ARTICLE IN PRESS
COLTEC-01736; No of Pages 9
Cold Regions Science and Technology xxx (2012) xxx–xxx
Contents lists available at SciVerse ScienceDirect
Cold Regions Science and Technology
journal homepage: www.elsevier.com/locate/coldregions

A new method for visualizing snow stability profiles

Fabiano Monti [a,b,*], Anselmo Cagnati [b], Mauro Valt [b], Jürg Schweizer [a]

[a] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[b] ARPA Veneto – DRST Centro Valanghe di Arabba, Arabba, Italy

ARTICLE INFO

Article history:
Received 18 January 2012
Accepted 22 February 2012
Available online xxxx

Keywords:
Avalanche forecasting
Snow stability evaluation
Snow stratigraphy
Snow cover simulation

ABSTRACT

Snow stability assessment by interpreting snow profiles is a time consuming and fairly subjective process, especially when snow stratigraphy was recorded without performing a stability test at the same time. Snow stratigraphy is clearly related to snow stability, as had been shown by various studies that linked specific snowpack properties such as grain size and type to instability. We suggest a new method to visualize snow stratigraphy in regard to stability based on six structural variables (also known as the threshold sum approach). Each snow layer is represented by the number of variables that are not in the corresponding critical range. This approach has not only been implemented for manually recorded snow profiles but also – after adapting the threshold values – for simulated snow stratigraphy provided by the numerical snow cover model SNOWPACK. The new visualization method, applied both to the manually observed and simulated profiles, was tested by analyzing the most critical avalanche situations of the winter 2008–2009 in the Dolomites (north-eastern Italian Alps). Results indicate that the new visualization method is well suited to quickly and intuitively derive snow stability, in particular from simulated snow stratigraphy. Stability information derived from simulated profiles was clearly related to the independently estimated degree of avalanche danger. Supplementing the snow cover model SNOWPACK with the adjusted threshold sum approach increases its usefulness for avalanche forecasting purposes.

1. Introduction

Assessing the avalanche danger for a given region or area is a difficult process that implies significant responsibility. McClung (2000) defined avalanche forecasting as the prediction of current and future snow instability in space and time relative to a given triggering level. Among the various ways to approach the matter, the conventional or synoptic approach is the most common one, and in general used by most avalanche forecasting services. It is mainly based on the skills, experience, and knowledge of the forecasters (Cagnati, 1994). This approach was described by LaChapelle (1980) and it has not been substantially changed since then. Individual forecasts are based on field data, which can be divided into categories according to their relevance. The most important data are those defined as low-entropy data, for example, observations of avalanches or in-situ stability tests. If such data are not available or in case low-entropy data has to be confirmed, medium-entropy data have to be used (e.g. snow stratigraphy data). Lastly, meteorological data are considered (LaChapelle, 1980).

Three disadvantages of this method can be highlighted: 1) The interpretation of the available data (e.g. snow profiles) is fairly subjective so much that many consider it to be an art rather than a science (Schweizer and Wiesinger, 2001); 2) The availability of low- or medium-entropy data is typically very limited; 3) The data analysis is time consuming and forecasters are often short in time as more and more high-entropy and unstructured (or non numerical) data have to be interpreted.

1.1. Threshold sum approach

Apart from recent avalanche occurrences snow profiles combined with stability tests represent the most direct and important source of information on snowpack instability for avalanche forecasters. Their interpretation can therefore be considered as a key for assessing snow instability and eventually also for evaluating the degree of avalanche danger (Schweizer and Wiesinger, 2001). If snow profiles are not combined with in-situ stability tests the subjectivity of their interpretation even increases.

Even if failure initiation is confined to weak snowpack layers, it is not possible to derive snow stability by solely analyzing the weak layer without taking into account the properties of the overlaying slab and the underlying snow cover (Schweizer and Jamieson, 2001). The slab properties are not only important for the amount of stress that is transferred by a skier to the weak layer (Habermann et al., 2008), but also determine the propensity for crack propagation (Gauthier and Jamieson, 2006; Sigrist and Schweizer, 2007). In the case of human-triggered avalanches, the failure plane usually has characteristic properties (McCammon and Schweizer, 2002).

