Forecasting shear strength and skier-triggered avalanches for buried surface hoar layers

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1. Extended abstract

In the Columbia Mountains of western Canada, skier-triggered slab avalanches on weak layers of buried surface hoar occur mostly within the first 10 to 20 days after a layer is buried (e.g. Chalmers and Jamieson, 2001), and the transition of such layers from unstable to stable conditions is difficult for avalanche professionals to forecast.

Schleiss and Schleiss (1970) introduced a snow Stability Ratio (Canadian Avalanche Association, 2002) based on shear frame tests of the weak layer, which has been used since c. 1960 at the Mount Fidelity study plot to extrapolate snowpack stability for natural avalanches in the Rogers Pass highway corridor. Föhn (1987) developed a stability index for skier triggering that was refined by Jamieson and Johnston (1998). When the index is based on shear frame tests in a study plot and extrapolated to surrounding avalanche slopes (average slope angle of 38°), the index is denoted Sk_{38} (Jamieson, 1995). Jamieson (1995) converted Sk_{38} into an equivalent rutschblock score RBcalc.

Over the winters 1995-2001, over 70 layers of buried surface hoar were monitored at study sites in the Columbia Mountains, using snow profiles and shear frame tests of surface hoar layers. The snowpack observations of this study were consistent with the guidelines of the Canadian Avalanche Association (2002), except for the thickness of a buried surface hoar layer, which was measured to the nearest millimetre. These sites were selected to be representative of the snowpack in surrounding avalanche starting zones. Within approximately 100 km of two sites, Mt. Fidelity and Mt. St. Anne, skier-triggered avalanches and the critical weak layers were often reported by surrounding helicopter skiing operations (Figure 1).

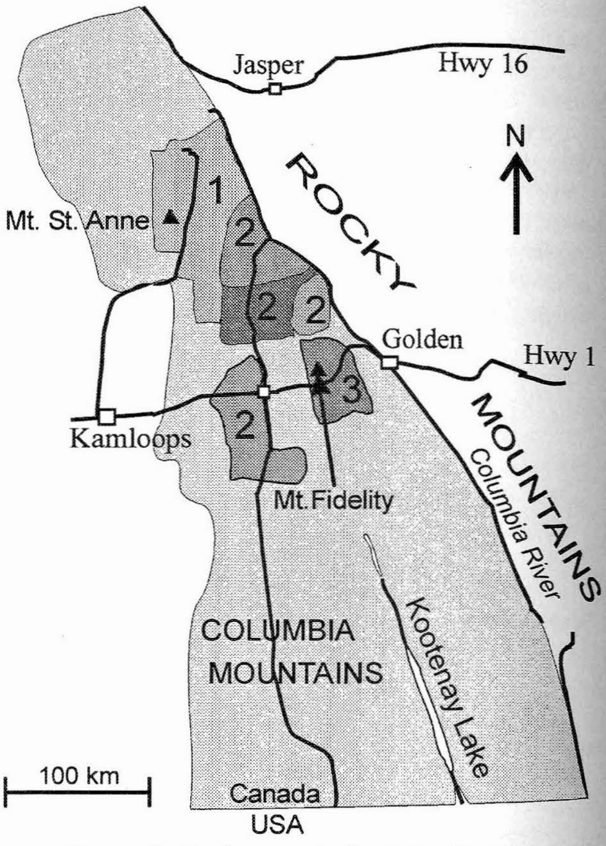

Figure 1: Study areas in the Columbia Mountains: 1) Mike Wiegele Helicopter Skiing, 2) Canadian Mountain Holidays Adamants, Gothics, Monashees, and Revelstoke, 3) Glacier National Park. Skier-triggered avalanche activity data for Mt. Fidelity region gathered from areas 2 and 3. Skier-triggered avalanche activity data for Mt. St. Anne region gathered from area 1.

The objectives of this study were:

1. to develop an empirical model that could be used to forecast the shear strength (Σ) of buried surface hoar layers in the Columbia Mountains, and
2. to assess the stability index RBcalc, based on forecast strength of surface hoar layers, with skier-triggered avalanche activity from the region.

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Table 1: Snowpack variables and units at time t_i (age of weak layer, in days, at start of prediction interval).

Variable	Description (units)
Σ_i	Shear strength of weak layer (kPa)
σ_i	Vertical load (force per unit area) due to snow overlying weak layer (kPa)
H_i	Thickness of snow slab overlying weak layer, measured vertically (cm)
HS_i	Total height of snowpack (cm)
$Thick_i$	Thickness of weak layer (cm)
Twl_i	Temperature of weak layer (°C)
TG_i	Magnitude of temperature gradient across weak layer (°C $10cm^{-1}$)
$Emin_i$	Minimum grain size in weak layer (mm)
$(TG/Twl)_i$	Average temperature gradient across weak layer divided by average weak layer temperature ($10cm^{-1}$)

Ideally, an observer may perform standard snowpack and weather observations in a snow study site, and then use the model to forecast the strength until the next snowpack observation day. The forecast strength and stability index, if accurate, may then be assimilated with other forecasting variables and methods to aid the forecaster in making decisions.

The model may be thus broken into two components:

1. estimating shear strength of the buried surface hoar layer on the day when the snowpack observations are made and,
2. estimating the strength change between the measurement day and an arbitrarily selected day up to eight days in the future. In an operational situation, the next measurement day would be the day on which a new set of snowpack observations is made (and the model is re-initialised).

