VULNERABILITY: CAUGHT IN AN AVALANCHE – THEN WHAT ARE THE ODDS?

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ABSTRACT: Vulnerability is an essential component in qualitative and quantitative avalanche risk analyses. It is the probable consequences given that the element-at-risk is hit by or caught in an avalanche. Since consequences vary with avalanche characteristics, there is a level of vulnerability associated with each type or size of avalanche. The avalanche size classification based on destructive potential is well suited to classifying vulnerability into different levels. We review vulnerability for vehicles on roads, buildings as well as backcountry recreationists and workers. Quantitative vulnerability typically requires some data, although expert estimation can be used with or without data. Quantitative vulnerability has the advantage that it can be used in comparisons with other risks to determine if a risk is acceptable. For backcountry recreation, data from non-fatal injuries are limited, so most calculations of vulnerability for people use only the expected probability of death. Using Canadian accident data, we estimate the vulnerability (probability of death) to roughly 0.004 to 0.007 for a Size D2 avalanche (destructive scale) and ten times higher for a Size D3 avalanche. We show how balloon packs can change the vulnerability of recreationists, and include an example of how vulnerability can be used in an avalanche risk assessment for a worksite.

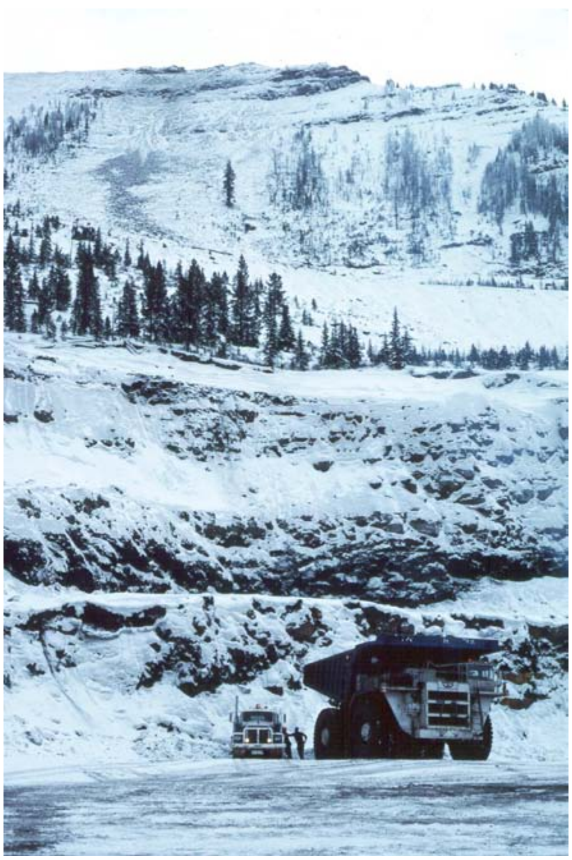

Figure 1: The vulnerability to avalanches for the person between the trucks is greater than for a person in the smaller truck, and both have greater vulnerability than the driver of the large truck. C. Stethem photo.

1. INTRODUCTION

At work and recreation in and near avalanche terrain, we are increasingly being asked “What is the avalanche risk?” That risk is the combination of two random variables (CAA, 2002):

a. the probability of the element-at-risk, e.g. person or building, being hit by an avalanche
b. the vulnerability of, or probable consequences to, the element-at-risk

The probability of being hit combines the probability of an avalanche occurring and the exposure of an element-at-risk to the avalanche. When data are limited, these terms are difficult to quantify and, it is often more practical to rank the terms as low, moderate, high, etc.

However, it is the vulnerability that is often poorly understood and the topic of this paper.

Papathoma-Köhle et al. (2011) provide a review of vulnerability to mountain hazards and definitions of vulnerability.

For landslides, IUGS (1997) defines vulnerability as “the degree of loss to a given element or set of elements *within the area affected by the landslide(s)*. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property it will be the

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value of the property; for person(s), it will be the probability that a particular life (the element-at-risk) will be lost, *given that the person(s) is affected by the landslide*." For snow avalanches, we simply replace "landslide(s)" with "avalanche(s)." Although not used in this paper, we note that vulnerability can be given in monetary units (e.g. Wilhelm, 1998).

