DERIVING SNOW STABILITY INFORMATION FROM SIMULATED SNOW COVER STRATIGRAPHY

Fabiano Monti[1,2], Jürg Schweizer[1] and Johan Gaume[1]

[1]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[2]ALPsolut S.r.l., Via saroch 1098b, c/o plaza placheda, 23030 Livigno, Italy

ABSTRACT: Increasing the spatial and temporal resolution of snow stratigraphy information and reducing the subjectivity of stability evaluation are among the options for improving avalanche forecasting. Whereas it has been shown that numerical snow cover models can successfully simulate the snow cover evolution during a whole winter season, predicting snow stability from stratigraphy has remained rather elusive. On the other hand, several semi-quantitative methods have been developed for detecting potential weak layers over the last decade such as the threshold sum approach (or the lemons). Furthermore, the skier stability index has actually been proven to be well related to the frequency of skier-triggered avalanches. We show how snow stability information can be derived by (1) searching for potential weak layers, and (2) assessing their stability. We refined the threshold sum approach as well as the skier stability index by accounting for the multi-layered character of the snowpack – considering, for example, the so-called bridging effect. The proposed approach can easily be implemented within the snow cover model SNOWPACK. Combining the two steps as described above allowed discriminating between rather stable and rather unstable snow stratigraphy in about 85% of the cases – comparable to the accuracy of stability tests. Hence, deriving snow stability information from simulated snow stratigraphy finally seems to become possible – which would clearly increase the value of snow cover modeling for avalanche forecasting.

KEYWORDS: Snow stability, Snowpack stratigraphy, Snow cover modeling, Avalanche forecasting

1. INTRODUCTION

Snow stratigraphy information is essential for avalanche forecasting but field observations are time consuming and sometimes not feasible due to avalanche danger. Assessing snow stability from simulated snow stratigraphy would help to increase snow cover information in space and time (Lehning et al., 1999). The 1D snow cover model SNOWPACK (Lehning et al., 2002a; Lehning et al., 2002b) simulates the snow cover characteristics, layer by layer. The model results are consistent with what generally is observed in the field (Monti et al., 2012a); therefore deriving actual snow stability information should be feasible as well.

Two different and complementary approaches (Monti et al., 2014) are generally combined for deriving stability information from manual snowpits: i) snow stratigraphy characteristics analysis; ii) stability tests (e.g. compression test, rutschblock test). As done in the field, deriving snow stability information from simulated profiles could be done in two steps: i) searching for potential weak layers, and ii) assessing their stability.

Monti and Schweizer (2013) developed a method to detect potential weak layers within the simulated snow cover by refining the threshold sum approach (TSA) originally presented by Jamieson and Schweizer (2005) and refined by Schweizer and Jamieson (2007) and Schweizer et al. (2008).

In their approach, Monti and Schweizer (2013) transformed each TSA variable (Table 1) into a dimensionless quantity, standardized within the single snow profile. Relative differences and values were used to identify the location of layers, which have a higher probability than others to be potential weak layers. This relative threshold sum approach (RTA) showed to discriminate better than the original TSA between failure and non-failure layers both for manually observed and simulated snow profiles (Monti and Schweizer, 2013). The RTA allows detecting potential weak layers within a snow profile but does not provide an absolute estimate of their weakness.

For assessing the stability of layers identified as potentially critical another approach is required.

* *Corresponding author address:* Fabiano Monti, WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland
tel: +41-81-417 0252; fax: +41-81-417-0110; email: monti@slf.ch

In SNOWPACK, one of the stability indices supplied by the model is the classic skier stability index SK38, proposed by Föhn (1987) and refined by Jamieson and Johnston (1998). The skier stability is based on the ratio between shear strength and shear stress:

$$SK38 = \frac{\tau_{I,II}}{\tau_{xz}+\Delta\tau_{xz}} \quad (1)$$

where τ_{I} and τ_{II} is the shear strength for persistent and non-persistent grain types, respectively (Jamieson and Johnston, 1998), τ_{xz} is the shear stress due to the weight of the overlaying slab and $\Delta\tau_{xz}$ is the additional shear stress due to the skier (Föhn, 1987). The approach proposed by Föhn (1987) is only valid for a uniform slab.

