WEAK LAYER DETECTION IN SIMULATED SNOW STRATIGRAPHY

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ABSTRACT: Numerical modelling of snow cover stratigraphy with, for example, the 1-D snow cover model SNOWPACK has the potential to increase the spatial and temporal resolution of snow stratigraphy information – data very much needed for avalanche forecasting. One of the key properties for interpreting snow stratigraphy in regard to stability is snow hardness. In manually observed snow profiles, differences in snow hardness between layers were found to be an indicator of instability. We improved the hardness parameterization implemented in the snow cover model SNOWPACK. Hardness is estimated from simulated snow density and grain shape. Using ordinal logistic regressions we calculated for the principal grain shapes the threshold density for all hardness steps (on a dataset of 14,521 manually observed layers). We thus implemented snow hardness as a discrete parameter in SNOWPACK. The structural stability index (SSI), and the threshold sum approach (TSA) were then used to detect potentially weak layers. Both indices strongly depend on the hardness parameterization. With the new hardness parameterization the agreement between measured and simulated snow hardness is fair. Furthermore, it does not require any further calibration and is thus more robust against future changes of the model. Potentially weak layers detected in simulated stratigraphy with either the SSI or the TSA corresponded in about half of the cases to observed CT failure layers. The correspondence improved if only sudden collapse fracture were considered. These preliminary results are promising as they suggest that stability information can be derived from simulated stratigraphy in particular after further improving the detection methods.

1. INTRODUCTION

The SNOWPACK model is operationally used in several countries (e.g. Switzerland, Canada, Italy, Japan) as supporting tool for avalanche forecasters. Predicting snow stability from simulated snow cover stratigraphy would be very useful since field observations are often time consuming and sometimes impossible due to avalanche danger. SNOWPACK is a 1-D snow cover model which calculates the snow stratigraphy and its temporal evolution using data collected at automatic weather stations (AWS) (Lehning et al., 1999). For each snow layer the physical properties and the microstructural characteristics are considered using the finite-element method (Bartelt and Lehning, 2002; Lehning et al., 2002a; Lehning et al., 2002b). There have been several studies on the relation between information supplied by SNOWPACK and observed snow stability. Schweizer et al. (2006) introduced a structural stability index (SSI) which combines two structural instability parameters (difference in grain size and hardness between adjacent layers) with the skier

stability index (SK38) as refined by Jamieson and Johnston (1998). Schirmer et al. (2010) found a positive correlation between observed snow stability and modelled snow stratigraphy variables (e.g. mean slab density, ratio of failure layer bond size to grain size). Recently, Monti et al. (2012) related stability derived from simulated snow stratigraphy quantified with the threshold sum approach (TSA) (Schweizer and Jamieson, 2007) to the avalanche danger.

Snow hardness is considered as one of the most important parameters to assess snow stability (Pielmeier and Schneebeli, 2003b). Despite its subjectivity (Pielmeier and Schneebeli, 2003a), the hand hardness test is still the most widely used. Several snow stability assessment methods (e.g. TSA) are strongly based on the hand hardness index. A satisfactory hardness parameterization implemented in the snow cover model SNOWPACK is thus fundamental to improve the usability of the model for assessing snow stability.

The aim of this study was therefore to first refine the snow hardness parameterization. Then we tested whether SNOWPACK can detect potential weak layers using the SSI and the TSA. The potential weak layers detected in simulated snow stratigraphy were thus compared to the failure layers found with the compression test (CT) (Jamieson, 1999) and to structural instabilities as identified with TSA in the corresponding manual profiles.

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2. DATA

To calibrate simulated hand hardness we employed two snow profile datasets collected in the surroundings of Davos (Eastern Swiss Alps) and in the Veneto region Arabba (North-eastern part of Italy). The Swiss dataset contains 2349 observed snow layers from snow profiles collated from 1560 m a.s.l. to 2810 m a.s.l.. The Italian dataset consists of 12172 snow layers from profiles collected between 1560 m a.s.l. and 2810 m a.s.l. during the winters of the period 1999 to 2012. Both datasets are used to derive hand hardness from density per grain shape while only the Swiss one is compared with simulated snow profiles (12, 437 layers). This allowed assessing the performance of the new snow hardness parameterization in the SNOWPACK model.

The SNOWPACK simulations were performed for two automatic weather stations (AWS), Weissfluhjoch (2540 m a.s.l.) and Wannengrat (2440 m a.s.l) near Davos, Switzerland (Fig. 1). We compared these simulations with 83 snow profiles manually observed in the study plots around both AWS from 1999 to 2012. The profiles were completed with one or more compression tests revealing 180 failure layers. In total, 1825 manually observed snow layers were associated with 7927 simulated ones.