Since the element-at-risk could be hit by avalanches with different characteristics, vulnerability is a set of values (a vector) with a value for each scenario. The scenarios should be distinct, e.g. wet or dry, so there is no overlap. The destructive scale for avalanche size, D1 to D5 (McClung and Schaerer, 2006, p. 322), is particularly useful since the scenarios are distinct and the probable fraction of loss typically increases with the destructive potential. However, the expected vulnerability (average loss or consequence) is often much less than the maximum potential loss. The (maximum) destructive potential to an individual from a size D2 avalanche is death (fraction of loss = 1) whereas the expected (average) probability of death is < 0.01 (Jamieson et al., 2009).

Even for a specific element-at-risk and avalanche scenario, the quantitative vulnerability is, in general, a statistical distribution of loss values. When data are limited – and they often are – uncertainty is large and some authors only estimate the expected (average) value. However, it is preferable, whenever practical, to present information about the distribution, e.g. quartiles, or minimum, median or mode and maximum. The uncertainty should be accounted for in risk analysis and decision making (Aven, 2008; ISO, 2009). For example, Figure 2 shows two triangular distributions of the vulnerability of a person (probability of death to an individual, PDI). In both distributions, the expected value (mean or average) is 0.02, but the shaded distribution has a maximum vulnerability of 0.04, which is almost twice that of the other (0.0225). Other distributions with the same mean could be concocted to show greater differences in the maxima.

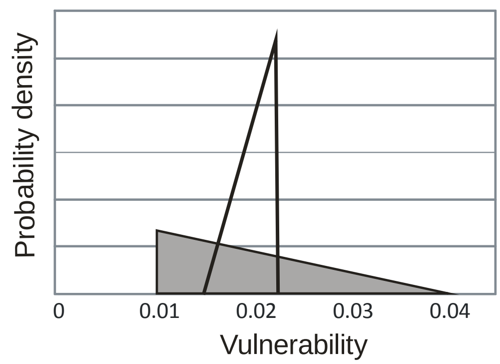

Figure 2: Two triangular distributions of vulnerability with a mean of 0.02 and different extremes.

Vulnerability can be either quantitative or qualitative, depending on the methods used to determine it. Limited data do not preclude the use of quantitative estimates. Vick (2002) and Morgan and Henrion (1990, p. 155) present methods for expert estimation of probabilities. Table 1 lists some advantages of quantitative and qualitative methods.

Table 1: Advantages of quantitative and qualitative methods of determining risk or vulnerability

Qualitative	Quantitative
Requires little or no data	More convincing comparisons with risk or vulnerability due to other hazards or activities
Easier, faster, less complex and typically less costly	More credible to senior management, reviewers and external authorities (if done well)
Less expertise with probability concepts and calculations required	Potentially less dependent on the experience of the assessment team
Ordinal ratings such as "low" may be more meaningful to some users than a probability like 10^{-4}	Assumptions more likely to be stated clearly Accuracy increases with time as data and experience with the methods increase
More readily understood for risk communication to wider audiences	Can be used in assessing whether a risk is acceptable due to established criteria
Requires fewer or no assumptions about the distribution of the variables	Uncertainty in variables can be combined, e.g. through Monte Carlo simulation
Ordinal ratings can imply real uncertainty	Uncertainty can, in some cases, be quantified

After presenting basic formulas for quantitative vulnerability, this paper presents examples of vulnerability for vehicles on roads, buildings and for people inside buildings and in undeveloped areas. For people in the backcountry, Section 6 illustrates carrying uncertainty in the source data though the calculation, as well as the effect of personal floatation devices (balloon packs) on vulnerability. The final section shows the use of quantitative vulnerability in a worksite risk assessment.

