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Hardness estimation and weak layer detection in simulated snow stratigraphy

Fabiano Monti *, Jürg Schweizer, Charles Fierz

WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland

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ABSTRACT

Numerical modeling of snow cover stratigraphy with, for example, the 1-D snow cover model SNOWPACK has the potential to increase the spatial and temporal resolutions 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 indicative of instability. We improved the hardness parameterization implemented in the snow cover model SNOWPACK. Hardness is estimated from the simulated snow density and grain type. Density thresholds for primary grain types and all hardness steps were calculated using ordinal logistic regression (on a data set of 14,522 manually observed layers). We thus implemented snow hardness as a discrete parameter in SNOWPACK. The new hardness parameterization observed agreed well with the simulated snow hardness. The structural stability index (SSI), and the threshold sum approach (TSA) were then used to detect potential weak layers in the simulated stratigraphy. We evaluated whether failure layers detected with compression tests (CT) in manually observed snow profiles corresponded to the potential weak layers found by either the SSI or TSA in the simulated stratigraphy. CT failure layers corresponded in about half of the cases to the potential weak layers detected with either the SSI or the TSA in the simulated stratigraphy. The agreement improved if only sudden collapse fractures were considered. These findings suggest that stability information can be derived from simulated snow stratigraphy in particular if the method for detecting weak layers is further improved.

1. Introduction

A prerequisite for dry-snow slab avalanches is a snowpack weakness below one or more cohesive slab layers. The susceptibility of a weak layer to failure initiation and crack propagation determines snow instability (Schweizer et al., 2003). Identifying potential weak layers is therefore among the key tasks in snow stability assessment. Estimating snow stability is widely based on snow profile interpretation, which is a fairly subjective method, especially when stability tests are not available (Schweizer and Wiesinger, 2001). To quantify profile interpretation Schweizer and Jamieson (2007) proposed a threshold sum approach (TSA) that evaluates six structural variables, and is similar to the so-called lemons introduced by McCammon and Schweizer (2002). While the number of variables in the critical range correlated with instability for known failure layers, the method provided poor results if used for detecting potential weak layers (Schweizer and Jamieson, 2007); it overestimated instability (Winkler and Schweizer, 2009). A widely used stability test is the compression test (CT) (CAA, 2007), which similarly to the TSA well detects weak layers (high sensitivity), but has a high false alarm ratio (low specificity) (Schweizer and Jamieson, 2010).

As 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. Whereas manually observed snow profiles are supplemented with a snow stability test to facilitate profile interpretation, this option is not available when interpreting simulated snow stratigraphy. Therefore, 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). Several studies related output from the 1-D numerical snow cover model SNOWPACK (Lehning et al., 2002a,b) to observed stability. Schweizer et al. (2006) proposed a structural stability index (SSI) which combines two structural instability parameters (difference in grain size and hardness between adjacent layers) with the classical skier stability index (SK38) introduced by Föhn (1987) and refined by Jamieson and Johnston (1998). The SSI proved to be superior to the SK38 in detecting failure layers (Schweizer et al., 2006). Recently, Monti et al. (2012) related modeled stability information derived with the TSA to regional avalanche danger.

While these studies demonstrated a link between modeled snowpack variables and observed signs of instability such as avalanche

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* Corresponding author at: WSL Institute for Snow and Avalanche Research, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland. Tel.: +41 81 4170 252.
E-mail address: monti@slf.ch (F. Monti).

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activity, snowpack stability estimates or avalanche danger, a profile-by-profile comparison between observed failure layers and simulated weak layers is still lacking.

The aim of this study is therefore to verify whether (1) observed failure layers can be detected in snow profiles simulated with the snow cover model SNOWPACK, and (2) if potential weak layers identified in simulated snow profiles correspond to observed unstable layers. We compared failure layers found with compression tests to potential weak layers identified in the simulated snow stratigraphy with either the structural stability index (SSI) or the threshold sum approach (TSA), and vice versa. Since both the SSI and the TSA strongly depend on snow hardness, we first had to refine the parameterization of the hand hardness index within SNOWPACK.