3. METHODS

3.1 *Hand hardness calibration*

The simulated snow hardness was obtained exploiting the relation between snow density and hand hardness with respect to grain shape (Geldsetzer and Jamieson, 2001). Recently a new snow settlement parameterization has been introduced in SNOWPACK, which affects the simulation of snow density and thus the parameterized snow hardness. Schweizer et al. (2006) refined the previous parameterization of the simulated snow hardness performing a multivariate statistical regression analysis for hand hardness index for each grain shape. To address the differences between simulated and observed snow densities, Schweizer et al. (2006) scaled the simulated to observed snow densities to obtain better agreement of the hardness index.

We performed a multiple ordinal logistic regression with snow density and grain shape as independent variables. For grain shape only the majority class was considered and the analysis took only the following grain shapes into account: precipitation particles (PP), decomposing and
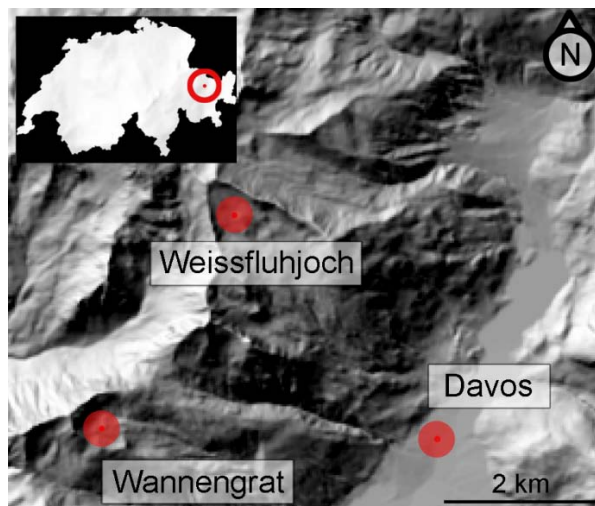

Figure 1: Map of study area: region of Davos. The locations of the two automatic weather stations Weissfluhjoch (2540 m a.s.l.) and Wannengrat (2440 m a.s.l.) are shown (Map source DHM25© Swisstopo).

fragmented precipitation particles (DF), rounded grains (RG), faceted crystals (FC), depth hoar (DH), melt forms (MF) and mixed forms (FCxr). For each of these grain shapes we calculated the density range corresponding to a certain hand hardness index. Finally, the snow hardness for a simulated layer was obtained by averaging the hand hardness index calculated for each of the two grain shapes that characterizes the layer (majority and the minority class).

With logistic regressions the discrete character of the hand hardness index is preserved. In addition, this makes it less sensitive to differences between measured and simulated snow density. We therefore did not scale the simulated densities to the measured ones, making the hardness estimation more robust to further improvements of the model.

3.2 *Weak layers comparison*

CT and TSA were used to detect potential weak layers in manually observed snow profiles. If available, the following five CT fracture characters were considered for the analysis: progressive compression (PC), resistant planar (RP), sudden planar (SP), sudden collapse (SC) and non-planar break (B) (van Herwijnen and Jamieson, (2007).

TSA was generally calculated for all interfaces within the profile using the six snow stratigraphy variables found to be related with snow stability: 1) difference in grain size; 2) failure layer grain size; 3) difference in hardness; 4) failure layer hard-

ness; 5) failure layer grain shape; 6) failure layer depth. If five or six of those variables were within their respective critical range (Table 1) the corresponding interface was considered as potentially unstable (Schweizer and Jamieson, 2007). Since we focused on weak layer characteristics, the critical variables were assigned to one of the two layers adjacent to the interface (Monti et al., 2012).

TSA and SSI were used to detect potential weak layers in the simulations. SSI (Schweizer et al., 2006) is the result of the combination of the skier stability index SK38, proposed by Föhn (1987) and refined by Jamieson and Johnston (1998), with structural information correlated with snow stability found by Schweizer and Jamieson (2007).

As for the manually observed profiles, the critical variables (TSA) were assigned to the simulated layers. The thresholds proposed by Monti et al. (2012) for snow hardness were modified according to our new hardness parameterization. Since snow hardness is now estimated as a discrete variable as in field observations, the thresholds for difference in hardness as well as failure layer hardness were the same as those used for manually observed profiles (Table 1).