* Corresponding author at: WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland. Tel.: +41 81 4170252; fax: +41 81 4170110.
E-mail address: monti@slf.ch (F. Monti).

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doi:10.1016/j.coldregions.2012.02.005

Please cite this article as: Monti, F., et al., A new method for visualizing snow stability profiles, Cold Reg. Sci. Technol. (2012), doi:10.1016/j.coldregions.2012.02.005

The threshold sum approach was first presented by Jamieson and Schweizer (2005) further refinements were described by Schweizer and Jamieson (2007) and Schweizer et al. (2008). The method establishes an objective and semi-quantitative way to derive snow instability from snow stratigraphy. Six structural variables have been identified as indicators of instability within the snow cover (Schweizer and Jamieson, 2003); three of them refer to interfacial 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.

Stability is assessed for each layer and for each pair of layers in a snow profile by counting the variables that have values in the critical range. For each pair there is an interface score and two layer scores one each for the layer above and below the interface. The final instability score is the sum of the interface score and the larger of the two layer scores. Whenever the total score is five or six, that interface is considered as potentially weak (Schweizer et al., 2008).

According to Winkler and Schweizer (2009), the threshold sum approach yields good results for determining unstable profiles (86% of correct unstables) but has problems in identifying stable conditions (38% of correct stables). The method was developed for persistent instabilities within the snow cover; the applicability for new snow (i.e. storm) or wet-snow instabilities was not verified.

1.2. Snow cover model SNOWPACK

Numerical modeling of snow cover stability may improve the spatial and temporal resolution of snow cover data for avalanche forecasters (Lehning et al., 1999). Simulations can be updated on an hourly basis and, contrary to manual profiles, the data are available during periods of high avalanche danger and from remote areas.

The 1-D snow cover model SNOWPACK is operationally used in several countries (e.g. Switzerland, Italy, Japan) to support the avalanche forecasters in assessing the avalanche danger. It calculates the stratigraphy of the snow cover and its temporal evolution using data from automated snow and weather stations (Bartelt and Lehning, 2002; Lehning et al., 1999; Lehning et al., 2002a, 2002b). SNOWPACK provides for each layer the relevant physical properties as well as some microstructural characteristics by solving the partial differential equations governing the mass, energy and momentum conservation within the snowpack using the finite-element method (Bartelt and Lehning, 2002).

The numerically calculated snow stratigraphy, a simulated snow profile, is comparable to a manually observed profile (Lehning et al., 2001). Its resolution is higher, i.e. layers are typically thinner than in the manually observed profiles (Schweizer et al., 2006). In addition to the parameters that are usually measured in the field other variables that cannot (or can hardly) be recorded manually, are available (e.g. bond size, shear strength). There are some fundamental differences between simulated and manually observed profiles (e.g. in simulated profiles the grain size for new snow is fictional) that need to be considered when analyzing simulated snow stratigraphy.

Along with snow stratigraphy, the model provides several stability indices (Lehning et al., 2004; Schweizer et al., 2006) to facilitate the interpretation of stratigraphy in regard to stability.

These stability indices are: the natural stability index (Sn38), the skier stability index (Sk38), the structural stability index (SSI), the deformation index (S_d) and the stability class index (SC). The Sk38 is extrapolated on a 38° slope and is defined for a certain layer depth as the ratio of shear strength (parameterized for persistent or non-persistent snow grain types) and shear stress due to both, the weight of the overlaying snow and the additional stress induced by a skier (Jamieson and Johnston, 1998). The SSI combines two structural instability parameters (difference in grain size and hardness between adjacent layers) with the Sk38 (Schweizer et al., 2006). The S_d identifies the depth where the stress due to an increase in load, e.g. during or after a snowfall, is concentrated (Lehning et al., 2004). The SC index provides an estimate of stability (poor, fair, good) by combining the information given by the SSI and Sk38 indices (Schweizer et al., 2006).

The SNOWPACK model is operationally used in several countries (e.g. Switzerland, Italy, Japan) to support the avalanche forecasters in assessing the avalanche danger. For example, the Arabba Avalanche Centre has used the model since 2004. During the 2007–2008 winter season, SNOWPACK simulations were verified for the upper Cordevole basin, in the Arabba municipality (Belluno, Italy) (Fig. 1); the basin covers the same study area as in the present work. The simulated snow characteristics agreed in 72% of the cases with manual observations (Monti, 2008; Monti et al., 2009). So far, the stability information provided by the model has not yet been analyzed in detail.