Due to the layered character of the snow cover (both of the slab and the substratum) the stress induced by a skier at the depth of the weak layer substantially varies (Habermann et al., 2008; Schweizer, 1993). For instance, a skier will have a rather small impact at depth if the surface layers are rather rigid – an effect often referred to as "bridging" (Schweizer and Jamieson, 2003).

The aim of this study was to develop a method for detecting potential weak layers within the simulated snow cover and providing the corresponding stability assessment.

For detecting the potential weak layers we first used the RTA, then, for evaluating the corresponding stability, we applied a refined SK38 that accounts for the multi-layered character of the snowpack. The suggested approach is based on a simplification of the multi-layered elasticity theory in order to easily compute the additional stress due to a skier at the depth of the weak layer taking into account the properties of the slab layers and the substratum.

2. DATA

The simulation performed for five automatic weather stations in the surroundings of Davos (Weissfluhjoch, 2540 m a.s.l., Gatschiefer 2310 m a.s.l., Hanengretji 2450 m a.s.l., and Bärentälli 2560 m a.s.l., Wannengrat (2440 m a.s.l) were used to compare simulated snow stability information to the verified regional snowpack stability on 29 days from winters 2001-2002 to 2013-2014.

For analysis, the manual snow profiles were classified into two stability classes (rather stable, rather unstable) by grouping the stability classes very poor, poor and fair, and good and very good, respectively (Schweizer and Wiesinger, 2001). In total 52 simulated profiles were compared to the corresponding verified regional stability conditions.

Table 1: Critical ranges of variables for calculating the stratigraphical threshold sum. Thresholds used for manually observed as well as for simulated snow profiles are given (Monti et al., 2012).

Variable or classifier	Threshold value	
	Observed	Simulated
Failure layer grain size (mm)	≥ 1.25	> 0.6
Difference in grain size (mm)	≥ 0.75	≥ 40%
Difference in hardness	≥ 1.7	≥ 1.7
Failure layer hardness	≤ 1.3	≤ 1.3
Failure layer grain shape	persistent	persistent
Slab thickness or failure layer depth (cm)	≤ 100	≤ 100

3. METHODS

3.1 RTA calculation

The RTA considers the same six variables as the TSA (Table 1) but without defining absolute thresholds, see Monti and Schweizer (2013) for details.

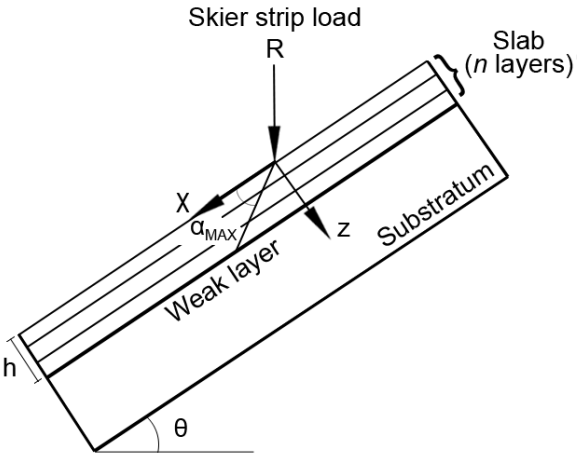


Fig. 1: Cross section of a slab showing R as the skier load, θ the slope angle, *h* the slab's depth and α_{max} the angle from the skier to the maximum induced shear stress.

3.2 Multi-layer skier stability index

Once the potential weak layers were identified, we aimed at estimating their stability by developing a refined skier stability index ($SK38_{ml}$) that takes into account the multi-layer character of the snowpack.

For that purpose, we generalized the approach introduced by Vakili (2008) to a multi-layered system. He combined two approaches to simplify the calculations of the deflection (thickness above which the effects of an additional load becomes negligible) in a three layer system: i) Substituting the upper two layers by a single layer of equivalent Young's modulus E_e and equivalent Poisson's ratio ν_e (De Barros, 1966); ii) Replacing of the upper layer of the two-layer system by an equivalent thickness h_e of the underlying material (Palmer and Barber, 1940).