To objectively compare the potential weak layers found in the observed profiles to layers recorded at about the same depth in the simulations (and vice versa) we adapted the method proposed by Lehning et al. (2001). With this method, 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 or simulated layers were searched for.

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 (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

To compare simulated and observed potential weak layers we either used the simulated or the manually observed profile as master profile. For assessing the SSI the simulated profiles were considered as the master and the potential weaknesses were compared to CT failure layers or TSA instabilities observed at about the same depth. To assess the TSA applied to the simulations, the observed profiles were considered as the master. We then searched for simulated snow cover weaknesses detected with TSA around the depth of the CT failure layer.

4. RESULTS

4.1 *Hand hardness estimation*

Comparing simulated to observed snow density is fundamental to assess the hand hardness index estimation. Modelled densities were gener-
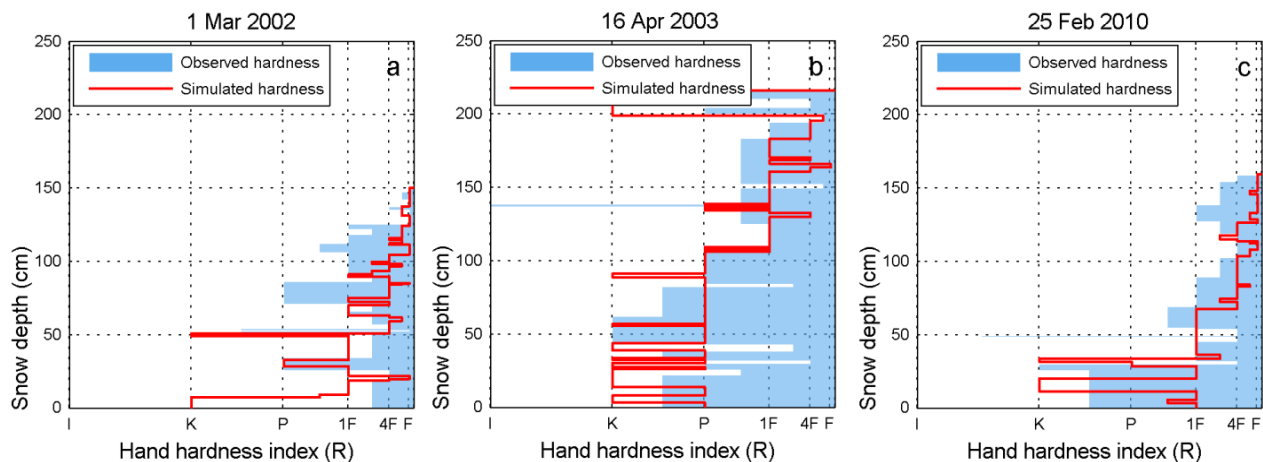

Figure 2: Observed (light blue areas) and simulated (red lines) hand hardness profiles for the site of the study plot at Weissfluhjoch.

ally higher than observed ones for all the grain shapes (except for FC and MF). For RG, DH, MF and FCxr the difference between observed and simulated snow density was relatively large. Obviously this difference also affects the hardness estimation.

Preliminary results show that the agreement between observed and simulated snow hardness is still fair (Fig. 2). For all three examples shown the hand hardness profile is generally well reproduced by the model. Simulated hardness was generally higher than the observed one in the lower part of the snowpack while the observed snowpack was harder in the near-surface layers.

4.2 *Weak layers detection*

For each potential weak layer found with the SSI in the simulated profile, we searched for the corresponding CT failure layer in the observed profile. In the example shown in Fig. 3a, the weakness as identified by the SSI (green arrow) did not correspond to any of the two CT failure layers. However, the layer detected by the SSI was also detected by the TSA and corresponded to the lowermost potential weakness identified by the TSA in the manual profile (red arrow within the tolerance range in the observed profile). Overall, in 48 out of 83 cases (58%) a potential weakness as detected by the SSI corresponded to a CT failure layer. The agreement did not improve, if only CT failure layers with sudden collapse fractures were considered.

In 55 out of 83 cases (64%) a layer detected by the SSI in the simulated stratigraphy was also identified as critical by the TSA in the manual profile.

Considering the manual profiles, only 37 of 180 failure layers (21%) found with the CT were considered critical by the TSA applied to the manual profiles. Excluding the failure layers without a fracture type classification or characterized as non-planar break (B), the agreement only slightly increased (23%). This shows the difficulty of identifying critical weak layers in manually observed profiles.