1.3. Objectives

The objective of our study is to develop a new method for displaying the threshold sum approach that (a) directly and intuitively provides information on the structural instability of a given snowpack (characterized by a snow profile) and (b) works with manually observed as well as with simulated snow profiles. The newly developed visualization is then applied for analyzing the winter 2009–2010 for the Dolomites (north-eastern Italian Alps). The stability indices automatically supplied by the model SNOWPACK are evaluated for the same period.

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. For comparison, the values originally suggested by Schweizer and Jamieson (2007) are also shown.

Variable or classifier	Threshold value		
	Original	Manually observed	Simulated
Failure layer grain size (mm)	≥1.25	≥1.25	>0.6
Difference in hardness	≥1.7	≥2	≥1
Failure layer hardness	≤1.3	≤1	≤2
Failure layer grain type	Persistent	Persistent	Persistent
Slab thickness or failure layer depth (cm)	18…94	≤100	≤100

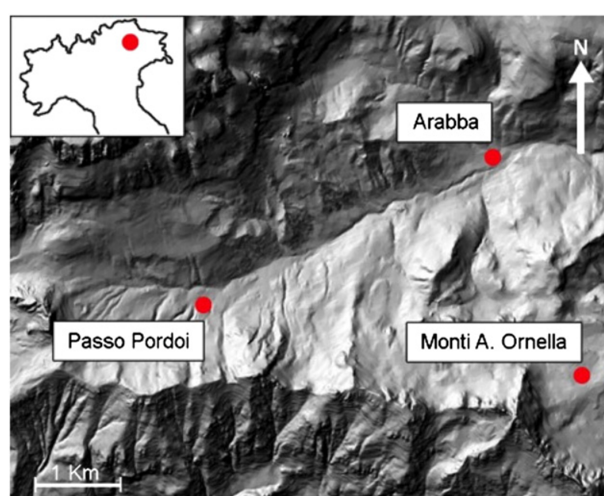

Fig. 1. Map of the study area: the region of Arabba (Italy) with the automatic weather station and study plot at Monti Alti di Ornella (MORN), and the study plot at Passo Pordoi (PORD) (data map source: Regione del Veneto-Segreteria Regionale per le Infrastrutture Unità di Progetto per il Sistema Informativo Territoriale e la Cartografia).

2. Methods

2.1. Threshold sum approach applied to SNOWPACK

The critical ranges of the threshold sum approach as proposed by Schweizer and Jamieson (2007) were adapted and simplified to reflect the observation procedure as applied by the Italian forecasting services (Table 1). The changes concern the hand hardness index of the failure layer, the change in hardness across the failure interface and the failure layer depth. The adapted values are given in Table 1 in the column "manually observed".

Moreover, because of differences between simulated and observed snow characteristics, the threshold sum approach had to be adjusted before it could be used to interpret snow stratigraphy simulated with the numerical snow cover model SNOWPACK. In order to apply the threshold sum approach to the SNOWPACK simulations, it is necessary to find the corresponding critical ranges for the simulated characteristics. In general, the properties of layers in manual profiles differ significantly — otherwise the observer would not have recorded separate layers, whereas differences between simulated layers may be rather subtle. Due to this fact, determining the differences between two adjacent simulated layers is not straightforward and the thresholds need to be adjusted.

The threshold value for the critical difference in grain size is the difference, expressed in millimetres, between the grain sizes of two adjacent layers (Schweizer et al., 2008). This way of defining the difference in grain size does not take into account that the difference between two grains should be related to their sizes. Whereas this might be negligible in manual profiles, it has to be considered for the simulated profiles where the differences in grain size tend to be smaller because of the type of simulation (as described earlier). We therefore introduced a relative differenceΔe. First, we calculated the average grain size (E_m) for a dataset of snow profiles including 26,959 snow layers (N = layers) recorded in the Veneto region between 1997 and 2011. Then, the critical difference 0.75 mm (ΔE_{crit}) as suggested by Schweizer et al. (2008) was divided by E_m = 1.87 mm in order to find the relative difference (ΔE):

$$\Delta E = \frac{\Delta E_{crit}}{E_m} = 0.4 \qquad (1)$$

Since the threshold value now depends on grain size, ΔE should be representative for all grain sizes. Therefore, the relative difference in grain size between two adjacent layers in the simulated profiles (Δe) has to be larger than 40% to be considered as critical:

$$\Delta e = \frac{e_2 - e_1}{e_1} > 0.4 \qquad (2)$$

where e_1 is the smaller grain size and e_2 is the larger grain size.

