A relative difference approach to detect potential weak layers within a snow profile

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ABSTRACT: Reducing the subjectivity of stability evaluation derived from snow profiles and increasing the spatial and temporal resolution of snow stratigraphy information are among the current possibilities to improve avalanche forecasting. In the last few years, several semi-quantitative methods (e.g. the threshold sum approach) have been developed to more objectively evaluate snow profiles. On the other hand, numerical modelling, for example, with the 1-D snow cover model SNOWPACK has the potential to supply snow cover stratigraphy information even in periods and from locations where manual observation are impossible. We propose a revised threshold sum approach (TSA) for snow profile interpretation. The considered snow cover properties are the same as with the TSA (i.e. grain size, type, hardness, depth, difference in grain size and hardness). Each variable was transformed in a dimensionless quantity and standardized within the single snow profile. Hence, 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) was preliminarily tested on a dataset of 107 manually recorded snow profiles, which were collected at skier-triggered avalanches. The characteristics of potential weak layers detected by RTA and TSA in simulated snow stratigraphy profiles were then compared with the characteristics of the failure layers found with compression tests in 83 manual profiles. Overall, the RTA was capable of detecting potential weak layers in manual as well as simulated snow profiles. Combined with the skier stability index it provides an estimate of stability.

KEYWORDS: snow stratigraphy, snow profile, snow stability evaluation

1 INTRODUCTION

Snow stratigraphy information is essential for avalanche forecasting and is considered as the most important data after direct observations of avalanches or in-situ stability tests (LaChapelle, 1980). However, snow profile interpretation is fairly subjective so much that many consider it to be an art rather than a science (Schweizer and Wiesinger, 2001). Reducing the subjectivity when interpreting snow profiles in regard to instability is a challenging task and in the last few years several semi-quantitative methods have been proposed. For example, the threshold sum approach (TSA) aims at deriving snow instability information from snow stratigraphy data (Schweizer and Jamieson, 2007).

The TSA identifies structural discontinuities related to mechanical instability by analyzing snow layers and their interface properties. Six snow parameters were related to structural instability within the snow cover (Schweizer and Jamieson, 2003); three of them refer to interface properties (difference in grain size and difference in hardness between two adjacent layers, and layer depth), three represent properties of the specific layer (grain size, hardness, and grain type). If the value of a variable reaches a given threshold (Table 1), it is considered as an indicator of potential instability.

The main disadvantages of the TSA are its low specificity (though the sensitivity is high) (Winkler and Schweizer, 2009) and the fact that it is based on absolute threshold values (e.g. grain size difference across interface ≥ 0.75 mm). Though the absolute threshold values were statistically optimized using a large dataset including profiles from various snow climates, they are partly subjective reflecting the recording procedures.

Moreover, before the TSA can be used for interpreting simulated snow stratigraphy (e.g. from the 1-D snow cover model SNOWPACK) the absolute thresholds need to be adapted, i.e. the corresponding critical ranges for the simulated characteristics need to be determined (Monti et al., 2012a). If some parameterisation of the model is refined (e.g. snow hardness estimation) the TSA thresholds have to be adjusted as well (Monti et al., 2012b).

The aim of this study was to develop a method to detect potential weak layers within the snow cover. We refined the TSA by transforming each variable in a dimensionless quantity, standardized within the single snow profile. Relative differences and values were used to

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identify the location of layers, which have a higher probability than others to be potential weak layers. This relative threshold sum approach (RTA) aims to be more robust in regard to (*a*) the subjectivity inherent to manual observations and (*b*) its applicability to simulated snow stratigraphy profiles obtained with, for example, the 1-D snow cover model SNOWPACK). Finally, we tested whether the potential weak layers detected within the simulated profiles were related to observed stability.

3 DATA

To evaluate the capability of RTA to detect potential weak layers we verified whether it was able to discriminate between failure layers or non-failure layers within 107 manually recorded snow profiles, which were collected at skier-triggered avalanches. Then we applied RTA to simulated stratigraphy performed for two automatic weather stations (AWS), Weissfluhjoch (2540 m a.s.l.) and Wannengrat (2440 m a.s.l) near Davos, Switzerland. We compared these simulations with 83 snow profiles manually observed in the flat study plots around both AWS from 1999 to 2012. The profiles were completed with at least one compression test (CT). In total 180 failure layers were found using the CT; for only 129 the fracture character (van Herwijnen and Jamieson, 2007) was indicated. In total, 1790 manually observed snow layers were associated with 7926 simulated layers.