This model consists of two empirical functions:

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

where Σ_i^* and $(\Delta\Sigma/\Delta t)_{ij}^*$ are functions of snowpack observations on day *i*.

Σ_i^* is the estimated shear strength on the snow observation day at the start of the forecast interval, Δt_{ij} is the time interval until a forecast day (up to eight days in the future), $(\Delta\Sigma/\Delta t)_{ij}^*$ is the model estimated rate of change in shear over the forecast interval. Using multiple stepwise regression, the important snowpack variables (Table 1) and empirical formulae for $(\Delta\Sigma/\Delta t)_{ij}^*$ and Σ_i^* in Equation 1 are yielded:

$$\Sigma_i^* = 0.336\ \text{kPa} + (0.0139\ \text{kPa d}^{-1} \cdot t_i) + (1.18 \cdot \sigma_i) - (0.00625\ \text{kPa cm}^{-1} \cdot H_i) + (0.000804\ \text{kPa cm}^{-1} \cdot HS_i) - (0.287\ \text{kPa cm}^{-1} \cdot Thick_i) + (0.0187\ \text{kPa °C}^{-1} \cdot Twl_i) + (0.0204\ \text{kPa mm}^{-1} \cdot Emin_i). \qquad (2)$$

$$(\Delta\Sigma/\Delta t)_{ij}^* = 0.119\ \text{kPa d}^{-1} - (0.000547\ \text{kPa d}^{-2} \cdot t_i) - (0.124\ \text{d}^{-1} \cdot \Sigma_i) + (0.107\ \text{d}^{-1} \cdot \sigma_i) + (0.000131\ \text{kPa d}^{-1}\text{cm}^{-1} \cdot H_i) + (0.000176\ \text{kPa d}^{-1}\text{cm}^{-1} \cdot HS_i) - (0.0473\ \text{kPa d}^{-1}\text{cm}^{-1} \cdot Thick_i) - (0.0378\ \text{kPa d}^{-1}\,10\text{cm °C}^{-1} \cdot TG_i) - [0.0827\ \text{kPa d}^{-1}\ 10\text{cm}^{-1} \cdot (TG/Twl_i)]. \qquad (3)$$

When tested for fit to the data used to construct it, the model accounts for 72% of the variability in the data.

Two time series of buried surface hoar, buried 10-February-1997 and 30-December-1999 at the Mt. St. Anne Study Plot, were withheld from the dataset used in model construction. The model was applied to the 11 data points of these two time series, and forecast shear strength at the end of an interval (nine data points) to within an average of 18% of the measured values.

The stability index RBcalc, calculated from shear strength in Equations 1-3 for the two test series, are plotted against skier-triggered avalanche activity reported on these layers by helicopter skiing operations in the surrounding region (Figure 2). For comparison, RBcalc derived from actual shear strength values are also plotted.

For the 10-February-1997 surface hoar layer, all of the reported avalanches occurred before measured and modelled RBcalc climbed through the 4-6 band of transitional stability. For the 30-December-1999 surface hoar layer, all of the avalanche days occurred before the measured RBcalc exceeded 6, and all but one of the avalanche days occurred before the modelled RBcalc exceeded 6.

While more data are required to verify the model, the presented data show the model is promising for predicting the regional stability of buried surface hoar layers in the Columbia Mountains.

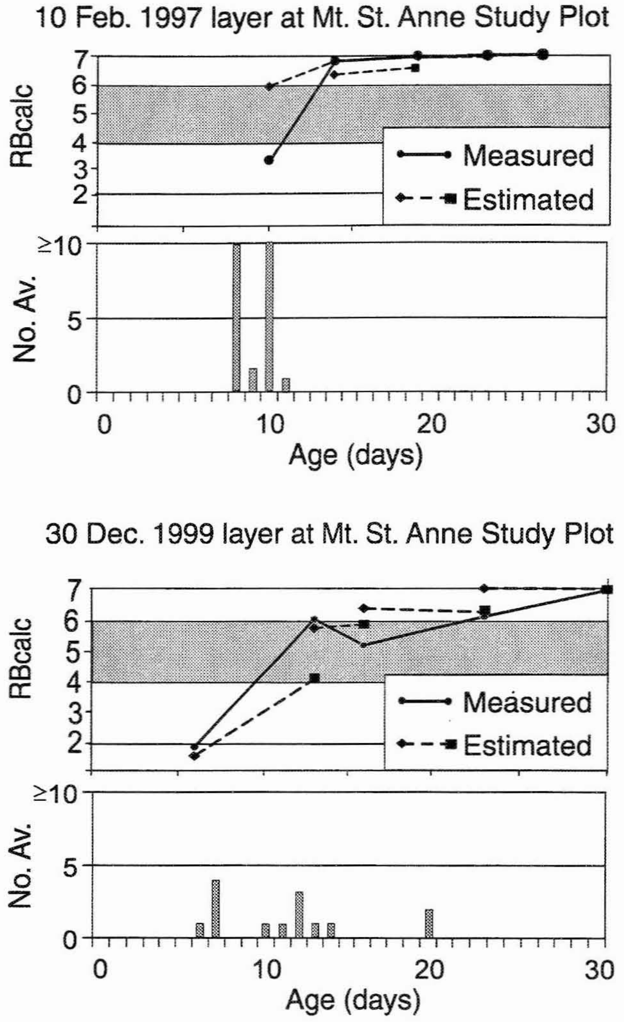

Figure 2: Skier-triggered avalanche activity and calculated rutschblock scores (measured and forecast).

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