Generalizing de Barros's (1966) result, we can replace the n slab layers by an equivalent slab of equivalent Young's modulus defined as

$$E_e = \left[\frac{\sum_{i=1}^{n} h_i \sqrt[3]{E_i}}{\sum_{i=1}^{n} h_i}\right]^3 \quad (5)$$

and of depth h_{tot} equal to the total slab thickness

$$h_{tot} = \sum_{i=1}^{n} h_i \quad (6)$$

The system is thus reduced to two layers. Then, Palmer and Barber (1940) assumed that the upper layer of this two layers system can be replaced by an equivalent layer with the same elastic properties as the underlying layer (the weak layer in our case) by calculating the equivalent thickness:

$$h_e = h_{tot} \sqrt[3]{\frac{E_e(1-\nu_{WL})^2}{E_{WL}(1-\nu_e)^2}} \quad (4)$$

The skier induced shear stress $\Delta\tau_{xz}$ can be computed by replacing the slab depth h by this equivalent depth h_e. Furthermore, Habermann et al. (2008), and van Herwijnen and Jamieson (2007) have shown that the substratum also has a considerable influence on the amount of stress $\Delta\tau_{xz}$ in the weak layer. This effect was taken into account by computing the additional stress in the middle of the weak layer, taken as the average between the additional stresses at the slab-WL interface and at the WL-substratum interface.

Finally, the $SK38_{ml}$ was obtained by using the refined $\Delta\tau_{xz}$ within the SK38 formulation (Eq. 1). All layers with index lower than 1 were classified as potentially unstable.

4. RESULTS

Within simulated stratigraphy, the RTA, the SK38 and the $SK38_{ml}$ can be calculated for each snow layer. In Figure 2 the two-step stability evaluation is shown and the effect of taking into account the layering can be seen. Close to the snow surface, the higher values of the $SK38_{ml}$ were related to the lower values of $\Delta\tau_{xz}$ due to the so-called "bridging" effect caused by the hard layers of the slab. Once the potential weak layer was identified by the RTA, its stability was evaluated using the corresponding value of $SK38_{ml}$.

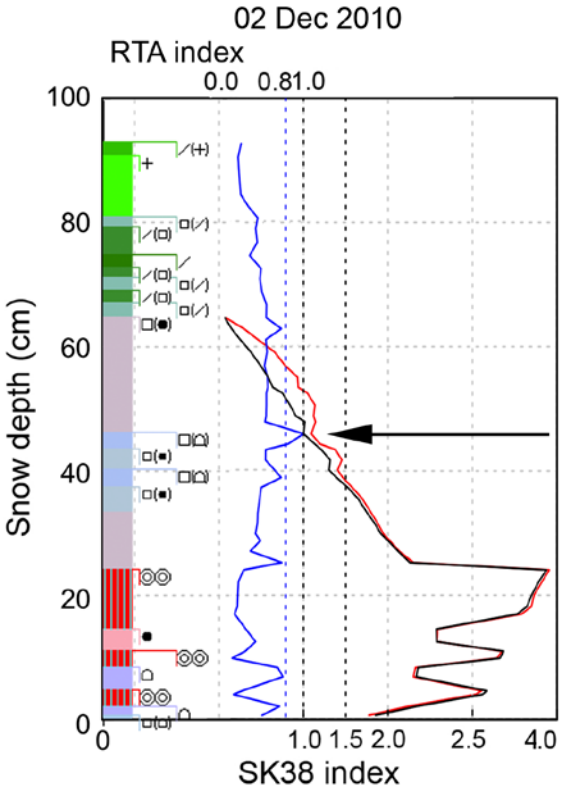


Fig. 2: Simulated snow profiles for Weissfluhjoch. Grain type (*F*) were reported both with the symbols and the colours according to the international snow classification (Fierz and others, 2009). The blue solid line is the RTA, the black solid line is the SK38 and the red solid line represents the $SK38_{ml}$. The layers with values of the RTA index higher than 0.8 were classified as potential weak layers; in this case one layer at 47 cm (highlighted by an arrow). Then, the stability of this layer can be evaluated based on either the SK38 or the $SK38_{ml}$. In this case, the potential weak layer had a valued of the SK38 lower than 1 (classified as rather unstable) and a value of the $SK38_{ml}$ value higher than 1 (classified as rather stable).