Snow stratigraphy was simulated for four 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.) and corresponding stability information was derived. These estimates were compared to observed snowpack stability on 10 days during the winters of 2001-2002 and 2002-2003 verified by numerous snow profiles recorded in the surroundings of the four AWS (Schweizer et al., 2003). In total 33 simulated profiles were compared to the corresponding verified regional stability conditions.

4 METHODS

4.1 RTA calculation

We propose a revised TSA for snow profile interpretation. The considered snow layer properties are the same 6 variables as with TSA (Table 1). No absolute thresholds were defined; the layer properties were analyzed relative to the properties of the profile at hand. Each variable was transformed in a dimensionless quantity, for example for grain size E of layer i:

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.

Variable or classifier	Threshold value	
	Observed	Simulated
Failure layer grain size	≥ 1.25 mm	> 0.6 mm
Difference in grain size	≥ 0.75 mm	≥ 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	≤ 100 cm	≤ 100 cm

$$E_{RTA}^{i} = \frac{E^{i} - m_E}{\sigma_E} \quad (1)$$

where, E_{RTA}^{i} is the relative grain size, E^{i} is the grain size of layer *i*, m_E is the mean grain size found in the profile, and σ_E is the corresponding standard deviation. This relative grain size was then scaled to an index in the range between 0 and 1 ($[E_{RTA}^{min}, E_{RTA}^{max}]$ to [0,1]):

$$I_E^i = \frac{E_{RTA}^{i} - E_{RTA}^{\min}}{E_{RTA}^{\max} - E_{RTA}^{\min}} \quad (2)$$

The score for each structural stability variable was assigned to the relative snow layer as indicated for TSA in Monti et al. (2012a). Finally, summing the 6 relative variables provided the relative threshold sum approach (RTA) index for a given layer i; the index was then again scaled in a range between 0 and 1 (Fig. 1).

4.2 RTA applied to simulated profiles

Unlike with TSA, RTA does not need any correction before it can be applied to simulated snow stratigraphy profiles. To verify if the RTA shows meaningful results when applied to simulated profiles we compared failure layers detected within manual profiles by compression test (CT) to potential weak layers detected within the simulations.

To objectively perform the comparison, the potential weak layers found in the observed profiles were related to layers recorded at about the same depth in the simulations; we adapted the method proposed by Lehning et al. (2001). In this way, first of all, the difference in snow height was removed by stretching the simulated stratigraphy; then, for mapping, a height range around the potential weak layer was calculated; within this range the corresponding manual layers were searched for.

To compare observed and simulated potential weak layers we used the manually observed profile as master profile. Then, we searched for simulated snow cover weaknesses detected with RTA around the depth of the CT failure layer. For the analysis, we considered the sudden collapse (SC) fractures separately (van Herwijnen and Jamieson, 2007).

4.3 Stability estimation for simulated snow stratigraphy profiles

RTA does not provide an estimate of stability but only indicates the weak layers within a profile from a structural point of view. In the numerical snow cover model SNOWPACK, mechanical or structural parameters are used to find potential weak layers and assess their strength (e.g. Durand et al. 1999; Lehning et al., 2004). One of the stability indices supplied by the model is the skier stability index SK38, proposed by Föhn (1987) and refined by Jamieson and Johnston (1998).

All the layers with RTA score higher than 0.8 were selected as potential weak layers and their stability was evaluated using the corresponding value of SK38. We classified all the layers with a SK38 value lower than 1 as potentially unstable (Fig. 2).

5 RESULTS

We verified whether the RTA index was able to discriminate between the failure layers (n = 138) identified within manual snow profiles collected on unstable slopes and the other layers (Fig. 3).

