SAWLEM: SLAB AND WEAK LAYER EVOLUTION MODEL

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ABSTRACT: Snowpack evolution models developed in Europe require meteorological and radiation instrumentation rarely used in North America. In contrast, SAWLEM uses a spreadsheet to model the evolution of persistent weak layers and the overlying dry slabs using weekly manual snow profiles in a study plot and daily measurements or long-term average values of snowfall. The shear strength of a persistent weak layer, dependent on the grain type, is estimated based on parameters such as slab load, grain size, thickness of the weak layer, thickness of the slab, snowpack height and temperature just below the weak layer from a detailed manual profile in a study plot. The calculated shear strength is adjusted daily based on the most recently measured snow profile parameters and recent snowfall rates or average long-term snowfall values in the area according to previously published empirical models. Slab load, ski penetration and skier stress at the base of the slab and subsequently skier stability indices based on the ratio of shear strength to shear stress such as Sk38 are calculated. For daily calculations of Sk38 the slab settles according to the long-term average and the 24 hour snowfall is added to the slab thickness in order to calculate the slab load on days without snowprofile observations. We summarize comparisons of the estimated and measured shear strength as well as correlations of Sk38 with skier-triggered avalanche activity in the Columbia Mountains.

KEYWORDS: slab avalanches, avalanche forecasting, snowpack stratigraphy, persistent weak layers

1. INTRODUCTION

Snowpack evolution models developed in Europe require meteorological and radiation instrumentation rarely used in North America. The slab and weak layer evolution model SAWLEM has been developed over several years and is based on consistent study plot measurements including the shear strength of persistent weak snowpack layers over 10 years. In the Columbia Mountains, weak layers of surface hoar and of faceted crystals are common and classified as persistent. SAWLEM uses different equations to estimate the shear strength – one is for surface hoar layers and one for layers of faceted crystals.

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In western Canada, it is not common that avalanche safety operations perform shear frame tests as a part of their regular snowpack observations, likely because the test is time consuming. Therefore the shear strength and a subsequently calculated skier stability index such as Sk38, which is one of the most significant variables correlating with avalanche activity (Zeidler, 2004, p. 154), are not used. SAWLEM estimates the shear strength from easy-to-measure snowpack properties and further the daily change in shear strength for about a week. The correlation of measured (with a shear frame) and calculated (using snowpack observations) shear strength is encouraging. Consequently SAWLEM can be used in forecasting operations that observe weekly snow profiles in a representative study plot but do not conduct shear frame tests.

Further the daily calculation of stability indices, such as the skier stability index Sk38, is possible based on the results of SAWLEM. Sk38 has shown to correlate with skier-triggered avalanche activity in two different forecast areas in the Columbia Mountains (Zeidler, p. 154, 178).

This paper is a summary of the work done over the past several years and introduces the most recent model (SAWLEM) to calculate the shear strength of surface hoar and faceted layers on a daily basis. A more detailed version, including the development of the equations can be reviewed in Zeidler and Jamieson (2006a, b) and Zeidler (2004). Compared to versions published prior to 2004, there are two main improvements: 1. the shear strength is adjusted for the normal load (overburden pressure normal to the slope) because it became apparent that the snow, which was removed during shear frame testing, had an effect on the shear strength; 2. the shear strength change since the last manual snow profile is now calculated from the change in vertical load above a weak layer. However not all forecasting operations have 24 hr precipitation values available and therefore the model was also tested using average loading rates from the Columbia Mountains in addition to daily precipitation values. The latter one is the preferred though, because current weather patterns are better reflected.

2. PREVIOUS WORK

2.1 Shear Strength

In the previous analysis we used the same Interval Model for forecasting the shear strength of surface hoar layers and layers of faceted crystals as introduced by Chalmers in 2001. The model requires that two formulas be developed, one to estimate the shear strength on a day with manual snowpack observations and one to determine the rate of change of shear strength between snowpack observations.

