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A field method for identifying structural weaknesses in the snowpack

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Abstract: Recent studies have confirmed what experienced avalanche workers have known for years: that human-triggered avalanches often coincide with specific structural patterns in the snowpack. In this paper, we examine the role of five structural parameters (weak layer depth, weak layer thickness, grain type, grain size and hardness transitions) in 145 human-triggered avalanches in the Swiss Alps and Canada, and 39 non-fracture profiles from the Teton and Snake River Ranges in the U.S. We show that, while no single parameter is a reliable predictor of instability, a simple linear sum of threshold values can provide an approximate indicator of unstable conditions. This threshold-sum method predicts the stratigraphic location of fracture planes in a majority of the cases reviewed and, based on a limited data set, appears to have predictive value when assessing false stable avalanche conditions. Because the method uses parameter threshold values that are based on field expediency as well as statistical significance, it is especially well suited for novices learning how to interpret snow profiles. As with standard stability tests, the method gives approximate results that are best used in conjunction with other tests and observations.

Keywords: avalanche forecasting, snow stratigraphy, snow stability evaluation, avalanche education

1. Introduction

Experienced avalanche workers and backcountry guides use a variety of clues to help them identify potential weaknesses in snow profiles. Some clues, such as stability test results, relate to the shear strength of the weak layer and are relatively easy to interpret. Other clues, such as sudden hardness transitions in the snowpack or the presence of persistent snow grain types, arise directly from the structure of the snowpack itself. Structural factors are generally more difficult to interpret since no single structural clue alone indicates instability. Rather, the factors combine in complex ways to create an unstable slab. Recognizing which combinations of structural clues indicate instability takes practice over many seasons.

For novices, the task of interpreting snow profiles is a daunting one. While they may have the basic skills to collect stratigraphic information from a snow pit, they lack a systematic way of mentally sorting and prioritizing what they find. For many, the snow pit becomes a tedious operation that yields an overwhelming amount of ambiguous and often conflicting information. The result is the well-known tendency of novices to rely on one or two stability tests while ignoring important structural clues in the snowpack.

In this paper, we present a simple method for analyzing structural factors in snow profiles. The method combines informal snowpack clues, long used by field practitioners, with statistical results from well-documented avalanche accidents. Intended for students learning to collect and document snow pit data, this method is meant to supplement other tests and observations while providing a starting point for novice decision making.

The method is based on 145 fracture profiles of human-triggered avalanches. Ninety-five profiles came from the Swiss Alps, and have been previously described by Schweizer and Jamieson (2001), and Schweizer and Lütschg (2001). Fifty profiles came from published accounts of avalanche accidents in Canada, described in Stethem and Schaerer (1979, 1980), Schaerer (1987) and Jamieson and Geldsetzer (1996). To evaluate the method under field conditions, we used 39 non-fracture profiles from the Teton and Snake River Ranges of Wyoming and Idaho, collected during the winters 1997 to 2001. As in other studies based on fracture profiles from specific geographic regions, the selection bias inherent in the source data suggests caution in broadly applying these results.

2. Previous work

In this paper, we distinguish between *mechanical instability* (the shear strength of weak layer relative to applied stress) and *structural instability* (the tendency of the surrounding snowpack to concentrate shear stresses at the weak layer and to propagate a shear fracture along that layer). A substantial body of work has focussed on mechanical instability of weak layers, particularly as it relates to stability tests (see Jamieson, 1995 for a thorough review).

Considerably less work has been done on the more complex issue of structural instability. Perla (1980) was among the first to formally investigate the properties of the overlying snowpack in slab avalanches and describe the complex nature of structural instability. Ferguson (1984) quantitatively described grain size

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and slab thickness as stratigraphic factors identified with instability and employed cluster analysis to derive conditional avalanche predictors. Föhn (1993) and Jamieson and Johnston (1992, 1998a) explored the influence of slab thickness and microstructure on shear failure and strength changes, and Schweizer (1993) investigated the role of slab thickness and hardness in skier-triggered avalanching. More recent investigations have examined the roles of grain type, slab thickness, grain size and hardness profile in avalanching, as described in Schweizer and Jamieson (2001), and Schweizer and Lütschg (2001). Wiesinger and Schweizer (2001) describe a stability rating system based on rutschblock score, hardness profile, grain type and size, and weak layer configuration. The rating system they propose shows particular promise for computer-based forecasting operations.