2. FORMULAS FOR RISK AND VULNERABILITY

The risk for an avalanche with specific scenario i is $R_i = P_i X_i V_i$ where P_i is the probability of the specific avalanche reaching or exceeding a specified location, X_i is the exposure of the element-at-risk, and V_i is the vulnerability of the element-at-risk (thing-of-value) to the specific avalanche event. Hence V_i is the probable fraction of loss given that event i occurred and that the element was hit by the avalanche ($P_i X_i$). Implicitly, the vulnerability is conditional on the avalanche occurring (P_i) and the element being exposed (X_i).

The random variables P_i, X_i and V_i should be defined so they are independent of each other, in which case the expected value $E(R_i)$ can be calculated $E(R_i) = E(P_i)\ E(X_i)\ E(V_i)$. In some basic risk analyses, only the expected values are calculated or estimated.

When there are multiple *independent* scenarios, e.g. a dry and a wet avalanche, the total risk, R_{total} is the sum of the specific risk due to each scenario $R_{total} = \Sigma_i (P_i X_i V_i)$.

Consider an unprotected powerline tower in the middle of the runout of a large avalanche path. Scenario *i* is defined as an avalanche with destructive potential (size) D_i reaching the runout zone. Since the tower is in the middle of the runout zone, $X_i = 1$.

In this hypothetical example, the greatest risk to the tower is due to a size D4 avalanche. The total risk over the design life of the tower, say 50 years, could be calculated by the encounter probability (LaChapelle, 1966), which in this case would be 0.97.

According to the vulnerabilities in Column 4 of Table 2, a size D3 avalanche that hits the tower is expected to cause damage equal to 10% of the replacement cost of the tower. Size D4 and D5 avalanches are expected to destroy the tower and incur the full replacement cost, i.e. $V_3 = V_4 = 1$. On a functioning powerline, replacement costs would include the cost of the tower itself, construction costs and costs associated with loss of power, which may far exceed the cost of the tower.

3. VULNERABILITY FOR VEHICLES TRAVELLING ON ROADS

The Avalanche Hazard Index (AHI) (Schaerer, 1989) has been used for British Columbia highways and elsewhere since the 1970s. It is a numerical index for the expected damage and loss due to snow avalanches interacting with vehicles on a road. To calculate the index, the expected frequency of moving and waiting vehicles being hit is multiplied the “destructive weight” W_j (Table 3).

Table 3: Destructive weight , W_j from the Avalanche Hazard Index (Schaerer, 1989)

Avalanche class (scenario) j	Relative impact force Q’	Relative cost C’	Destructive weight (vulnerability) W_j
Powder snow	1	1	0
Slough	0.5	0.6	0
Light snow	44	20	3
Deep snow	102	92	10
Plunging snow	94	152	12

Table 2: Expected values for a hypothetical risk calculation for a tower in an avalanche path

Scenario (size ~ destructive potential)	Annual probability of reaching the tower (P_i)	Exposure (X_i)	Vulnerability (fraction of loss) (V_i)	Annual risk
D1	0	1	0	0
D2	0	1	0	0
D3	0.1	1	0.1	0.01
D4	0.05	1	1	0.05
D5	0.01	1	1	0.01
			Total	0.07

For the cost, Schaerer (1989) estimated the probabilities of loss of life, injury and vehicle damage, as well as adverse publicity, possible law suits and effect on future traffic volume for each scenario. He estimated costs for each type of impact to calculate the expected cost for each avalanche scenario. The costs (C') were normalized by the expected cost of damage due to a powder snow avalanche. The destructive weight (W_j) was calculated by averaging the relative impact force (Q') and the relative cost (C'), dividing by 10 and rounding to the nearest integer. This yields a semi-quantitative term for vulnerability. Other authors have modified the vulnerability values to suit the particular problem being analyzed, e.g. Owens and Fitzharris (1989) used a constant value of W_j =10 for hikers on mountain tracks in New Zealand.

Mostly since 2000, more quantitative methods have being developed for assessing the snow avalanche risk to transportation corridors (Margreth et al., 2002, 2003; Kristensen et al., 2003; Hendrikx et al., 2006; Rheinberger et al., 2009). These, of course, require more quantitative estimates of vulnerability. Typically, the vulnerability is defined as the probability of death for persons inside vehicles that are hit by avalanches. Table 4 gives the death rate for passenger cars based on Swiss data (Wilhelm, 1999; Rheinberger et al., 2009). The vulnerability for people on trains is lower.

