ON COMBINING SNOW COVER AND SNOW INSTABILITY MODELLING

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ABSTRACT: Snow cover models hold the winter's meteorological record and develop snow cover properties in time under meteorological forcing. With numerical weather prediction becoming increasingly reliable – even in complex terrain – and recent advances in understanding avalanche release, the time is ripe for a deterministic model chain targeting snow instability forecasting. We use meteorological data from the Weissfluhjoch study plot in Davos, Eastern Switzerland, to run the snow cover model SNOWPACK. At the same site daily snow micro penetrometer measurements are available providing snow mechanical data. The data cover the period from December 2014 to April 2015 when two pronounced weak layers persisted. To assess the potential of snow cover modelling for snow instability prediction during that period we ran a mechanical model with snow cover model output. The mechanical model takes into account failure initiation, crack propagation and slab tensile support during the phase of dynamic crack propagation. Comparison with the snow micro penetrometer data showed that the snow cover model picks up the important weaknesses and reproduces temporal variations of snow instability. Moreover, our modeled snow instability metrics showed a temporal trend similar to what avalanche activity indices suggest. Hence, we believe that combining weather forecasting with snow cover and snow instability modelling is a promising approach to enhance future avalanche forecasting.

KEYWORDS: avalanche forecasting, snow cover modeling, snow instability.

1. INTRODUCTION

Avalanche danger forecasts support decision makers in snow covered mountain areas and hence contribute to public safety. In contrast to other natural hazard forecasts, avalanche forecasting still much relies on point measurements and observations that are used as indicators for an increase or decrease of the danger. That is partly because our understanding of fracture in snow is limited and the required snow properties to describe avalanche release are not readily available – in particular not in due time and across a mountain region.

In the past years our understanding of dry-snow slab avalanche release has improved (Schweizer et al., 2016) and metrics have been developed to describe the fracture processes leading to avalanche release. Failure initiation describes the formation of a fracture in a weak layer, which may grow to a self-propagating crack, if the slab provides sufficient energy and the tensile strength to support sustained propagation. The metrics describing these processes include the skier stability index (Monti et al., 2016) or the failure initiation criterion (Reuter et al., 2015) 2015), the critical crack length (Sigrist & Schweizer, 2007) or the skier crack length (Gaume & Reuter, 2017), and the slab tensile criterion (Reuter & Schweizer, 2018).

Calculating such metrics requires snow cover properties. Using meteorological data from automatic weather stations (AWS) or numerical weather forecasting (NWP), such snow cover data can be obtained from snow cover models. Combining NWP and snow cover modelling not only provides data at higher temporal and spatial resolution than observations; this combination can provide a numerical avalanche forecast if coupled to a snow instability model.

The model chain SURFEX/Crocus/MEPRA uses snow cover model data for snow instability prediction (Giraud, 1992; Giraud and Navarre, 1995) and similarly does the snow cover model SNOWPACK (Lehning et al., 2004). Validation so far, however, mostly focused on a single metric. Refining the calculation of the skier induced stress, Monti et al. (2016) predicted classes describing the likelihood of failure initiation and Gaume et al., (2016) compared the critical crack length to field measured data points.

In this work we present a validation of a model chain including snow cover modelling and snow instability modelling. To this end, we derived three metrics from snow cover data modelled with SNOWPACK and compared them to the same metrics derived from snow micro penetrometer measurements for the winter season 2014/2015.

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2. METHODS

We used snow micro-penetrometer (SMP) measurements and meteorological data from automatic weather stations (AWS) both from the Weissfluhjoch study plot, Davos, Switzerland.

2.1 *SMP field measurements*

We use a data set of side-by-side SMP measurements from the period between 1 December 2014 and 1 March 2015. On 26 days during that period a set of 5 adjacent SMP measurements was measured at around 8:00 in the morning. During the entire period bi-weekly snow pit data are available which facilitate the analysis of the SMP signal, in particular following the weak layers.

2.2 *SMP-derived mechanical properties*

The snow micro-penetrometer (SMP) measures vertical signals of penetration resistance. Following the approach for signal interpretation suggested by Löwe and van Herwijnen (2012) snow microstructural parameters, namely element length, deflection at rupture and rupture force, are obtained. Based on these three microstructural properties snow density, slab elastic modulus, tensile strength, specific fracture energy and weak layer strength were derived as described by Reuter and Schweizer (2018). SMP signals were averaged into slab layers, the weak layer and a basal layer to save computation time in finite element (FE) simulations.