Similarly, critical values for the hand hardness index and its difference between adjacent layers were determined. No adjustments were required for the critical variable grain type (persistent). Table 1 compiles critical ranges used both for manually observed and simulated profiles.

2.2. Simplified representation of snow profile stability

In the last years a few national avalanche forecasting services (e.g. Switzerland and Italy) included the threshold sum approach into their snow profile software, as they considered it useful for analyzing snow profiles. With a graphical snow profile viewer it is possible to display the number of critical variables for a specific interface (Fig. 2a). Both the structural variables referring strictly to the interface (grain size difference, hardness difference and depth), and the structural parameters describing layer properties (hardness, grain size, grain type) are assigned to the interface between two adjacent layers. In the case of the layer properties, the layer with the higher number of structural instabilities is considered, independently of whether it is the lower or the upper layer. The method of assigning all six variables to the same interface was selected because it is assumed that in most cases fracture will occur near a layer interface (Schweizer et al., 2003a, 2003b).

However, for the graphical representation we suggest a different approach and assign all the six structural variables to one of the two adjacent layers (Fig. 2b) based on the following rules: (i) the variables that already refer to layer properties are assigned to that layer; (ii) the variables referring to the interface between two adjacent layers are assigned to the softer one of the two layers (based on the hand hardness index); if two adjacent layers have the same hardness value, the interface variables are assigned to the upper layer since the stress induced by a skier decreases with increasing depth and hence is larger in the upper than in the lower layer; (iii) the variable for critical depth is assigned to all the layers that are found within the critical range for weak layer depth. Following these rules it is possible to establish a simplified stability profile (Fig. 2b).

The simplified stability profile highlights the number of structural variables for a given layer that are not in the critical range. For example, if for a given layer the number of structural variables in the critical range is 5, the stability value assigned to the layer is 7–5 = 2. In order for the minimum stability value to be 1 rather than 0, the number of variables is subtracted from 7 instead of 6, the maximum number of variables in the critical range. Consequently, the "simplified stability" (SSD) varies from 1, for the potentially most unstable layers, to 7 for the most stable ones. According to Schweizer and Jamieson (2007), the layers with SSD ≤ 2 are considered as potentially unstable. This type of representation was selected in order to obtain a graph similar to the classical hardness profile. In addition, on the side, arrows indicate the potential failure interfaces if five or more variables are in the critical range. To make the interface analysis consistent with the simplified stability profile the critical variables referring to the softer of two adjacent layers, are assigned to the corresponding interface. The colors of the bars refer to the primary grain type of the layer according to the color scheme proposed by Fierz et al. (2009).

2.3. Analyses methods

The manually observed and simulated profiles were classified into either stable or unstable according to the number of critical variables. Schweizer and Jamieson suggested classifying profiles as unstable if the number of critical variables in any given layer reaches 5 or 6. We assume that with avalanche danger level 1 (Low) and 2 (Moderate) the snow cover is rather stable whereas with danger level 3 (Considerable) and particularly 4 (High) it should be rather unstable.

The performance of the proposed method was mostly analyzed qualitatively and partly quantitatively. The following performance measures were used: accuracy (measure of the overall success of a model) and the probability of detection (POD) (Schweizer and Jamieson, 2007; Wilks, 1995).