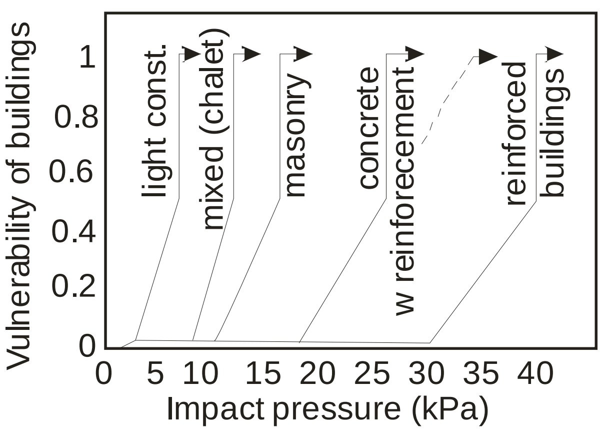

Figure 3: Vulnerability of buildings (after Wilhelm, 1998).

4. VULNERABILITY FOR BUILDINGS

Wilhelm (1998) estimated the vulnerability for various types of construction according to the impact pressure from dense flow avalanches (Figure 3). For example, he estimated that an avalanche with impact pressure of 20 kPa would cause damage of roughly 10% of the replacement cost of a concrete building with reinforcement, and would destroy a masonry building, a typical chalet with mixed construction or a building with light construction. His vulnerability estimates increase linearly as shown by the dotted line for concrete buildings with reinforcement. However, when the damage to a building reaches 50% of the building's replacement cost, it is likely to be demolished, as shown by the solid vertical lines for vulnerability > 0.5.

Table 4: Death rate (vulnerability) for passengers in cars (Rheinberger et al., 2009)

Scenario	Death rate per vehicle hit
Low pressure avalanches	0.05
Powder snow avalanches	0.09
Dense flow avalanches	0.27
Where avalanches may push cars off a road and down a steep slope	0.35

Keylock et al. (1999) presented the vulnerability (fraction of reconstruction cost) for typical Icelandic houses and reinforced concrete structures according to the destructive size of the avalanche (Figure 4).

For the vulnerability of buildings due to powder avalanches, see Barbolini et al. (2004). For vulnerability of various designs of buildings impacted by avalanches, see Bertrand et al. (2010) and de Biagi et al. (2012).

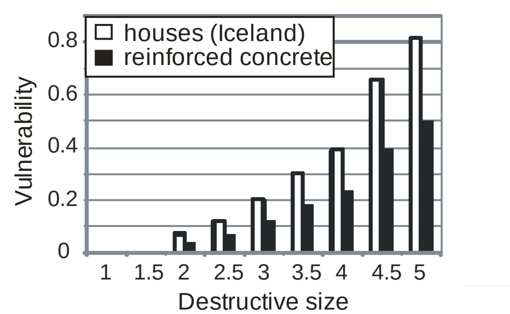

Figure 4: Vulnerability of buildings (fraction of reconstruction cost) for two types of construction according to the avalanche size scale based on destructive potential (Keylock et al., 1999)

5. VULNERABILITY FOR PEOPLE INSIDE BUILDINGS

For people inside houses, Jónasson et al. (1999) calculated the probability of an individual death (PDI, vulnerability) as a function of avalanche speed. Their estimates were made using mortality data from the avalanches that hit the communities of Flateyri and Súdavík in Iceland in 1995 and velocity estimates from a dynamics model. Although their data only were only for speeds less than 28 m/s (about 230 kPa), they argued that the probability of death would only increase slightly for higher speeds because houses, and in particular basements, provide some protection. Using a flow density of 300 kg/m^3 and an impact coefficient of 1, avalanche speeds have been converted to impact pressure in Figure 5. The curve is only valid for wood and concrete houses constructed similarly to those in Flateyri and Súdavík.

