frequency and/or severity of avalanche accidents (but does not eliminate them). This margin of safety may be described in terms of space or time, e.g. waiting an extra day for the storm snow to stabilize, or travelling 20 m back from the (uncertain) top of the slope. Sometimes the margin of safety is labelled in relative terms such as low, moderate or high. The margin of safety is the qualitative analogue to choosing a non-exceedance probability greater than 0.5.

5.4 Team decision-making

Independent thinking in a team environment is a valuable method to ensure uncertainty is considered, infrequent outcomes are not overlooked, and to maintain a margin of safety by yielding to the most conservative voice. Teams of experts can seek a consensus, or veto potentially risky options. For avalanche safety operations such as backcountry ski guiding, individual routes are often discussed and then “opened” or “closed” for guiding for the day. Some operations prefer that these decisions be made in face-to-face meetings rather than by radio in the field.

6 STRATEGIES FOR COMMUNICATING UNCERTAINTY

Uncertainty is an important part of hazard and risk assessments. Hence, it should be explicitly communicated to the risk owner (ISO 2010), and others involved in assessing hazard and risk (Morgan and Henrion 1990, p. 39).

6.1 Communicating quantitative uncertainty

Quantitative uncertainty is often expressed as a confidence interval as in traditional statistical analysis. For example, Haegeli et al. (2014) find that airbags increase the probability of survival by an average of 11 percentage points (from 78 % to 89 %) and the 95 % confidence interval for the increase is 4 to 18 percentage points. Confidence intervals can also be displayed graphically, typically as whiskers (e.g. Figure 3).

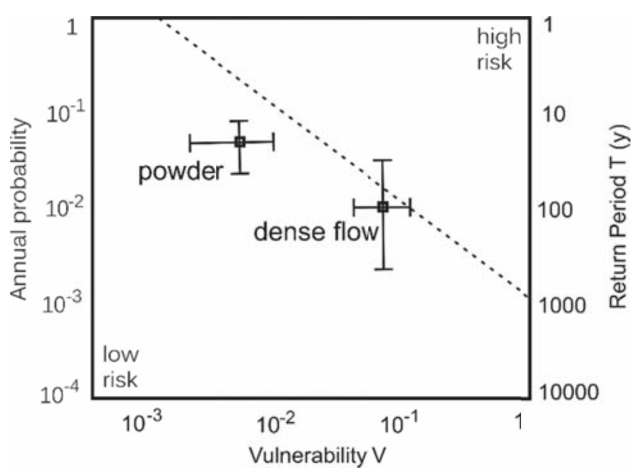

Figure 3. The risk graph shows the quantitative uncertainty in annual probability and vulnerability as whiskers (confidence intervals) for two hypothetical scenarios: a dense flow avalanche and a powder avalanche that threaten a ski lift tower. The dense flow scenario has lower probability of impact and greater vulnerability, whereas the powder avalanche scenario has higher probability and lower vulnerability. Since diagonal lines such as the dashed line represent a constant level of risk (product of probability of impact and vulnerability), the dense flow scenario – especially considering its uncertainty – constitutes higher risk to the tower.

Example of quantifying uncertainty for planning: Size 3 and larger avalanches are not expected to reach the parking lot with a return period less than 30 years (annual non-exceedance probability 1:30 y).

6.2 Communicating qualitative uncertainty

Qualitative uncertainty can be communicated in at least three ways:

1. Use of a finite ordered list of levels, in which fewer classes (i.e., lower resolution) implies greater uncertainty. Examples: avalanche likelihood (very unlikely, unlikely, possible, likely, almost certain) (Statham et al. 2010a) or avalanche size (McClung and Schaerer 2006, p. 322). More classes (i.e., greater resolution) imply less uncertainty. Also, the individual classes can be labeled with words like “typical” or “nominal” to further highlight the deficiency in knowledge and hence communicate uncertainty.
2. Stating or displaying the applicable range of a variable. For example, avalanches ranging from Size 2 to 3 can be displayed graphically as a whisker, or the length (or width) of a rectangle, or axes of a blob with a convex perimeter, keeping in mind that the axes represent ordinal variables (Statham et al. 2010b, Figure 4).
3. List of possible outcomes, e.g. wind slab or storm slab avalanches could occur today.

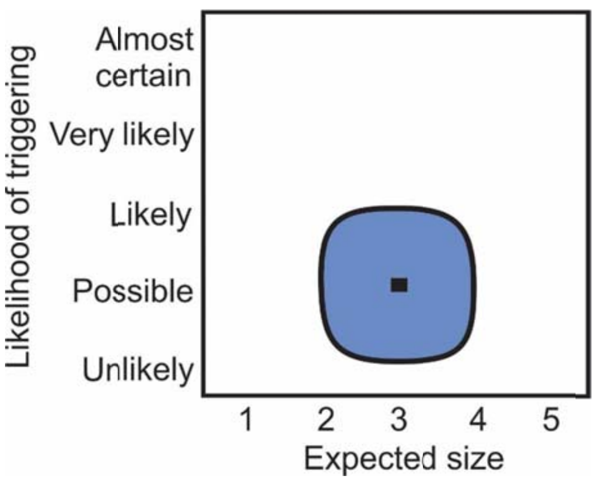

Figure 4. For a given forecast area, day, and character of avalanche, this avalanche hazard chart displays the qualitative uncertainly in expected avalanche size (2 to 4) and in the likelihood of triggering (Unlikely to Likely). Blobs for more than one avalanche character can be shown on the same graph. This is the qualitative analogue of Figure 3. After Statham et al. 2010b.

Qualitative uncertainty is sometimes simply expressed in terms of confidence levels in which high confidence is associated with low uncertainty and vice versa. Example for a short-term qualitative hazard assessment: If a slab avalanche releases above the highway corridor today, confidence is high that it will not exceed Size 2.

6.3 Knowledge base

Since epistemic uncertainty arises from the assumptions behind a model or process and limitations in the underlying data (Aven and Renn 2014), these sources of uncertainty should be communicated to the risk owner. For example, “the 10 year runout is based on an analysis of trim lines in vegetation and 20 years of historical records from the Department of Highways. Longer records would reduce the uncertainty in the 10-year runout but were not available.”

7 SUMMARY

Snow avalanche risk assessments are used in planning for diverse types of land use as well as for short-term operational decisions for ski areas, backcountry travel, etc. Nowadays, uncertainty is often explicitly included in risk assessments. Sources of uncertainty can include weather, climate, snowpack, human perception, as well as the severity of avalanche terrain to which people are exposed to the hazard over time and space. While there are many strategies for reducing uncertainty, one important strategy is to identify knowledge gaps early in the assessment process and seek additional information to reduce the gaps. The explicit inclusion of uncertainty can be used in safety margins and non-exceedance probabilities to ensure much of the uncertainly in risk lies below the acceptable level. Additional methods for communicating uncertainty to the risk owner and others include stating a list of possible outcomes, providing a range of values, and non-exceedance probabilities.

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