In this study, we have not attempted to derive a set of universally accurate principles that work in all conceivable situations. Rather, our goal was to develop a expedient decision-making tool that novices can use to quickly recognize common instabilities. Educational psychologists have long recognized that simple, domain-specific rules, although they may not be universally accurate, are a crucial stepping stone in the process of moving from novice to expert (see, for example, Davis and Davis, 1998).

3. Description of profile parameters

We examined five parameters that are commonly assessed during the process of documenting a snow profile. For each parameter, we examined its significance in the human-triggered avalanches reported in the Swiss and Canadian data sets. In the comparisons that follow, we considered $p < 0.05$ to indicate a significant difference between parameter distributions.

3.1 Depth of the failure plane

In order to pose a hazard, a potential failure plane must be shallow enough to be triggered by a snow rider, hiker or snowmobiler. Föhn (1987), Jamieson (1995) and Schweizer and Camponovo (2001) have shown that skier forces dissipate rapidly below about 0.5 – 0.8 m. But because avalanches are frequently triggered in locations where weak layers are shallowly buried (Jamieson and Johnston, 1998b), slab depths from fracture line studies of human triggered avalanches may not accurately indicate how thick a slab must be in order to trigger it. On the other hand, a novice choosing a snow pit site that is both safe and representative of a start zone may find slab depths more typical of the fracture line than the trigger point. So, while we cannot be certain that fracture line data exactly defines hazardous slab thicknesses, we can be reasonably certain that the data is valuable for interpreting snow pit findings.

Consistent with previous investigations, we found that the vast majority (96%) of slab thicknesses were 1.0 m or less, with a median depth of 0.55 m (Figure 1). It is interesting to note that the slab thicknesses from the Swiss Alps (median of 0.52 m) differed by a small but statistically significant amount from Canadian slab thicknesses (median of 0.65 m). The Mann-Whitney (tied rank, normal approximation) probability of the two distributions being the same was p_{MW} = 0.0038, or a 99.6% percent chance that the two distributions are in fact different. This difference may arise from a number of sources, including regional snow depth (Swiss median was 1.18 m, Canadian median was 1.50 m, with p_{MW} = 0.0044), slab hardness and density, or other factors.

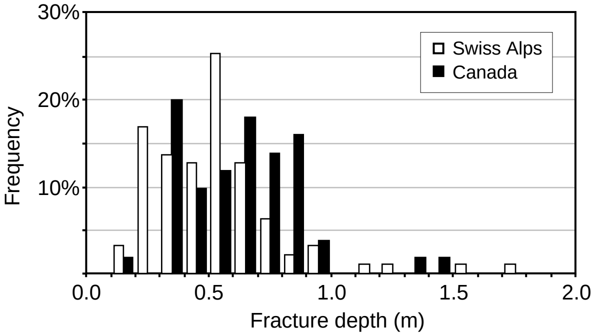

Figure 1. Fracture depth in Swiss (N=95) and Canadian (N=50) human-triggered avalanches.

3.2 Weak layer thickness

Thin weak layers are widely implicated in human-triggered avalanches, largely because of their tendency to concentrate shear stresses across their thickness (Schweizer, 1993). Unfortunately, there exists no standard definition of what “thin” means, or even what, precisely, constitutes a weak layer.

In assessing weak layer thickness, we defined layers that were perceptibly softer than the overlying slab as weak layers. We considered all other layer boundaries to be interfaces, including those where weak layers were so thin as to be indistinguishable (such as those with very small surface hoar crystals). Based on these definitions, we found that 37% of the failure planes in the combined data occurred on interfaces and 63% occurred in weak layers.