By analysing the simulated profiles with the proposed approach, profiles were classified into two stability classes (rather stable, rather unstable) and compared to the verified regional snowpack stability (N = 52) (Figure 3). Out of 36 cases with “rather unstable” regional stability rating, 33 were forecasted correctly by the model; out of 16 cases with “rather stable” regional stability rating only 5 were misclassified.

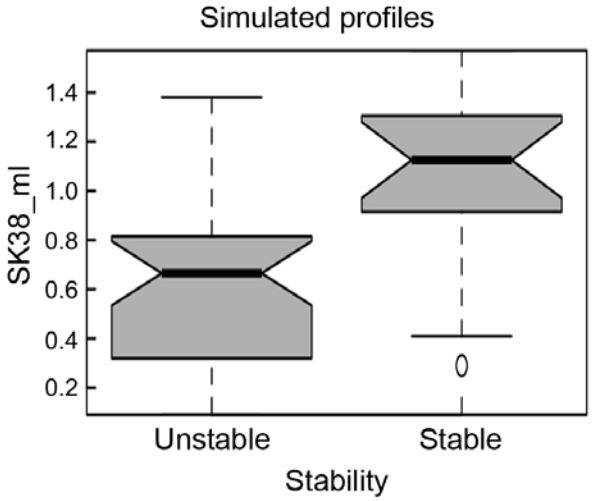


Fig. 3: Comparing predicted to observed regional stability for 29 days during the winters from 2001 to 2014 Predicted stability is the SK38 calculated for potential weak layers previously detected by RTA. Observed stability is based on assessing manual snow profiles in the vicinity of the stations (N = 52). Boxes span the interquartile range from 1st to 3rd quartile with a horizontal line showing the median. Notches at the median indicate the confidence interval ($p < 0.05$). Whiskers show the range of observed values that fall within 1.5 times the interquartile range above and below the interquartile range; circles denote outliers.

5. CONCLUSIONS

We used the relative threshold sum approach for detecting potential weak layers within simulated snow profiles. We then estimated their stability by applying a refined skier stability index ($SK38_{ml}$) that takes into account the multi-layered character of the snow cover. Thus, the effects of the slab (e.g. “bridging”) and substratum properties were considered for calculating the additional stress due to a skier at the depth of the weak layer. Applying the $SK38_{ml}$ to the simulated profiles was straightforward since for each layer all the parameters required to compute the stability index were available. This allowed predicting the stability of the simulated profile as well as showing the stress distribution within the slab.

The results suggest that deriving snow stability information from simulated snow profiles is possible, as has previously been demonstrated by Durand et al. (1999) in a similar way, but so far has rarely been verified with field data. Hence snow cover models may well provide valuable information for operational avalanche forecasting. However, extensive validation at an operational level is lacking so far, but planned for the future. Of course, the approach can also be used if snow cover models run with input from weather models, to forecast future snow stability conditions.

REFERENCES

De Barros, S.T., 1966. Deflection factor charts for two- and three-layer elastic systems, 45th Annual Meeting of the Highway Research Board, Washington DC, U.S.A., 17-21 January 1966. Highway Research Board, pp. 83-108..

Durand, Y., Giraud, G., Brun, E., Mérindol, L. and Martin, E., 1999. A computer-based system simulating snowpack structures as a tool for regional avalanche forecasting. J. Glaciol., 45(151): 469-484.

Föhn, P.M.B., 1987. The stability index and various triggering mechanisms. In: B. Salm and H. Gubler (Editors), Symposium at Davos 1986 - Avalanche Formation, Movement and Effects, IAHS Publ., 162. International Association of Hydrological Sciences, Wallingford, Oxfordshire, U.K., pp. 195-214.