RTA proved to discriminate better than TSA between failure and non-failure layers. Using 0.8 as threshold, RTA showed a sensitivity of 0.85 and a specificity of 0.89 (compared to 0.67 and 0.86, respectively, for TSA).

To verify if RTA can be applied to simulated snow stratigraphy profiles, for each failure layer found with the CT (n = 180) in an observed profile, a corresponding potential weak layer was searched in the simulated profile. The RTA discriminated well between failure and non-failure layers (Fig. 4) in simulated profiles. Considering all CT failure layers (regardless of the fracture type) and using 0.8 as threshold for RTA, the two methods, RTA and TSA, showed a similar sensitivity (POD = 0.48); results improved if only failure layers with SC fractures (n=15) were considered: sensitivity for RTA 0.73 and for TSA 0.8; specificity 0.89 for RTA and 0.86 for TSA).

Finally, we compared the stability output of the snow cover model SNOWPACK, derived by the coupling of RTA and SK38, to the observed (verified) regional stability (n = 33). Out of 12 cases with regional stability classified as 'poor', 11 were forecasted correctly by the model. Nine out of 10 cases classified as 'fair' were classified as 'poor' by the model. Lastly, the model correctly classified 8 out of 11 cases that were rated as 'good'.

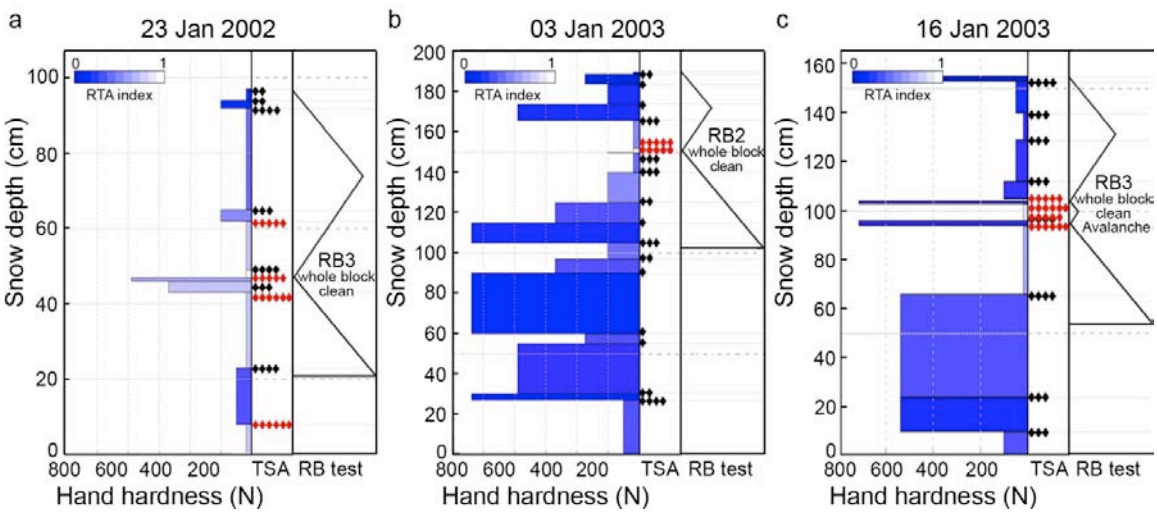

Figure 1: Manual snow profiles (a, b, c) combined with rutschblock test (RB test). For each profile, a hand hardness profile, filled with the colors related to the relative threshold sum approach (RTA) index values, is shown. The number of variables in the respective critical range determined with the threshold sum approach were reported (TSA); an interface was considered as potentially unstable if 5 or 6 variables were in the respective critical range (in red). The RTA index detected potential weak layers both in generally well (b, c) as well as poorly (c) consolidated snowpacks. For mostly soft snowpacks, RTA did not show several (false) potentially critical layers as was the case with TSA (see profile a).