2.4. Case study: winter 2008–2009 in the Dolomites (North-eastern Italian Alps)

The most active avalanche periods during the winter of 2008–2009 (December to February) have been analyzed with the proposed simplified visualization of snow stability. A total of 16 manually observed profiles were compared to the simulated profiles obtained with SNOWPACK. All the manual profiles were performed in level study plots located in the upper Cordevole basin: near the automatic weather station (AMS) at Monti Alti di Ornella (MORN), at 2250 m a.s.l., and in the Passo Pordoi (PORD) study plot (2142 m a.s.l) (Fig. 1). We will only show the profiles from the study site MORN, but occasionally refer to those from PORD in the text.

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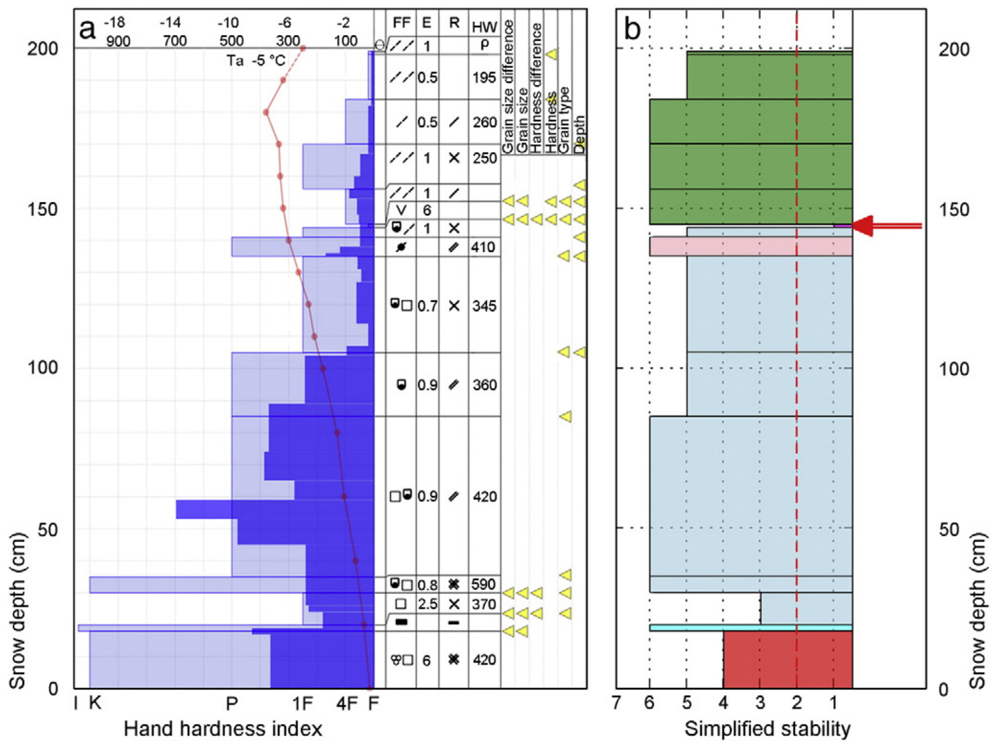

Fig. 2. (a) Snow profile manually observed at the study plot Monti Alti di Ornella on 28 January 2009 with profiles of hand hardness index (light blue) and ram hardness (dark blue) given on the left, and the layer characteristics (grain type, grain size, hardness and density) given on the right. The yellow triangles indicate the critical values assigned to the interfaces as used today in snow profile viewers. (b) Simplified stability profile. The critical variables are assigned to the layers. For each layer, the principal grain type is indicated by the corresponding color according to Fierz et al. (2009). The red arrows pinpoint the interfaces with more than 5 critical variables.

The input data for running the model SNOWPACK was measured at Monti Alti di Ornella where an automatic weather station is located. Measurements include air temperature, relative humidity, reflected shortwave radiation, snow surface temperature, wind direction and speed as well as snow temperature at various depths within the snowpack. Results from stability tests were not available as reference since these data are not collected on a regular basis by the observers of the Arabba avalanche center. It was therefore not possible to relate avalanche activity to stability data, for example, by combining rutschblock score and rutschblock release type with the threshold sum as suggested by Schweizer et al. (2008).

Instead, we used the verified danger level as reference. Verification involved hind-casting the stability conditions following the conventional synoptic approach (LaChapelle, 1980). Manual snow profiles, avalanche occurrence data, and weather conditions were considered. In addition, stability reports performed for the municipalities and the Civil Protection were used to support the verification.