Cappabianca et al. (2008) presented a vulnerability curve for people inside concrete buildings (Figure 5). The vulnerability reaches a maximum of 0.46, substantially less than the maximum of 0.95 for the Icelandic houses in Jónasson et al. (1999). The higher vulnerability from 20 to 100 kPa for concrete buildings is likely an artifact of the small data sets and/or the assumptions in the two studies.

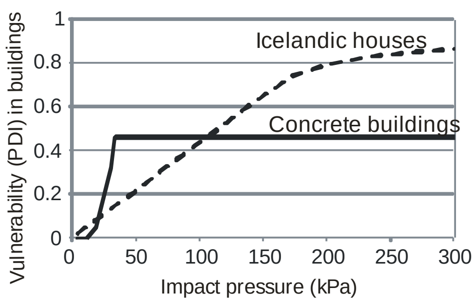

Figure 5: Probability of death (vulnerability) to individuals (PDI) inside houses as a function of impact pressure. After Cappabianca et al. (2008) and adapted from Jónasson et al. (1999).

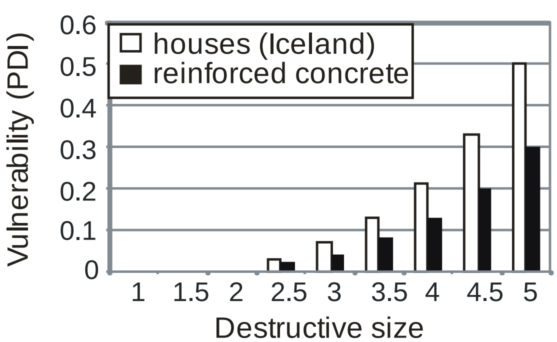

Figure 6: Probability of death to a person inside a building as a function of avalanche size. After Keylock et al. (1999).

For risk mapping in Iceland, Keylock et al. (1999) estimated the size of the avalanches in Súdavík and Flateyri that had struck houses and then interpolated and extrapolated from the fatality rate for these avalanches to get the probability of death to an individual by avalanche size (Figure 6). They estimated that the PDI in reinforced concrete buildings would be 60% of the rate in typical Icelandic houses.

6. VULNERABILITY FOR BACKCOUNTRY RECREATIONISTS

In this section, we consider the vulnerability for backcountry recreationists using data collected since 1985. This differs from people inside buildings because:

- Most of the people triggered the avalanches in the start zone where the forces are lower, and opportunities for escaping much of the force and burial mass are greater;
- Some people successfully escape to the side or out of the avalanche;
- Many have some awareness or training in how to act once caught in an avalanche; and
- An increasing number of victims are rescued by companions, aided by transceivers, probes and shovels.

Although the recreationists receive no protection from buildings, each of the listed factors tends to reduce PDI.

Numerous studies have reported survival rates, or its complement the PDI, according to burial time (e.g. Falk et al., 1994; Haegeli et al., 2011). However, this paper relates PDI to indicators of destructive potential such as avalanche type, impact pressure or destructive size. Most of the studies of survival versus burial time acknowledge that that their results may be affected by a reporting bias. Specifically, the less serious involvements, partial burials, or shorter burial times that result in survival are likely under-reported.

Using accident data from near Davos, Switzerland from the winters of 1988 to 1997, Schweizer and Lütschg (2001) found the probability of death if caught in a human-triggered avalanche was 0.11. Although this particular dataset included many small avalanches, they acknowledged that some non-fatal avalanches may not have been reported (selection bias), suggesting PDI ≤ 0.11.

In a study of rescue devices including balloon packs, Brugger et al. (2007) analyzed Swiss data (winters of 1991 to 2004) and Austrian data (1999 to 2005) to find a PDI of 0.19 for persons without balloon packs. They acknowledged that some accidents, presumably more non-fatal ones, may not have been reported, implying a lower PDI.