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

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 day *i* (kPa), $\Delta t_{ij} = t_j - t_i$ is the number of days between day *i* and day *j*, $(\Delta\Sigma/\Delta t)_{ij}^*$ is the estimated rate of change in shear strength (kPa d^{-1}) between day *i* and day *j*, and Σ_j^* is the forecast shear strength on day *j* (kPa).

Simple, multiple and logarithmic regression analyses were performed in order to find the best models (Zeidler, 2004, p. 73-145). The possible predictor variables to determine the shear strength on a day with snowpack observations and the rate of change between snowpack observations included e.g. the height of the snowpack, the load and the thickness of the slab above the weak layers, the temperature of the weak layer as well as 5 cm above and below, the maximum and minimum grain size of the weak layer and the slab density. In Sections 2.2 and 2.3, the shear strength evolution models for layers of faceted crystals and layers of surface hoar crystals are introduced.

2.2 Layers of faceted crystals

For the formulation of SAWLEM for layers of faceted crystals a dataset of 19 time series with a total of 102 shear strength measurements and 83 shear strength changes were available from the Rocky and the Columbia Mountains. Because of the limited dataset and because the shear strength behavior did not differ significantly in the two snow climates we used the entire dataset because of the advantages of a bigger dataset (Zeidler, 2004, p. 83).

In the analysis of layers of faceted crystals a power law relationship of shear strength and load yielded the best performance with an r^2 value of 0.83. The rate of change of shear strength is based on long-term average loading rates for the Columbia Mountains and daily loading rates as measured either automatically or manually at weather stations. The rate of change of shear strength did not significantly correlate with most of the other predictor variables and load is the most important predictor for shear strength (e.g. Johnson, 2000). Consequently, using average loading rates, Eq. (1) can be adapted for layers of faceted crystals in the Columbia Mountains as:

$$\Sigma_j^* = 1.53\ \mathrm{Load}_i^{0.64} + 0.062\ \Delta t_{ij} \qquad (2)$$

Using daily loading rates (Pcp_{ij}), Eq. (1) may be expressed as:

$$\Sigma_j^* = 1.53\ \mathrm{Load}_i^{0.64} + Pcp_{ij} \qquad (3)$$

SAWLEM predicted the shear strength of layers of faceted crystals with an accuracy of 77% and 79% depending on whether the shear strength change in between snowprofile observations is based on daily or average loading rates respectively. But even though the prediction was better using average loading rates, analyses of the test series suggested that daily loading rates reflect better specific precipitation patterns (Zeidler, 2004, p. 105-107). In addition, average loading rates tended to overestimate the shear strength in the test series. An overestimation implies a prediction of more stable conditions than observed, which might lead to costly decisions in avalanche terrain. Consequently daily loading rates are preferred where available.

2.3 Layers of surface hoar crystals

The dataset for the surface hoar analysis consisted of 102 time series with 581 shear strength measurements and 533 shear strength changes from an intermountain and a continental snow climate where the surface hoar was not deeper buried than 100 cm. Again as for the layers of faceted crystals one dataset for both snow climates was used, because descriptive statistic did not show a significant difference in the shear strength (Zeidler, 2004, p. 113).

In the analysis of layers of surface hoar crystals a multiple regression for estimation shear strength was selected because it yielded the best performance (p. 137-140). Even though the fit of shear strength was similar for the simple logarithmic and multiple regression, the multiple regression is preferred because it involves Load and other predictors physically related to shear strength. The r^2 for the multiple regression yielded a value of 0.83. The rate of change of shear strength is based on long-term average loading rates for the Columbia Mountains and daily loading rates, because neither a simple nor a multiple regression could be found that was significant and did not violate the assumptions for the regression analysis. Consequently the evolution of shear strength for layers of surface hoar crystals (Eq. 1) can be written as:

$$\Sigma_j^* = (0.642 - 0.265\ \text{Thick} + 0.044\ T_{-5} + 0.001\ \text{HS} - 0.009\ \text{H} + 1.573\ \text{Load}) + 0.062\ \Delta t_{ij} \quad (4)$$

for average loading rates and as

$$\Sigma_j^* = (0.642 - 0.265\ \text{Thick} + 0.044\ T_{-5} + 0.001\ \text{HS} - 0.009\ \text{H} + 1.573\ \text{Load}) + \text{Pcp}_{ij} \quad (5)$$

for daily loading rates.