2.3 *Meteorological data*

The meteorological readings from the study plot include air temperature and relative humidity, wind speed and direction, incoming shortwave and longwave radiation, and precipitation. In case data gaps longer than 1 day existed the data of the AWS were excluded in that particular period. Data gaps shorter than 1 day were filled by linear interpolation. Variables were filtered by introducing reasonable lower and upper limits. Precipitation measurements were corrected for under-catch.

2.4 *Snow cover modelling (SCM)*

Snow cover properties were modeled with the snow cover model SNOWPACK for a flat (incline 0°) site. The modeling time step was 60 min after resampling the data from the AWS. The model was initiated on 1 October 2014, when no snow was present at the AWS and ran until 1 March 2015. Full simulated profiles were available hourly. For the snow instability modelling we extracted snow density and layer thickness each day at 8:00 am from the full simulated profiles.

We tagged two different weak layers (Figure 1) which we identified from the snow pit observations. The slab layers are the layers above the weak layer. The base is below.

First we aggregated layers with their adjacent layer if their density difference was less than 10% and obtained profiles of snow layer density. The purpose is mainly to save computation time in FE simulations and to avoid layers thinner than the mesh size. Then, we derived from the modeled density profiles other mechanical parameters based on common parametrizations, including the elastic modulus (Scapozza, 2004), tensile strength (Jamieson & Johnston, 1990), and the shear strength (Conlan & Jamieson, 2015). Their parametrization allows modelling the shear strength evolution with time and increases the shear strength more after loading.

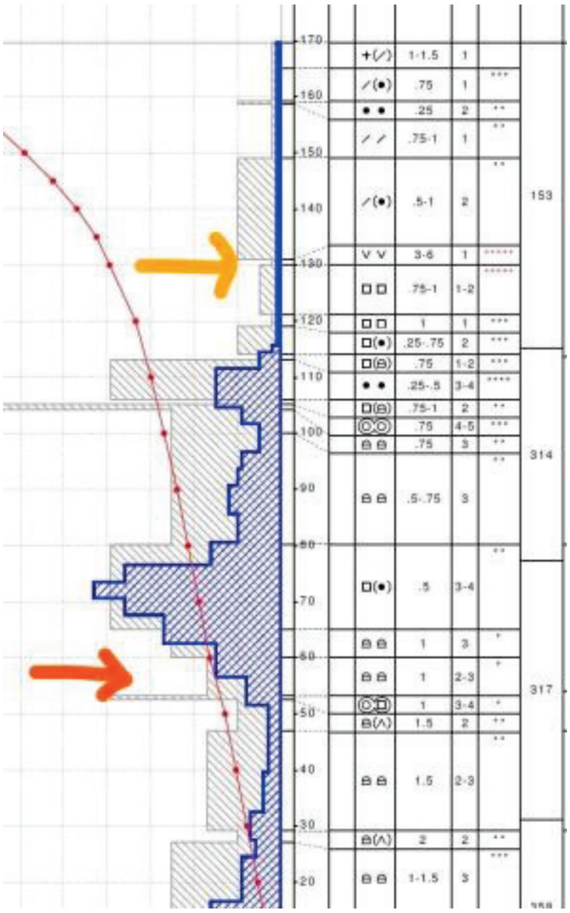

Figure 1: The snow profile from 31 January 2015 shows two distinct weaknesses, an old faceted layer which was buried on 5 November 2014 and a surface hoar layer which was buried on 25 January 2015.

The specific fracture energy was estimated from strength, modulus and initial critical crack size based on the concept of energy release (Griffith, 1921).

2.5 *Snow instability modelling*

We derived three snow instability metrics from the arrays of mechanical properties obtained from SMP measurements and from snow cover modelling as suggested by Reuter and Schweizer (2018): the failure initiation criterion, the critical crack length and a criterion for slab tensile support.

The failure initiation criterion *S* is a ratio comparing the strength of the weak layer to the stress at the depth of the weak layer. To take into account the variations of density and modulus we used a FE simulation to obtain the additional shear stress within the weak layer due to the weight of a skier on top of the slab.

We modeled the critical crack length r_c similar to the situation of a Propagation Saw Test using the expression for the mechanical energy presented by van Herwijnen et al. (2016) including their FE based calibration for slope angle and ratio of crack length to slab thickness.

