Contrasting stable and unstable snow profiles with respect to skier loading

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Abstract: A Swiss-Canadian data set of over 400 snow profiles from skier-triggered slopes and slopes that have been skied but not triggered was contrasted to derive statistically relevant differences that can be used in snow profile interpretation. For some typical slab properties such as slab thickness and density, as well as for snow temperature, no significant difference was found between stable and unstable profiles. However, the analysis showed that the following parameters are indicators of snow instability with respect to skier loading: low rutschblock score, large and persistent grains in soft failure layer, large difference in grain size and hardness across the failure interface. According approximate critical values to distinguish between stable and unstable profiles were given, that can be used by practitioners as well as for model development.

Keywords: snow stratigraphy, avalanche formation, avalanche forecasting, snow cover stability, snow stability evaluation, skier triggering

1. Introduction

Snow profiles with stability tests are the most direct stability information for avalanche danger assessment, besides avalanche occurrences. However, profile interpretation is lacking objectivity. The interpretation scheme proposed by Schweizer and Wiesinger (2001) is based on experience rather than data. Although unstable profiles seem to have specific characteristics, as shown by Schweizer and Jamieson (2001), it is unclear so far whether these characteristics are unique for unstable profiles or present in most profiles. The only comparison of stable with unstable profiles was only partly conclusive (Ferguson, 1984). Therefore we contrast a data set of over 400 snow profiles from skier-triggered slopes and slopes that have been skied but not triggered to derive statistically relevant differences. The analysis is focused on skier triggering and only dry snow conditions are considered. These limitations follow from the fact that in Europe and North America most avalanches that cause fatalities, are dry slabs triggered by people (Atkins and Williams, 2001; Jamieson and Geldsetzer, 1996; Tschirky et al., 2001).

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2. Data

We explore two data sets of snow profiles: one from Switzerland (typical snow depth 2 m) and one from the Columbia Mountains of western Canada (typical snow depth 3 m). For each country we have “unstable” profiles from skier-triggered avalanches that have been taken usually one day after the release, and about the same number of “stable” profiles taken from avalanche start zones that were skied but not triggered. The profiles from these slopes were gathered during various field studies for avalanche research or for stability evaluation purposes. The data were collected during the winters 1988-89 to 2001-02. For all profiles the primary weakness is known. Either it is the failure plane of the skier-triggered avalanche, or it has been found with a stability test such as the rutschblock test or compression test. In total 424 cases were analysed as shown in Table 1. To simplify the following analysis we do not differentiate between Swiss and Canadian data, but contrast snowpack properties from stable slopes with those from unstable slopes. This combining of datasets is questionable since the snow climates are different - but both are transitional, between maritime and continental.

Table 1: Characteristics of snow profiles

Country	stable	unstable
Switzerland	105	103
Canada	99	117
Total	204	220

3. Methods

Generally, snow cover properties were classified according to Colbeck et al. (1990). Layer thickness, grain type, grain size, hand hardness index, and snow temperature were recorded. For the analysis, average properties for the slab were derived, and the grain type summarized as non-persistent, persistent (facets, depth hoar, or surface hoar) or crust. Hand hardness for individual layers is indexed from 1 to 6 for Fist (F), Four-Finger (4F), One-Finger (1F), Pencil (P), Knife (K) and Ice (I), respectively (Geldsetzer and Jamieson, 2001). Snowpack consolidation or hardness distribution within the snowpack was classified according to the hardness profile types given in Schweizer and Lütschg (2001). In addition to the data gathered in the field, the hardness and grains size differences across the failure interface were considered (Schweizer and Jamieson, 2001). Where compression test results were available but not rutschblock results, we converted the compression scores to equivalent rutschblock scores according to Jamieson (1999).

Special attention was given to the primary weakness as revealed by the avalanche release or a stability test. We followed a partly new approach. In most cases the failure is reported to be at the boundary (interface) between two adjacent layers. The softer of the two layers we consider as the “failure layer”, the layer across the failure boundary as the “adjacent layer”. If the failure interface was not reported we assumed the failure interface to be adjacent to the layer with the larger hardness or grain size difference, or in case of no difference for the upper and lower layer, we chose the lower layer as the adjacent layer.