For two test series, SAWLEM predicted the shear strength of layers of surface hoar crystals with an accuracy of 71% and 63% depending on whether the shear strength change in between snow profile observations is based on average or daily loading rates respectively. Again the test series showed that daily loading rates have greater value because specific weather patterns were better reflected in the calculations and the use of the daily loading rate will account better for periods with below or above average snowfall.

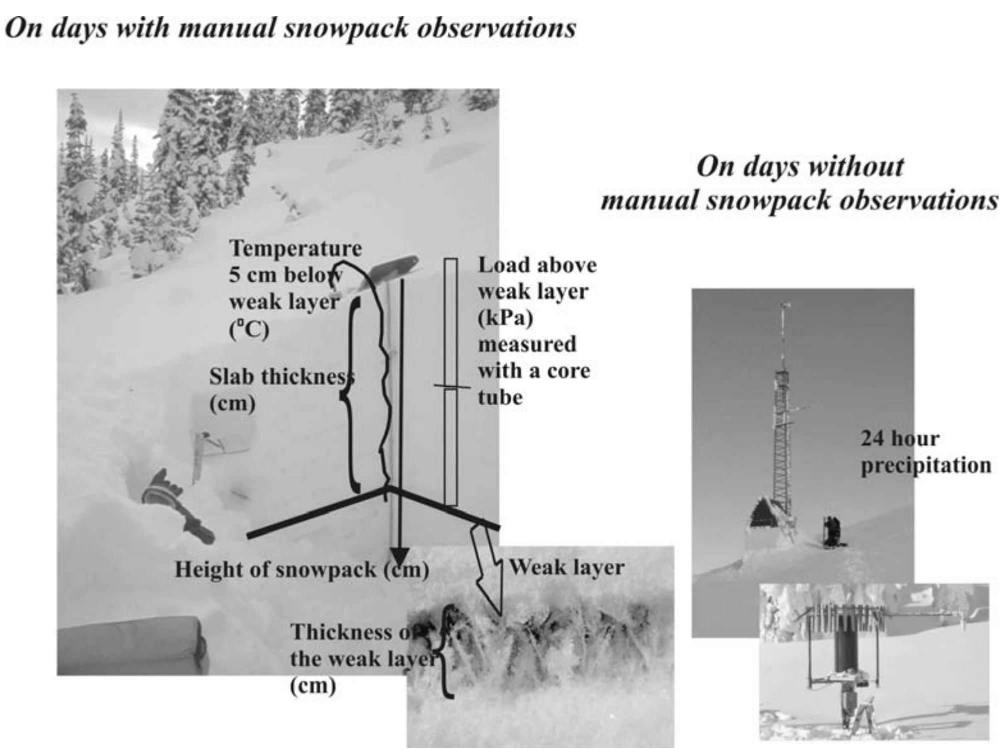
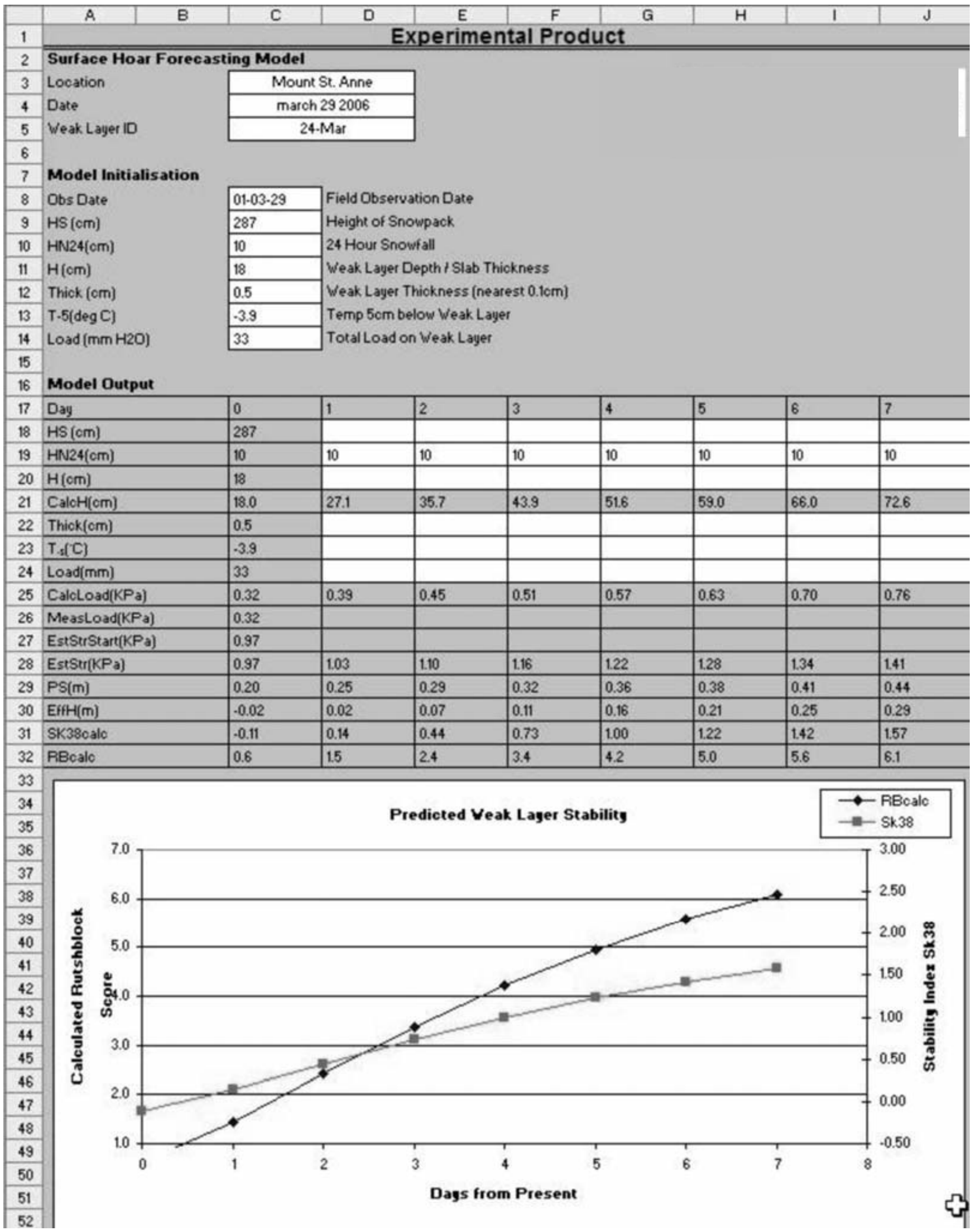