From recreational incidents reported to the Canadian Avalanche Centre from 1984 to 2011, the PDI for avalanches of destructive size D2 to D3.5 is shown in Table 9. However, Jamieson et al. (2009) estimated that recreationists only reported 5 to 10% of non-fatal involvements to the Canadian Avalanche Centre. Adjusting the PDI for these estimates of unreported involvements in which recreationists were caught and survived yields lower ranges for PDI shown in Columns 4 and 5 of Table 9.

Flotation devices such as balloon packs were rarely used in Canada prior to 2005. However, using European data, Brugger et al. (2007) found that with these devices the PDI was reduced from 0.19 to 0.03, yielding a 0.16 improvement.

7. EXAMPLE OF A WORKSITE RISK ASSESSMENT USING VULNERABILITY

Avalanche workers are exposed to a variety of worksite risks, including avalanches. In risk assessment, the highest risk due to specific hazards, especially those which may approach or exceed the acceptable level, are often selected for mitigation to reduce the specific risks (e.g. Wilhelm, 1998). Comparison of risks due to various hazards or activities, e.g. driving, snowmobiling, avalanches, can be done qualitatively or quantitatively. As noted in Table 1, quantitative methods yield more convincing comparisons between risks due to different sources, and can be compared against established levels of acceptable risk. Quantitative risk assessment requires quantitative vulnerability.

Consider a hypothetical avalanche research program conducting field studies throughout the winter. Most of the avalanche risk occurs on about 100 of these days when the field team of two workers typically ski across or down two avalanche start zones, one at a time. If the field teams are only exposed to start zones when the avalanche danger is Moderate, the interquartile range of probability of being caught per exposure to a start zone is $1x10^{-5}$ to $2x10^{-4}$ (Jamieson et al., 2009). Using the frequency-weighted vulnerability from Table 9, the probability of a fatality for one exposure to a start zone is $2x10^{-7}$ to $6x10^{-6}$. The encounter probability of a fatality over a winter (100 days with two people each separately exposed to two start zones = 400 exposures) is $7x10^{-5}$ to $2x10^{-3}$. If 200 of the 400 exposures to start zones occur when the danger is Considerable, the cumulative risk over a winter rises to $1x10^{-3}$ to $1x10^{-2}$.

The risks can be adjusted for more or less exposure or reduced by applying more risk controls than was common for Canadian recreationists during 1984 to 2011. Further, vulnerability controls such as balloon packs could be applied. The baseline risk levels could be modified subjectively due to factors such as improved transceivers and training in companion rescue, or avoiding paths with terrain traps.

While neither these nor Jamieson et al.'s (2009) calculations have been peer reviewed, they do illustrate how quantitative estimates of vulnerability can be used in a worksite risk assessment. Further, these calculations enable comparisons with occupational risks due to other sources such as rockfall or activities such as travel in vehicles on roads.

8. SUMMARY

Vulnerability, along with exposure and the probability of the event occurring are key components of risk for slope hazards. Because vulnerability, and often probability and exposure, are not the same for all avalanches, it is helpful to break down the possible avalanches into distinct

Table 9: Vulnerability (PDI) for recreationists in Canada by avalanche size, 1984-2011

Avalanche size	Relative frequency of recreationists caught (n = 1343)	Probability of death if caught (all triggers)		
		Assumed reporting rate for non-fatal involvements		
		All (100%)	10%	5%
D2	0.55	0.07	0.007	0.004
D2.5	0.22	0.20	0.02	0.01
D3	0.17	0.43	0.07	0.04
D3.5	0.06	0.63	0.15	0.08
Frequency-weighted vulnerability		0.19	0.03	0.02

scenarios, such as by destructive size or avalanche type. Also, in any risk analysis, the terms probability, exposure and vulnerability, should be defined so as to be statistically independent.

As shown in Section 7, uncertainty can – and where practical should – be carried through vulnerability and risk estimations so it can be considered in risk management (ISO, 2009).

Qualitative and quantitative approaches each have their advantages. However, quantitative risk assessment requires that vulnerability be quantified as has been done recently for many avalanche risk mapping projects and for recreation. Recent studies have quantified vulnerability for buildings, people in buildings, people in cars, and recreationists in backcountry areas.

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