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A threshold sum approach to stability evaluation of manual snow profiles

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Abstract

Snow profile interpretation has developed in the last few years from being based on experience into a semi-quantitative scientific method. Emphasizing structural rather than mechanical instability, threshold values were developed for key parameters such as weak layer grain size and hardness, and differences in grain size and hardness between layers. Despite promising attempts so far it has not been shown that this method works to quantitatively interpret snow profiles, in particular if the principal weakness is unknown. Our aim was to provide an easy and robust method based on a threshold sum approach to assess snowpack stability based on layer properties. Second, we investigated whether that method was also suited to find the principal weakness (in case it is unknown) and assess the probability for a skier-triggered avalanche on this weakness. Our data set consisted of 500 manual snow profiles observed over 16 years on skier-tested and skier-triggered avalanche slopes from both western Canada and Switzerland. A weighted threshold sum with the failure layer depth as independent variable scored highest (77% for the learning data set, 65% for the test data set). Detection of potentially critical layers proved to be less successful, in particular for the Swiss profiles. If the principal weakness was unknown, the stability classification for the potentially critical layers agreed with the observed stability for the Swiss profiles in about 53% and for the Canadian profiles in about 62% of the cases. The results emphasize that stability assessment should include – besides stability tests that help locate the principal weakness – analysis of snow layer properties, in particular grain size, type and hardness. The proposed threshold sum considering seven variables is well suited for profile analysis of manual profiles by practitioners. Stability classification of snow profiles simulated by snow cover models such as SNOWPACK will need further adaptation, in particular for application in transitional snow climates.
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1. Introduction

Snowpack stability evaluation for avalanche forecasting relies on weather data, snowpack data and avalanche observations. Snowpack data in the form of snow profiles and stability tests are the crucial information in the absence of avalanche occurrence data to derive snow stability (Schweizer et al., 2003). Stability tests are powerful, but occasionally give misleading results, i.e. false-stable predictions. Also, stability test results seem to be more susceptible to spatial variations of snowpack properties than e.g. layer characteristics such as grain type and size (Kronholm, 2004).

Consequently, McCammon and Schweizer (2002) proposed to augment information on mechanical instability such as the shear strength or stability test scores with data on structural instability such as grain type and

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size, or hardness difference across a potential failure interface. Structural instability was defined as the tendency of the surrounding snowpack to concentrate shear stresses at the weak layer or interface and to propagate a shear fracture along that layer or interface. They showed that, while no single parameter was a reliable predictor of instability, a simple count of the variables that were in a critical range (threshold sum) provided an approximate indicator of unstable conditions. No comparison to stable profiles was given and it is not clear whether the threshold sum can discriminate between stable and unstable conditions.

Based on a comparison of snow profiles from skier triggered avalanches with profiles from skier-tested slopes that did not release Schweizer and Jamieson (2003) showed that there are significant variables to predict instability and proposed corresponding critical ranges for each variable. Besides the score from a mechanical test (rutschblock), they found the following snow stratification variables to be indicative of snowpack instability: difference in grain size across the failure interface, failure layer grain size, difference in hardness across the failure interface and failure layer hardness. However, the multivariate classification tree they proposed was difficult to apply for operational forecasting and they did not provide any verification of their findings. In addition, their whole analysis was based on the assumption that the critical failure layer was known, i.e. a mechanical test was required to identify the critical weakness. This restriction hinders some applications, in particular, the application of their results to simulated snow cover profiles.

The aim of the present study was to combine the approaches by McCammon and Schweizer (2002) and Schweizer and Jamieson (2003) to (1) provide a robust and easy to use method to assess the probability of skier triggering from snow layer properties at the failure interface, and (2) demonstrate that the method can also be used to find potential failure layers when the location of the critical failure layer is unknown, or to identify additional weaknesses that did not show up in the stability test, or to apply the method to snow profiles simulated by a snow cover model such as SNOWPACK (Lehning et al., 1999).

2. Data

We used snow profile data from the Columbia Mountains of western Canada and the Swiss Alps collected during the winters of 1988–89 to 2003–04. About half of the profiles were taken near the fracture line of or on slopes adjacent to skier-triggered avalanches; these were called “unstable” profiles. The other half were so-called “stable” profiles observed on slopes that were skied but no avalanche was released. We split the data set into a learning data set of 424 cases, the same as used by Schweizer and Jamieson (2003), and a test data set of 109 profiles as shown in Table 1. The test data set included primarily profiles from the winters 2002–03 and 2003–04. Many of the stable profiles in the test data set had relatively poor stability due to targeted sampling (McClung, 2002) compared to the learning data set.

However, comparing the two samples for all seven variables showed that there were no statistically significant differences between the samples except for the variable failure layer hardness ($p=0.02$). Failure layers were slightly softer in the test sample (mean = 1.5, median = 1) than in the learning sample (mean = 1.7, median = 1–2). The suspected bias due to targeted sampling was in part confirmed by a slightly lower RB score in the test sample (mean = 3.9, median = 4) than in the learning sample (mean = 4.3, median = 4). However, the difference was statistically not significant ($p=0.06$).

For cases with missing data, values were not imputed so that for a multivariate analysis the learning data set reduced to 296 cases without any missing data. There were no missing values in the test data set. Overall, there were 230 stable cases and 175 unstable cases with no missing data.

3. Methods

Five variables were analyzed that showed very high significance as classifiers in the analysis by Schweizer and Jamieson (2003): Rutschblock (RB) score, failure layer (FL) grain size, failure layer hardness and differences in grain size and hardness across the failure interface. These were supplemented with failure layer grain type which also was highly significant in their analysis and failure layer depth. Failure layer depth was introduced to take into account the fact that the probability of skier triggering strongly decreases with increasing slab thickness (Schweizer and Camponovo, 2001; Schweizer and Jamieson, 2001). For shallow weak layers, in the range of the penetration depth, the probability of triggering is also decreasing.

Table 1
Characteristics of snow profile data sets used for model development and testing (number of profiles)

Data set	Country	Stable	Unstable
Learning	Canada	99	117
	Switzerland	105	103
Test	Canada	38	16
	Switzerland	30	25

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