Figure 1: Required snowpack observations and weather data

2.4 Summary of required snowpack observations for SAWLEM

Figure 1 shows the required snowpack observations to calculate SAWLEM. Even though the decrease in accuracy of $(\Delta\Sigma/\Delta t)_{ij}^*$ with time has not been analyzed, we found weekly observations satisfactory to calculate the shear strength based on manual observations. Thus, the forecasting model is reset once per week. More frequent snowpack observations are expected to lead to smaller errors of estimation.

Figure 2 is an example of a spreadsheet used to calculate SAWLEM on a daily basis.



Experimental Product

Surface Hoar Forecasting Model

Location	Mount St. Anne
Date	march 29 2006
Weak Layer ID	24-Mar

Model Initialisation

Obs Date	01-03-29	Field Observation Date
HS (cm)	287	Height of Snowpack
HN24(cm)	10	24 Hour Snowfall
H (cm)	18	Weak Layer Depth / Slab Thickness
Thick (cm)	0.5	Weak Layer Thickness (nearest 0.1cm)
T-5(deg C)	-3.9	Temp 5cm below Weak Layer
Load (mm H2O)	33	Total Load on Weak Layer

Model Output

Day	0	1	2	3	4	5	6	7
HS (cm)	287							
HN24(cm)	10	10	10	10	10	10	10	10
H (cm)	18							
CalcH(cm)	18.0	27.1	35.7	43.9	51.6	59.0	66.0	72.6
Thick(cm)	0.5							
T_{-5}(°C)	-3.9							
Load(mm)	33							
CalcLoad(KPa)	0.32	0.39	0.45	0.51	0.57	0.63	0.70	0.76
MeasLoad(KPa)	0.32							
EstStrStart(KPa)	0.97							
EstStr(KPa)	0.97	1.03	1.10	1.16	1.22	1.28	1.34	1.41
PS(m)	0.20	0.25	0.29	0.32	0.36	0.38	0.41	0.44
EffH(m)	-0.02	0.02	0.07	0.11	0.16	0.21	0.25	0.29
SK38calc	-0.11	0.14	0.44	0.73	1.00	1.22	1.42	1.57
RBcalc	0.6	1.5	2.4	3.4	4.2	5.0	5.6	6.1

Figure 2: Example of SAWLEM spreadsheet used to calculate daily values of the shear strength of a weak surface hoar layer and the corresponding stability index Sk38 over a one week period.

3. STABILITY INDICES

The development of the slab and weak layer evolution model is based on measurements in a uniform study plot over several years and reflects the shear strength changes over time. The study plots were chosen to be uniform and in a sheltered area found over time to develop persistent weak layers at least as many as on nearby starting zones and hence to reflect a worst case scenario. Consequently the model does not apply to wind affected areas and does not account for spatial variability. However the calculation of stability indices based on the calculated shear strength values, can help the forecaster, along with other signs of instability, to assess the likelihood of avalanching.

Slab load, ski penetration and skier stress at the base of the slab and subsequently skier stability indices based on the ratio of shear strength to shear stress such as Sk38 can be calculated using the estimated shear strength Σ_j*. For daily calculations of Sk38 the slab settles according to the long-term average and the 24 hour snowfall is added to the slab thickness in order to calculate the slab load on days without snow profile observations (Zeidler, 2004, p. 149). Jamieson (1995, p. 147) and later Zeidler (2004, p. 154, 178) showed that the skier stability index Sk38 correlated with skier triggered avalanche activity. Jamieson (1995, p. 148-158) found that an Sk38 value of less than 1.5 indicates instability on persistent weak layers; however, more avalanches released at values of Sk38 less than 1. Zeidler (2004, p. 154, 178) correlated a Daily Skier Instability Index (DSI) with Sk38 and found a negative correlation (Spearman R of –0.32, $p < 0.01$). This result was expected since lower values of Sk38 indicate lower stability and increased probability of skier triggering (Jamieson, 1995: 148-158, 215-221; Jamieson and Johnston, 1998). DSI was introduced as response variable to allow the inclusion of days on which skier-triggered avalanches were likely but due to limited skiing or terrain choices no avalanches were skier-triggered. The index is based on actual avalanche activity and the end-of-the-day stability ratings.

4. CONCLUSIONS

In order to use SAWLEM it is necessary to have weekly snowpack observations from a regular study plot available. In the Columbia Mountains of Canada it is not unusual to have more than one persistent weak layer of concern within the snowpack. Before the measurements are taken the weak layers should be identified. The weekly observations should include load and the thickness of the slab above the weak layer, the temperature 5 cm below the weak layer, the thickness of the weak layer and the snowpack height. Using these observations it is possible to estimate the shear strength of a weak layer (different equations for layers of surface hoar and layers of faceted crystals) on days with snowpack observations. The evolution over time is based on the daily loading rates (or average loading rates) and consequently the weak layer gains strength according to the added load. Load has shown to be the most influential predictor for shear strength.