To estimate whether or not a slab fracture is likely to arrest the onset of crack propagation in the weak layer, the tensile support of the slab during crack propagation can be estimated. The slab tensile criterion *T* is the portion of the slab thickness that is prone to fail in tension when tensile stresses form in the slab ahead of the crack tip at the onset of crack propagation.

We projected the results we obtained from the SCM data on the SMP results by linear mapping. This adjustment does not affect the trends we study, but allows using thresholds specific of SMP data.

3. RESULTS

Before we look at the evolution of snow instability during the period between 1 December 2014 and 1 March 2015, we compare avalanche data to the snow instability metrics we obtained for the two data sets: snow micro-penetrometer measurements (SMP) and snow cover modelling (SCM).

We select one of the prominent weak layers of the season, either a layer of rounding facets buried on 5 November 2014 or a surface hoar layer which was buried on 25 January 2015.

3.1 *Failure initiation*

The probability that a weak layer fails under the load of a skier can be described by the failure initiation criterion. Being a ratio between strength and stress, low values refer to a higher probability of failure. Figure 2 shows the evolution of the failure initiation criterion of the aging surface hoar layer which was buried on 25 January 2015. Both, the SCM and the SMP approach show a very similar evolution of the failure initiation criterion, although the SCM results are smoother. While the weak layer strengthened over time, the failure initiation criterion remained below the critical threshold of *S*=233 reported by Reuter and Schweizer, (2018) indicating that the probability of failure was high during that period. The steps in the graph appear on days after a snow fall.

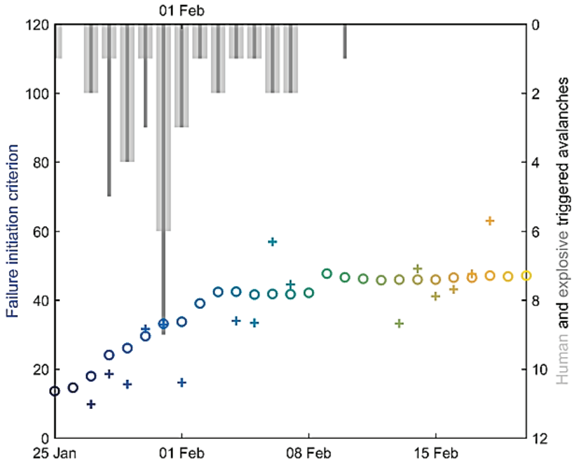

Figure 2: The failure initiation criterion derived from snow cover model output (circles) and snow micro-penetrometer data (crosses) at the Weissfluhjoch study plot for the layer of surface hoar buried on 25 January 2015 are shown over time (color). Bars show the number of artificially triggered avalanches.

3.2 *Critical crack length*

Short critical crack lengths indicate a high propensity of the snow cover to propagate cracks that formed during failure initiation. Figure 3 shows the evolution of the critical crack length over time modeled from SCM and SMP data. Overall, an increase is observed with both approaches, but the trend is considerably smaller for the SCM data than for the SMP data. Low values of the SMP derived crack length coincided with an increase of the number of observed artificially triggered avalanches the day after, such as on 31 January 2015. The SCM results, however, increased rather monotonously and missed times of increased triggering probability.

3.3 *Temporal evolution of snow instability*

By means of SCM complete records of snow properties can be obtained provided that meteorological data do not have gaps. Using the SCM output to drive the fracture mechanical model, a complete record of snow instability is obtained filling the gaps of our SMP measurement series.

Figure 3 shows the temporal evolution of the layer of rounding facets buried on 5 November in snow instability space. That means, the temporal evolution is characterized by three axis labeled failure initiation criterion, critical crack length and slab tensile support. We can now follow the weak layer from the time it was buried until it became inactive.

High triggering probability would be identified in the lower left corner of the graph by open circles, when the critical crack length is short, the failure initiation criterion is low and the slab tensile support is sufficient for full propagation.