To compare stable to unstable data, we use the non-parametric Kruskal-Wallis or *H*-test. If the *p*-value of significance is $p < 0.05$, the two samples are considered as significantly different, i.e. the variable is a significant indicator of instability. Comparing categorical variables such as grain type or profile type, the distributions are compared by cross-tabulating the data and calculating the Pearson χ^2 statistic.

4. Results

Comparing elevation, aspect and slope angle shows no significant difference between stable and unstable profiles. This suggests that the following results do not depend on terrain factors. Table 2 compiles the results of the statistical analysis for the snow profile variables. Combining the Swiss and Canadian data sets adds variability which is undesirable, but the variables that show up as significant, are accordingly quite indicative for discriminating between stable and unstable profiles. The most indicative snowpack variables are: failure layer grain size and hardness, differences in hardness and grains size across the failure interface, and not surprisingly, the rutschblock score. Most slab properties such as hardness, thickness, and snow temperature show no predictive power in regard to skier triggering for the

Table 2: Stable-unstable comparison of snow profile variables. For the grain type and the hardness profile type the most frequent types are given, instead of the median. Highly significant variables are marked in bold (p<0.001) with three asterisks, significant variables with one asterisk (0.001<p<0.05).

Variable	*N*	Median		*p*
		stable	unstable	
Snow depth (cm)	404	186	187	0.24
* Slab hardness	410	2 (4F)	1.8 (4F-)	0.003
Slab thickness (cm)	424	45	47	0.63
Slab snow temperature (°C)	402	-5.5	5.0	0.45
Slab density (kg m^{-3})	257	160	140	0.07
* Failure layer grain type	424	4,2,7	7,4,2	0.001
***Failure layer grain size (mm)**	421	1.1	2	<0.001
***Failure layer hardness**	401	2 (4F)	1 (F)	<0.001
Failure layer thickness (cm)	424	3	1.5	0.15
Failure layer snow temperature (°C)	359	-4.4	-4.0	0.94
Adjacent layer grain type	397	3,6,4	3,4,6	0.10
Adjacent layer grain size (mm)	357	0.75	0.75	0.09
Adjacent layer hardness	423	3 (1F)	3 (1F)	0.96
Adjacent layer thickness (cm)	424	8	8	0.53
***Grain size difference across failure interface (mm)**	356	0.5	1.1	<0.001
***Hardness difference across failure interface**	401	1	1.7	<0.001
***Rutschblock score**	369	5	3	<0.001
* Type of hardness profile	424	6,7	6,7	0.001

data sets analysed. Also, adjacent layer properties vary too widely to be useful discriminators.

5. Discussion

Table 2 reveals that the following parameters are indicators of snow instability: soft slabs, large and persistent grains in a soft failure layer, large difference in hardness and grain size across failure interface, and low rutschblock scores.

Applying other statistical methods like discriminant analysis and binary classification trees confirm the importance of these parameters, and suggest the approximate ranges associated with instability shown in Table 3. An example of a hardness difference of 1.7 would be failure layer hardness of F and adjacent layer hardness of 1F-. Interestingly, grain size (difference across interface and that of the failure layer) is ranked higher than hardness (difference across interface and that of the failure layer). Preliminary analysis suggests that using the ranges in Table 3 to classify snow profiles into either stable or unstable would result in about 60-75% correct classifications. We emphasize that while these critical ranges may be useful for assessing snow profiles in the Swiss Alps or Columbia Mountains, a complete stability evaluation as a basis for decisions also depends on other factors such as recent avalanche activity, weather and snowpack distribution.

Table 3: Parameters of instability and proposed "unstable" ranges for snow profile classification.

Parameter	Critical range
Rutschblock score	< 4
Grain size difference	≥ 0.75 mm
Failure layer grain size	≥ 1.25 mm
Hardness difference	≥ 1.7
Failure layer hardness	$\leq$ F+

6. Conclusions

Based on a large data set of stable and unstable profiles from Switzerland and Canada we have shown that distinct characteristics between most stable and unstable profiles exist. This will provide a data based method for profile interpretation used for stability evaluation that was so far lacking objectivity. For the future we propose to apply statistical classification methods to derive a model for classifying snow profiles.

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