Habermann, M., Schweizer, J. and Jamieson, J.B., 2008. Influence of snowpack layering on human-triggered snow slab avalanche release. Cold Regions Science and Technology, 54(3): 176-182.

Lehning, M., Bartelt, P., Brown, R.L., Russi, T., Stöckli, U. and Zimmerli, M., 1999. Snowpack model calculations for avalanche warning based upon a new network of weather and snow stations. Cold Reg. Sci. Technol., 30(1-3): 145-157.

Lehning, M., Fierz, C. and Lundy, C., 2001. An objective snow profile comparison method and its application to SNOWPACK. Cold Reg. Sci. Technol., 33(2-3): 253-261.

Jamieson, J.B. and Johnston, C.D., 1998. Refinements to the stability index for skier-triggered dry slab avalanches. Ann. Glaciol., 26: 296-302.

Jamieson, J.B. and Schweizer, J., 2005. Using a checklist to assess manual snow profiles. Avalanche News, 72: 57-61.

LaChapelle, E.R., 1980. The fundamental process in conventional avalanche forecasting. J. Glaciol., 26 (94): 75-84.

Lehning, M., Fierz, C., Brown, R.L. and Jamieson, J.B., 2004. Modeling instability for the snow cover model SNOWPACK. Annals of Glaciology, 38: 331-338.

Monti, F., Schweizer, J. and Fierz, C., 2014. Hardness estimation and weak layer detection in simulated snow stratigraphy. Cold Reg. Sci. Technol., 103: 82-90.

Monti, F. and Schweizer, J., 2013. A relative difference approach to detect potential weak layers within a snow profile. In: F. Naaim-Bouvet, Y. Durand and R. Lambert (Editors), Proceedings ISSW 2013. International Snow Science Workshop, Grenoble, France, 7-11 October 2013. ANENA, IRSTEA, Météo-France, Grenoble, France, pp. 339-343.

Monti, F., Cagnati, A., Valt, M. and Schweizer, J., 2012a. A new method for visualizing snow stability profiles. Cold Reg. Sci. Technol., 78: 64-72.

Monti, F.,Schweizer, J., and Fierz, C., 2012b. Weak layer detection in simulated snow stratigraphy. Proceedings International Snow Science Workshop, Anchorage, Alaska state, USA, pp. 16-21 September 2012: 92-97.

Palmer, L. and E. Barber 1940. Soil displacement under a circular loaded area. Highway Research Board Proceedings.

Schweizer, J. 1993. The influence of the layered character of snow cover on the triggering of slab avalanches. Annals of Glaciology, 18: 193–198.

Schweizer, J. and Jamieson, J.B., 2007. A threshold sum approach to stability evaluation of manual snow profiles. Cold Reg. Sci. Technol., 47(1-2): 50-59.

Schweizer, J. and Jamieson, J.B., 2003. Snowpack properties for snow profile analysis. Cold Reg. Sci. Technol., 37 (3): 233-241.

Schweizer, J. and Wiesinger, T., 2001. Snow profile interpretation for stability evaluation. Cold Reg. Sci. Technol., 33(2-3): 179-188.

Schweizer, J., McCammon, I. , Jamieson, J.B., 2008, Snowpack observations and fracture concepts for skier-triggering of dry-snow slab avalanches. Cold Reg. Sci. Technol., 51(2-3),: 112–121.

Thumlert, S. and Jamieson, B., 2014. Stress measurements in the snow cover below localized dynamic loads. Cold Regions Science and Technology, 106–107(0): 28-35.

Vakili, J., 2008. A simplified method for evaluation of pavement layers moduli using surface deflection data, The 12 th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), Goa, India, 1-6 October, 2008, pp. 4314-4319.

van Herwijnen, A. and Jamieson, J.B., 2007. Fracture character in compression tests. Cold Reg. Sci. Technol., 47(1-2): 60-68.

Winkler, K. and Schweizer, J., 2009. Comparison of snow stability tests: Extended column test, rutschblock test and compression test. Cold Reg. Sci. Technol., 59(2-3): 217-226.