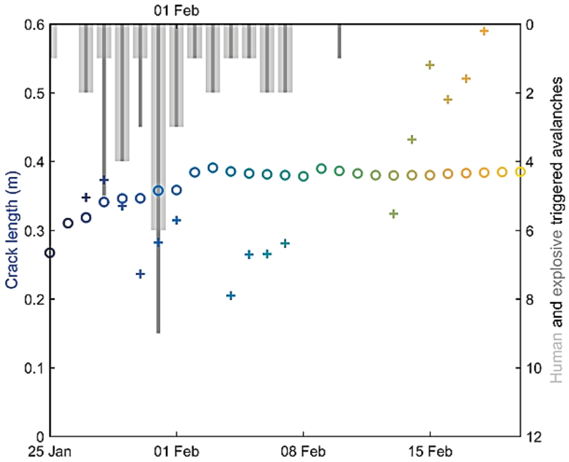

Figure 3: The critical crack derived from snow cover model output (circles) and snow micro-penetrometer data (crosses) at the Weissfluhjoch study plot for the layer of surface hoar buried on 25 January 2015 are shown over time (color). Bars show the number of artificially triggered avalanches.

Over the period the failure initiation criterion increased rather monotonously. The crack length, however, decreased at certain times and the slab tensile support was only provided after a first period.

For a validation we can compare with cycles of artificially triggered avalanches, which occurred on 31 December and 1 January (40 incl. 16 human triggered), 3–5 January (16 incl. 4 human triggered), 8–10 Jan (5 all explosives) and 18 January (3 human triggered). These times of increased avalanche activity are best picked up by the critical crack length in our data.

In general, high triggering probability indicated by the number of avalanche observations lined up well with times when our modeled criteria were below reported thresholds (Reuter and Schweizer, 2018).

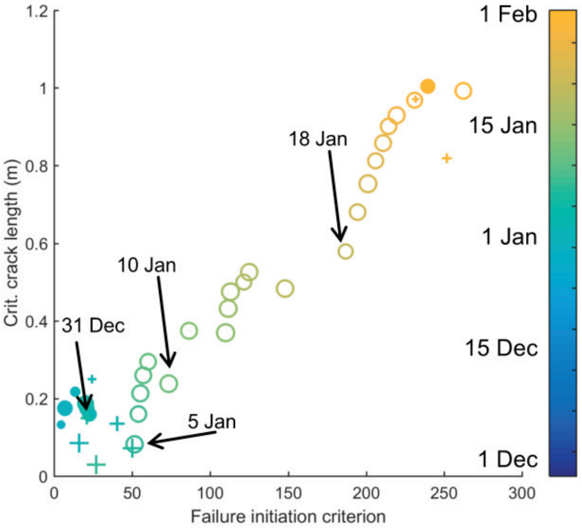

Figure 4: Temporal evolution of a layer of rounding facets buried on 5 November 2014. Crosses show SMP results and circles show SCM model results. The circle size refers to the criterion for slab tensile support. Open circles indicate that full propagation is likely. Colors indicate time.

Based on their thresholds ($r_c < 0.3$ m $S < 233$) the weak layer active time was between 1 January and 11 January when most of the avalanches were reported.

4. DISCUSSION

Our simulations represent a first step towards combining snow cover modelling and fracture mechanical modelling to assess snow instability. The approach we chose considers all snow layers identified by the snow cover model and takes into account the relevant fracture processes. The aim was to assess whether temporal trends of snow instability can be resolved with the present modelling approaches.

For a layer of surface hoar the SCM model approach did pick up the trends, but did not well identify when the instability peaked. For a layer of faceted crystals our three instability criteria predicted a weak layer active time fairly in line with avalanche observations.

Improvement of the model chain seems possible especially with respect to the derivation of snow properties, which, in case of the snow cover model data, were all density derived. Possibly, including more structural information, such as the modeled grain type could enhance the overall performance of the model chain.

In fact, we initially used the shear strength parametrization of Jamieson and Johnston (2001) as implemented in SNOWPACK, but obtained better results with the parametrization of Conlan and Jamieson (2015). The latter takes into account the increase of shear strength after a snow fall and a more gradual increase in the days thereafter.

5. CONCLUSIONS

Our analysis showed that snow cover modelling picked up the important weaknesses of the 2014/15 winter season with standard SCM adjustments, namely a weak layer of surface hoar and rounding facets.

A comparison with model results based on snow micro penetrometer data showed that the snow cover model reproduced fairly well temporal variations of snow instability, suggesting that the modeled slab and weak layer properties are in the right order of magnitude.

After all, the coupling of snow cover modelling and snow instability modelling allowed filling the gaps in our manual SMP measurements and nicely explains how snow instability evolved in January and February 2015. Hence, we believe that combining weather forecasting with snow cover and snow instability modelling is a promising approach to improve our understanding of how weaknesses evolve with time and support future avalanche forecasting.

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