On the other hand, the 180 failure layers, found with the CT, were compared to the potential weaknesses found with the TSA in the simulated profiles. In the example shown in Fig. 3b, both CT failure layers corresponded to a simulated layer considered as critical by TSA. In total, 87 of the 180 (48%) observed CT fractures corresponded to a potentially critical layer as identified by the TSA in the simulated profiles. If only the 15 failure layers characterized as SC fracture were considered, the correspondence increased to 80%. This is considerably higher than the correspondence found between CT sudden collapse fractures and TSA applied to the observed profiles which was only 47%.

It has to be pointed out that a failure layer detected by the CT does not necessarily correspond to a really unstable layer, as it is known that the CT is underestimating stability (Schweizer and Jamieson, 2010; Winkler and Schweizer, 2009).
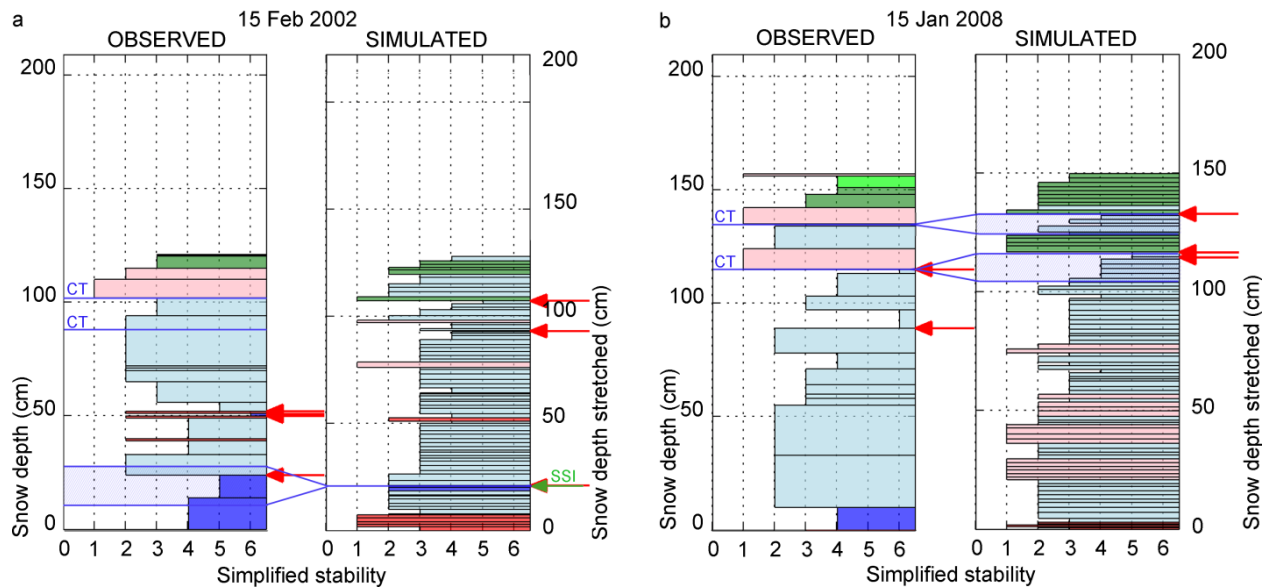

Figure 3: Simplified stability profiles as proposed by Monti et al. (2012). a) Comparison of the weak layer found with the SSI in the simulated profile with the corresponding manually observed profile. b) Comparison of two CT failure layers in the manually observed profile with the corresponding simulated layers.

5. CONCLUSIONS

The new hand hardness parameterization implemented in the SNOWPACK model keeps hardness as a categorical variable allowing an easier interpretation of the hardness profile since it is expressed in terms of the hand hardness index as recorded in the field. Despite differences between observed and simulated layer density we did not empirically adjust the simulated densities to improve the hardness estimation.

To assess whether the SNOWPACK model can detect potentially weak layers we applied the currently implemented structural stability index (SSI) and the threshold sum approach (TSA) to the simulated and manually observed profiles completed with compression tests (CT). Weak layers identified by the SSI corresponded to failure layers detected by CT for 58% of the profiles. For 48% of the CT failure layers a corresponding potentially weak layer as identified by TSA in simulated profiles was found. The agreement increased to 80% if only snow layers characterized as sudden collapse fractures were considered. The agreement between CT failure layers and potential weaknesses as identified by TSA in the manual profiles was low.

These preliminary results are promising as they clearly indicate a relation between simulated snow stratigraphy and potential instabilities recorded in observations. In the future, we plan to improve the detection methods and use a dataset of observed profiles with really critical weak layers.

ACKNOWLEDGMENTS

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