Figure 2 shows the distribution of weak layer thickness in Swiss and Canadian human-triggered avalanches. The two distributions are quite different; the median thickness in Swiss weak layers was 2 cm, whereas the median thickness in Canadian weak layers was 7 cm ($p_{MW} < 0.001$). Regional differences in snowfall, variations in data collection technique, and

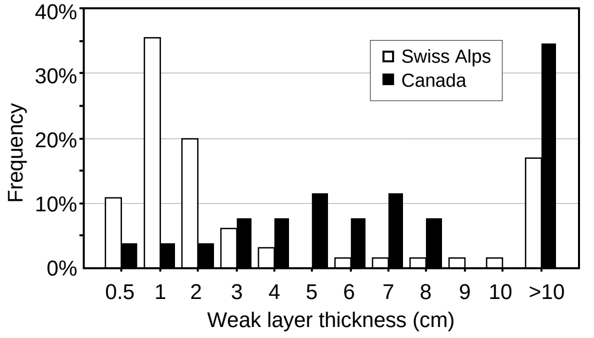

Figure 2. Weak layer thicknesses in Swiss (N=65) and Canadian (N=26) human-triggered avalanches.

other factors may explain at least part of this difference. In the combined data, 78% of all weak layers were 10 cm thick or less.

3.3 Hardness transition

Field practitioners have long recognized that abrupt hardness transitions in the snowpack signal a concentration of shear stresses at weak layers and interfaces. Schweizer and Lütschg (2001) reported that in Swiss accidents, hardness transitions across fracture planes had a median value of 1.5 hand hardness steps, a result that we duplicated in this study. We also found that hardness transitions across fracture planes in Swiss and Canadian accidents were not statistically different (t-test probability, $p_t = 0.760$), so we combined hardness data from the two data sets (Figure 3). In the combined data, 90% of the fracture planes in weak layers and interfaces had a hand hardness difference of 1 step or more. There was no significant difference between the hardness transitions at interfaces (including weak-layer lower boundaries) and weak-layer upper boundaries ($p_t = 0.433$) in the combined data set.

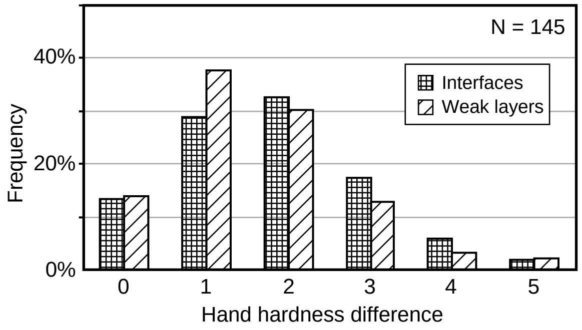

Figure 3. Hand hardness differences across fracture planes in Swiss and Canadian avalanche accidents.

3.4 Grain type

Certain grain forms have long been recognized as playing a key role in avalanche formation. Persistent grain types (facets, depth hoar and surface hoar) as well as ice lenses, crusts and grain type transitions typically raise suspicion in any snow profile.

Figures 4a and 4b summarize the occurrence of ICSI (1990) grain types in weak layers and interfaces of Swiss and Canadian human-triggered avalanches. Precipitation particles (pp), decomposed forms (df), rounded grains (rg) and wet grains (wg) were less common in weak-layer fracture planes, while facets (fc), depth hoar (dh) and surface hoar (sh) were more common. Persistent grain types occurred in 94% of all weak layers. Rounded grains and facets dominated interface fractures, with persistent grain types being present in 61% of interface fractures. Traces of surface hoar (not shown in Figure 4b) were reported in 2 of the 51 fracture plane interfaces; all other instances of surface hoar were considered to be weak layers. Regional differences in snow climate may account for at least some of the variation between grain type in Swiss and Canadian fracture planes. In the combined data set, persistent grain types were present in 82% of the fracture planes, a finding which agrees well with previous studies (Schweizer and Jamieson, 2001).