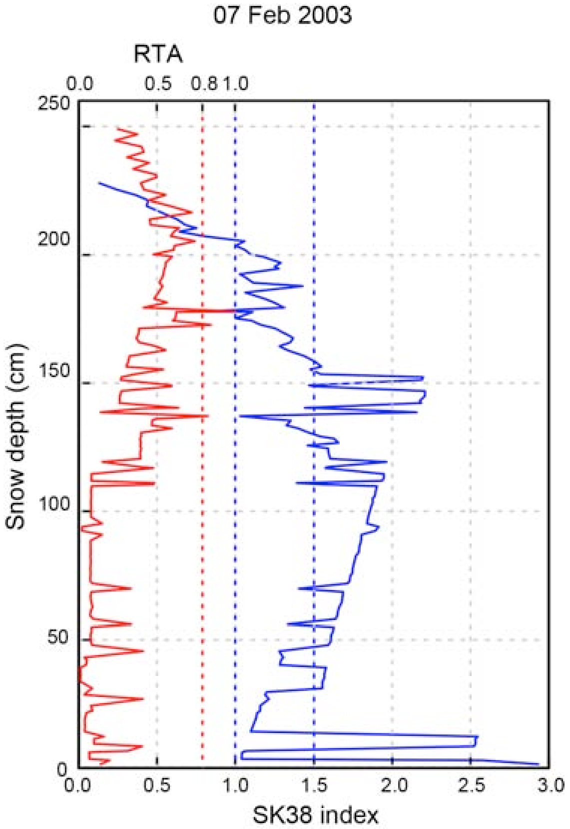

Figure 2: RTA and SK38 profiles. The layers with RTA index values higher than 0.8 (red line) were classified as potentially unstable (in this case three layers, at 178cm, 172 cm and 137 cm). Then, the stability of these layers was evaluated with the SK38 index (blue line). In the example shown, the layer at 178 cm had a SK38 value lower than 1 and was consequently classified as unstable.

5 CONCLUSIONS

We refined the threshold sum approach (TSA) for snow profile interpretation. The newly developed relative threshold sum approach (RTA) discriminated well between failure layers and non-failure layers in a given manual snow profile. The RTA allows detecting potential weak layers within a snow profile but does not provide an absolute estimate of their weakness. RTA can be applied to simulated snow stratigraphy (e.g. the SNOWPACK model) without further refinements. The classification results for simulated snow stratigraphy are comparable to the ones obtained with the threshold sum approach but with the advantage of not using absolute thresholds (robustness to future model improvements).

The RTA and the skier stability index (SK38) were combined to provide an estimate of stability. Compared to a small dataset of observed stability, the new method discriminated well between the stability classes 'poor' and 'fair' vs. 'good'. These preliminary results suggest that snow stability information can be derived from simulated snow stratigraphy data.

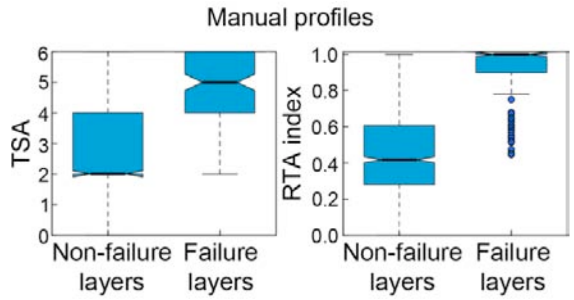

Figure 3: TSA and RTA index for non-failure layers and failure layers detected with rutschblock test. The observed difference between the two distributions were judged to be statistically significant (non-parametric Mann-Whitney U-test, $p<0.001$). Boxes span the interquartile range from 1st to 3rd quartile 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.

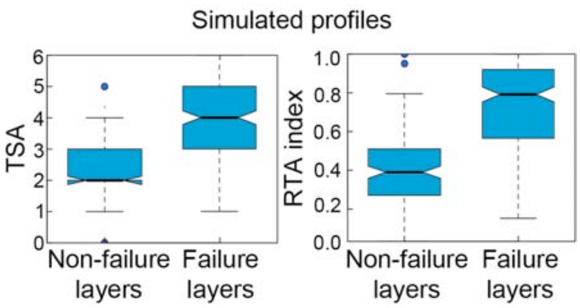

Figure 4: TSA and RTA index for simulated non-failure layers and failure layers corresponding to the failure layers detected in the manual profiles by compression test (CT). The observed differences between the distributions were judged to be statistically significant (U-test, $p<0.001$).

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