2. Data

2.1. Hand hardness calibration

For the hand hardness parameterization we used two snow profile data sets collected by snow observers of the WSL Institute for Snow and Avalanche Research SLF and the ARPAV Avalanche Center of Arabba (north-eastern Italian Alps). The Swiss data set consisted of 2349 observed snow layers from 312 snow profiles recorded in the area surrounding Davos (from 1560 m a.s.l. to 2810 m a.s.l.). The Italian data set consisted of 12,173 snow layers from 1125 profiles collected in the whole Veneto Region (from 1170 m a.s.l. to 2940 m a.s.l.) during the winters 1999–2000 to 2011–2012. For both data sets hand hardness was related to density depending on the grain type. In order to assess the suitability of the new hardness parameterization, the Swiss hardness data were compared to modeled hardness (12,437 layers) from 143 profiles (simulated for the locations of Weissfluhjoch and Steintälli) covering about the same area and time as the observed ones. These data are mostly similar to the data used by Schweizer et al. (2006) and their characteristics can be found therein. Our analysis was confined to only dry snow layers.

2.2. Weak layer detection

Meteorological input data measured at the two Automated Weather Stations (AWS), Weissfluhjoch (2540 m a.s.l.) and Steintälli (2440 m a.s.l.), above Davos, Switzerland, were used to simulate snow stratigraphy with the 1-D model SNOWPACK. We compared these simulations with 83 manually observed snow profiles each included at least one CT. In total 180 failure layers were found using the CT; for only 129 the fracture character (van Herwijnen and Jamieson, 2007) was indicated. The field data were collected in the flat study plots surrounding the two AWS during the winters 1999–2000 to 2011–2012. In total 1790 manually observed snow layers could be compared to 7926 simulated layers.

3. Methods

In the following, we will first describe how we developed the new hardness parameterization. Then, we will discuss the methods for failure layer detection in manually observed and simulated snow stratigraphy. We compared the CT, SSI and TSA within and between manually observed and simulated profiles (Fig. 1). One can ask whether an observed failure layer is represented in the simulated snow stratigraphy, or vice versa, whether for a potential weakness in a simulated profile a corresponding failure layer was observed. Both directions of comparison were performed for assessing the value of the simulated snow stratigraphy for evaluating snow instability.

3.1. Hand hardness calibration

Snow hardness is credited as one of the most important parameters to assess snow stability (Pielmeier and Schneebeli, 2003b). Several types of hardness tests were developed in the last 80 years. Despite its subjectivity (Pielmeier and Schneebeli, 2003a), the hand hardness test is still the most widely used. Hand hardness is estimated by gently pushing the fist, four fingers, one finger, a pencil or a knife into to the

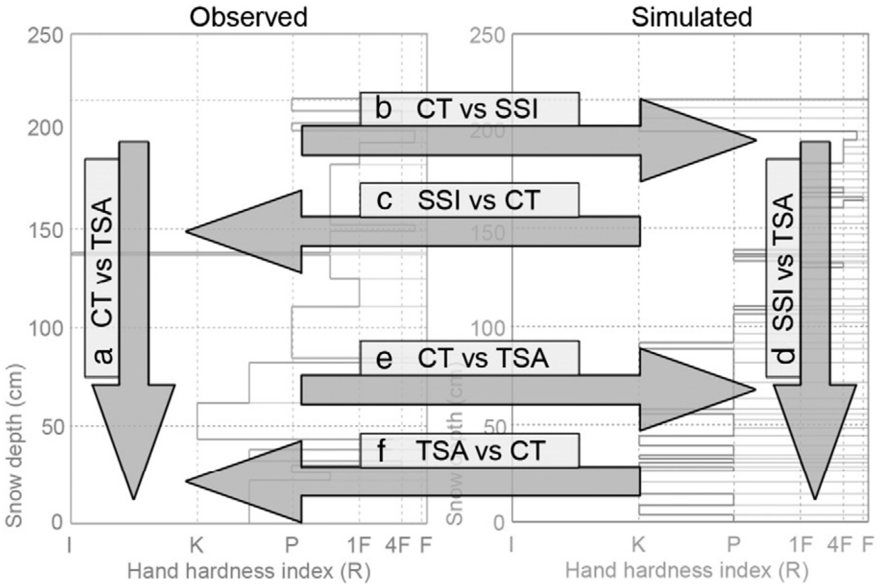

Fig. 1. Overview of the comparisons performed within and between observed and simulated profiles. Arrows are labeled a) to f): a) CT failure layers versus the TSA for observed profiles; b) CT failure layer versus a potential weak layer identified by the SSI at the corresponding depth in the simulated profiles; c) potential weak layer identified by the SSI versus CT failure layer at the corresponding depth in the observed profiles; d) potential weak layer identified by the SSI versus the TSA in the simulated profiles; e) CT failure layers versus a potential weak layer identified by the TSA at the corresponding depth in the simulated profiles; f) potential weak layer identified by the TSA versus CT failure layers at the corresponding depth in the observed profiles.