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Refinements of empirical models to forecast the shear strength of persistent weak snow layers PART B: Layers of surface hoar crystals

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Abstract

Buried layers of surface hoar often release skier-triggered avalanches in the Columbia Mountains of Canada and their shear strength can be used to assess the stability of a slab overlaying these layers. In 2001 Chalmers introduced an Interval Model to calculate the shear strength of layers of surface hoar based on manual snowprofile observations. We refined his model by adjusting the measured shear strength for the normal load and included only data points where the weak layer depth did not exceed 100 cm to better account for skier triggering. Further, we used average and daily loading rates as well as a regression analysis to determine the best estimate of the shear strength change. Our final Forecasting Model used a multivariate regression to calculate the shear strength on days with snowprofile observations and as well as average and daily loading rates to forecast the shear strength on days without manual snowprofile observations. The performance of the model (r^2) was 0.71 and 0.63 using average and daily loading rates, respectively. A companion paper, Part A, develops a forecasting model for weak layers of faceted crystals.

Keywords: Avalanche forecasting; Snow stratigraphy; Surface hoar; Snow cover stability

1. Introduction

The stability of a slab overlaying a weak layer depends partly on the shear strength of the weak layer, which can be measured with a shear frame. Unfortunately shear strength measurements are time consuming and are not done on a regular basis in most forecasting operations. Therefore it is desirable to be able to calculate the shear strength without shear frame testing so that this information can be used in daily avalanche forecasting. Although the shear strength of snow is influenced by the number, size, shape and orientation of intergranular bonds (Yoshida, 1963; Keeler, 1969; Colbeck, 1997), shear strength changes are hard to quantify and consistent measurements are rare. Chalmers (2001) and Zeidler and Jamieson (2002) have shown that the calculation of the shear strength based on snowprofile observations is promising, although the estimation of the shear strength change on days when no snow profiles are recorded is more difficult.

Hägeli and McClung (2003) analyzed the characteristics of natural avalanches and list three types of

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persistent weak layers most relevant to avalanche occurrences in the Columbia Mountains of Canada: 1) faceted crystals, 2) surface hoar and 3) interfaces with melt–freeze crusts. In Part A of this paper we developed an empirical model to calculate the shear strength of layers of faceted crystals; Part B is concerned with layers of surface hoar crystals. Prominent surface hoar layers are generally prone to natural avalanche activity for about three to four weeks after burial (Hägeli and McClung, 2003). Similar to the characteristics of natural avalanche activity, layers of surface hoar are the failure layers for many skier-triggered avalanches in the Columbia Mountains and skier triggering is less likely after about 30 days (Chalmers, 2001). In the Columbia Mountains it is common that two to three prominent surface hoar layers per winter are observed in the snowpack.

Chalmers and Jamieson (2003) used multivariate regressions to calculate the shear strength on days with snowprofile observations and to forecast the shear strength change on days without snowprofile observations in the Columbia Mountains of Canada. The fit of their results yielded coefficients of determination of $r^2=0.74$ and 0.32, respectively. Combining these two regression models, estimates of shear strength and stability within eight days of a snowprofile were promising. Their Forecasting Model accounted for 72% of the variability in their data and for five independent test series the shear strength was estimated on average to within 22% of the measured values. The authors used shear strength measurements up to 30 days from the day the surface hoar was buried. However, in this paper we consider the weak layer depth more important for skier triggering and use a cut-off of 100 cm instead of 30 days. In addition, we adjusted the measured shear strength to the normal load (see Part A), which is reduced during shear frame testing. Further we assess a strength change regression (Zeidler, 2004) as well as average and daily loading rates to estimate the shear strength change on days without snowprofile observations.

2. Study area

As in Part A most study sites were on or close to Mt. St. Anne and Mt. Fidelity as well as in the Bobbie Burns in the Columbia Mountains and at Bow Summit in the Rocky Mountains (Fig. 1).

The Rocky Mountains are in a continental snow climate which is characterized by low snowfall, cold temperatures and shallow snow covers whereas the Columbia Mountains are in an intermountain snow climate with a combination of maritime and continental influences which results in deeper snowpacks than in the Rocky Mountains and fewer persistent weak layers (LaChapelle, 1966; Hägeli and McClung, 2003).

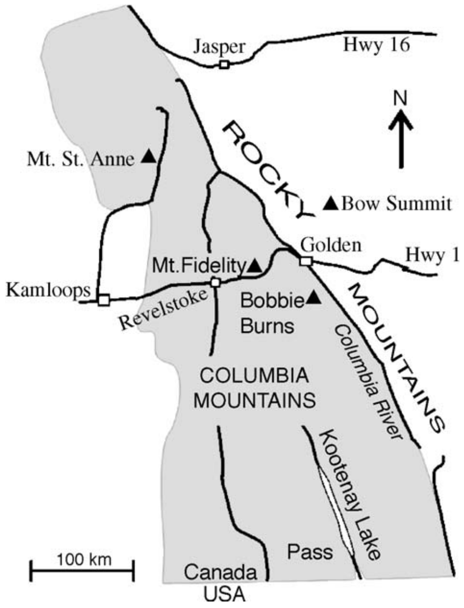

Fig. 1. Map showing the location of study sites at Mt. St. Anne, Mt. Fidelity, Bobbie Burns and Bow Summit.

However, the shear strength change of persistent weak layers is generally comparable in the two snow climate zones (Zeidler, 2004), but some differences are discussed subsequently.

Meteorological variables were available from remote weather stations at Mt. St. Anne at an altitude of 1900 m near Blue River and at 1905 m on Mt. Fidelity in Glacier National Park. In addition precipitation data were available from Bow Summit and the Bobbie Burns. Snowpack data and the shear strength of persistent weak layers were recorded once or twice per week in a level study plot on Mt. St. Anne and on a study slope (25–37°) at 1890 m on Mt. Fidelity.

3. Methods

3.1. Model building

In this analysis we used the same basic equation as Chalmers' in 2001 in his Interval Model for forecasting the shear strength of surface hoar layers:

$$\Sigma_j{}^* = \Sigma_i{}^* + \Delta t_{ij}(\Delta\Sigma/\Delta t)^*_{ij} \tag{1}$$

where Σ^*_i and $(\Delta\Sigma/\Delta t)^*_{ij}$ are functions of snowpack observations on day i; Σ^*_i is the estimated shear strength