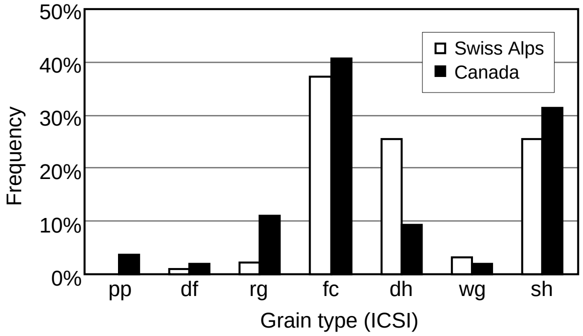

Figure 4a. Grain type in Swiss (N=65) and Canadian (N=28) human-triggered weak layers.

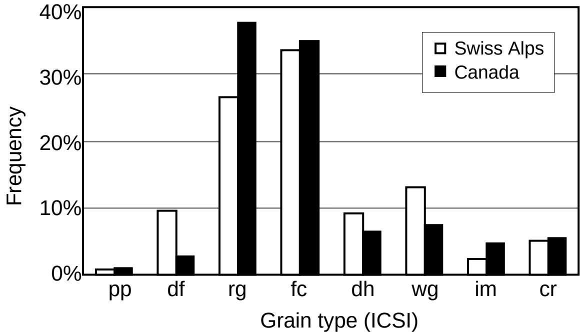

Figure 4b. Grain type in Swiss (N=29) and Canadian (N=22) human-triggered interfaces.

3.5 Grain size

Distinct changes in grain size in a snow profile are routinely recognized as likely locations for potential fracture planes. Colbeck (2001) has described a theoretical framework under which fracture between snow grains of dissimilar sizes might take place. In both the Swiss and Canadian accident data, 65% of all fracture planes had a grain size difference across them of 1 mm or greater. In 10% of the fracture planes, the grain size difference was greater than 4 mm: all of these cases involved fracture planes on large surface hoar crystals or on clear ice lenses.

Maximum grain size difference does not stand out as a strong comparative predictor of fracture location among *differing* snow profiles, but it appears to be an important parameter within *individual* profiles. In profiles where all grain sizes were known, 74% of the fractures occurred at the point of maximum grain size transition.

4. Parameter thresholds and avalanche conditions

So far, we have examined how various structural parameters are distributed in Swiss and Canadian avalanche accidents. Table 1 shows threshold values we assigned to these parameters, some based on informal

Parameter	*Threshold*	*Percentage*
Depth	≤1 m	96%
Weak layer thickness	≤ 10 cm	78%
Hardness difference	≥ 1 step	90%
Grain type	persistent	86%
Grain size difference	≥ 1 mm	65%

Table 1. Threshold values for structural parameters in fracture planes. Percentage indicates the number of accidents included in the threshold value.

thresholds used by field practitioners and some chosen as a balance between statistical significance and ease of use in the field. Consistent with field experience, Table 1 shows that no single parameter was a perfectly reliable indicator of instability.

To understand how combinations of these parameters, rather than their singular presence, suggests instability, we used a simple linear sum of threshold conditions to assign a score to each fracture plane in the Swiss and Canadian data sets. The results appear in Figure 5.

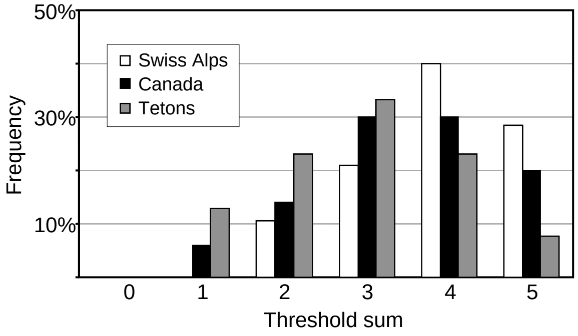

Figure 5. Threshold sums in fracture planes in Swiss (N = 95) and Canadian (N = 50) human-triggered avalanches, and non-fracture profiles in the Teton Range (N = 39).

Fracture planes from human-triggered avalanches in the Swiss Alps had a median threshold sum of 4. In contrast, Canadian fracture planes had a median threshold sum of 3.5. The difference between the two threshold-sum distributions was statistically significant ($p_t = 0.028$). While at least some of this difference may be due to regional variations in threshold values (as already shown), we cannot rule out the possibility that threshold sums are regionally dependent.