On days after manual snowpack observations, the 24 hr precipitation is used to calculate the shear strength for both layers of faceted crystals and layers of surface hoar. Alternatively it is possible to use the average loading rate based on data over several years. However it is recommended to use daily precipitation values to determine the load, because specific weather patterns are better reflected and because above and below average snowfall years are more precisely modeled.

SAWLEM can be readily implemented with a spreadsheet.

In limited trials, the stability index calculated by SAWLEM correlated with regional skier-triggered avalanches in the Columbia Mountains of western Canada.

The limitations of the current version of SAWLEM include:

- The weak layers must consist of dry surface hoar or faceted crystals. The shear strength and hence skier stability of layers of unusually small or large crystals or otherwise atypical weak layers in the Columbia Mountains are probably not well modeled.
- The slabs must be dry and typical of slabs in the Columbia Mountains.
- The study plot must be uniform and sheltered and must develop weak layers typical of some nearby start zones.
- Although the shear strength estimates compared well with two independent time series (for both layers of surface hoar crystals and layers of faceted crystals), this is only a limited assessment of the accuracy.
- At best, SAWLEM's shear strength or stability estimates may augment forecasts

based on other variables compiled with experience. These estimates should not replace any existing method for forecasting skier-triggered dry slab avalanches.

- Although SAWLEM can estimate stability indices for natural avalanches, this has not been verified.

ACKNOWLEDGEMENTS

For support we are grateful to the Natural Sciences and Engineering Research Council of Canada, Mike Wiegele Helicopter Skiing, Canadian Avalanche Association, Parks Canada, Helicat Canada including the supporting members Backcountry Snowcats, Baldface Mountain Lodge, Bella Coola Heli Sports, Big Red Cats, Blackcomb Cat Skiing, Black Tusk Helicopter Inc, Canadian Adventure Company, Canadian Mountain Holidays, Cat Powder Skiing, Cariboo Snowcat Skiing and Tours, Chatter Creek Mountain Lodges, Coast Range Heliskiing, Crescent Spur Helicopter Holidays, Dream Catcher Heliskiing, Fernie Wilderness Adventures, Great Canadian Helicopter Skiing, Great Northern Snowcat Skiing, Highland Powder Skiing, Island Lake Resort Group, Klondike Heli-Skiing, Last Frontier Heliskiing, Mica Heli Guides, Monashee Powder Snowcats, Mustang Powder, Northern Escape Heliskiing, Pantheon Helisports, Peace Reach Adventures, Purcell Helicopter Skiing, R.K. Heli-Skiing, Retallack Alpine Adventures, Robson Heli-Magic, Selkirk Tangiers Heli-Skiing, Selkirk Wilderness Skiing, Skeena Heliskiing, Snowwater Heli-skiing, Stellar Heliskiing, TLH Heliskiing, Valhalla Powdercats, Whistler Heli-Skiing, White Grizzly Adventures, as well as the supporting member of Canada West Ski Area Association including Apex Mountain Resort, Ski Banff @ Norquay, Big White Ski Resort, Castle Mountain Resort, Panorama Mountain Village, Kicking Horse Mountain Resort, Mt. Washington Alpine Resort, Silver Star Ski Resort, Red Resort, Ski Marmot Basin, Sun Peaks Resort, Sunshine Village, Whistler Blackcomb, Whitewater Ski Resort, Resorts of the Canadian Rockies including Skiing Louise, Nakiska, Kimberley Alpine Resort, and Fernie Alpine Resort.

For careful field measurements, we are grateful to Jill Hughes, Michelle Gagnon, Alec van Herwijnen, Kyle Stewart, Paul Langevin, Ryan Gallagher, Ken Matheson, Cam Campbell, Leanne Allison, Tom Chalmers, Ken Black, James Blench, Joe Filippone, Alan Jones, Steve Lovenuik, Greg McAuley and Rodden McGowan.

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