5. Applications

To assess how the threshold-sum method might apply to another region, we evaluated 39 non-fracture profiles from the Teton and Snake River Ranges in Wyoming and Idaho. Because these ranges form a continuous massif and experience very similar weather conditions, we considered them as a composite data set. While the two ranges probably have some regional snowpack differences from the Swiss and Canadian accidents, we feel that the similarities (particularly with regard to the threshold values we chose) justify the comparison.

The non-fracture profiles had a median threshold sum of 3 at the most significant fracture plane. The difference in threshold conditions between the Teton data set and the combined Swiss and Canadian data was highly significant ($p_t < 0.001$). However, the difference between the Teton data and the Canadian data alone showed about the same level of significance ($p_t = 0.029$) as the difference between the Swiss and Canadian data. This suggests that regional variation in median threshold sums may explain the difference between the fracture and non-fracture profiles.

When observers collected the non-fracture profiles, they also made a subjective assessment of snow stability on similar slopes, characterized as very poor (5), poor (4), fair (3), good (2), or very good (1). As expected, their stability assessments correlated well with the rutschblock scores they obtained in their snow pits (Spearman tied-rank correlation, $r_s = -0.702$, $p_s = 0.002$). Stability assessments also correlated with the maximum threshold sum in each snow profile, although to a lesser degree ($r_s = 0.428$, $p_s = 0.018$). Importantly, the threshold sum did *not* directly correlate with rutschblock score ($r_s = -0.174$, $p_s = 0.345$), suggesting that observers were not always basing their stability assessments on rutschblock scores alone. In other words, when significant weak layers or interfaces were present in the snowpack (threshold sums of 4 or 5), observers had a tendency to rate the stability as lower, even when rutschblock scores might indicate otherwise.

So-called “false stable” conditions exist when rutschblock and other tests indicate stability and yet an avalanche still occurs (Jamieson, 1995). These conditions appear to be rather uncommon; we were able to find only nine fully documented cases of false stable conditions (rutschblock scores of 6 or 7). In about half of these cases, the slab depth was greater than 0.7 m, meaning that the rutschblock test may not have been effective in loading the fracture plane. In other cases, the fracture profile could not be not dug on a slope that was fully representative of the start zone. For these and other reasons, rutschblock tests at the fracture profile site may not have accurately represented stability conditions on the slope that failed. Nevertheless, all of these nine false-stable profiles had threshold sums of four or five. This very small data set suggests the possibility that the threshold-sum method can detect potentially hazardous structural instabilities, even when rutschblock scores (which measure spatially variable mechanical instability) are high. One possible explanation is that structural instabilities, which are assessed by the threshold-sum method, exhibit less spatial variation than mechanical instabilities, which are assessed by conventional stability tests. Of course, further study will be needed to fully verify this relationship.

The threshold-sum method also shows promise for identifying which weakness in a snow profile will become the bed surface in an avalanche. In 41 profiles, we were able to identify the layer(s) that had the maximum threshold sum. In 37 (90%) of those cases, the bed surface coincided with one of these maxima. Of the remaining four cases, three involved fracture planes in new precipitation particles or fragmented forms. In other words, the threshold-sum method accurately predicted the stratigraphic location of the fracture plane in over 97% of cases where the avalanche occurred in older snow.

6. Summary

We presented a simple method for assessing structural weaknesses in snow profiles, based on threshold values for five parameters (Table 1). This method supplements tests which are aimed at finding mechanical weaknesses (such as stability tests), thereby diminishing the chances of a false-stable result. Key features of the method are:

1) Threshold-sum values of four or five correlate well with unstable conditions.
2) Based on a limited data set, this correlation appears to hold even under false stable conditions.
3) In a given profile, the layer with the maximum threshold sum will likely form the bed surface of any subsequent avalanche.

Profile interpretation is a skill acquired over many seasons. This method offers novices an early opportunity to see the significance of snow profile analysis by giving them a framework to apply their results to decision making in avalanche terrain. While our verification of the method is somewhat preliminary, we nevertheless believe that the method has value in providing novices with an alternative to over-reliance on stability tests.

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