For each avalanche period, the snow and weather conditions are summarized, along with observed stability, manually observed and simulated profiles are compared considering snow stratigraphy (classical snow profile) and the simplified stability profile.

3. Results

3.1. Winter 2008–2009: weather, snow cover and avalanche activity

The winter of 2008–2009 was characterized by exceptional snowfalls on the southern slopes of the European Alps (Valt and Cianfarra, 2009). In Arabba, for example, 316 cm of new snow were recorded during the period of 28 November to 17 December 2008. Fig. 3 presents the snow depth (MORN), the avalanche danger level and the avalanche activity during the winter 2008–2009 for the region around Arabba.

Two periods with considerable snowfall (28 November–2 December 2008 and 10–12 December 2008) caused the first and second avalanche cycle of the season in that region. Before the first heavy snowfall, several weak layers consisting of persistent grain types existed in the upper part of the snowpack whereas melt forms characterized the lower parts near the ground. In addition, surface hoar was observed but probably was not widespread, since it was not consistently observed throughout the study area. Due to the thin, early-season snow cover and the still irregular snow depth hardly any avalanche activity was observed before the end of November (Fig. 3b). At 28 November 2008 it started snowing onto the weak thin snowpack. In the evening of 29 November 2008 many large avalanches reaching the valley bottoms occurred. The last large avalanche was recorded on 1 December 2008.

A second avalanche cycle started during the second heavy snowfall period and gradually phased out around 16 December 2008. During both periods, avalanches with a return period of 20 years were observed.

In the following days, it warmed up so that at lower elevations the already moist snowpack became unstable. This cycle ended around 27 December 2008. At the elevation of the two study plots (about 2200 m a.s.l.), the warming effect was not very pronounced so that its influence on snow stability was low.

The next period of significant avalanche activity was related to the snowfall period of 19–22 January 2009. During this period, the upper part of the snowpack consisted again of faceted crystals and the most prominent weak layer was a previously buried surface hoar layer. Faceted grains and surface hoar were the result of a cold spell during the first 10 days in January 2009. A light snowfall occurred between 14 and 15 January 2009. Starting from the evening of 19 January 2009, a new storm deposited 60–70 cm of new snow. At the beginning, the snowfall was accompanied by strong winds. The first avalanches released from the steepest slopes in the late afternoon of 20 January 2009 and the avalanche activity continued during the 2–3 following days (Valt and Pesaresi, 2009).

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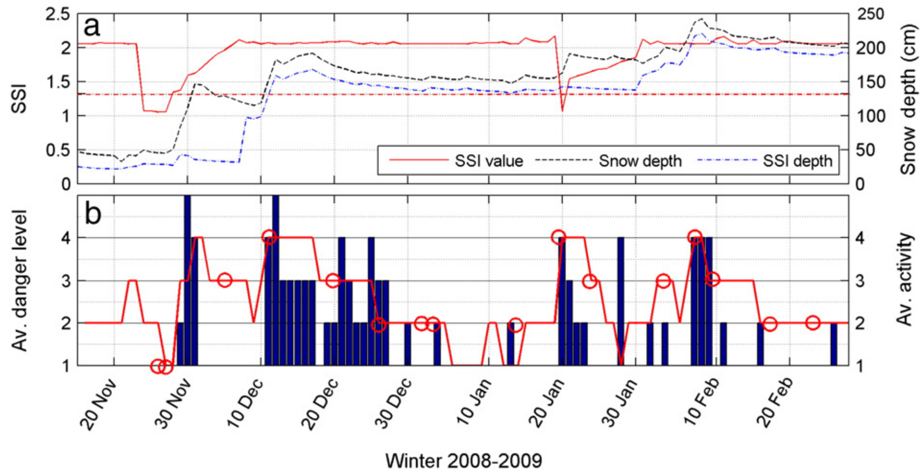

Fig. 3. (a) Snow depth, depth of SSI, and value of SSI for the period 5 November 2008 to 28 February 2009. The dashed red line indicates the critical stability threshold for the SSI (Schweizer et al., 2006). (b) Regional avalanche danger rating and avalanche activity index at Monti Alti di Ornella during the winter 2008–2009. The circles indicate the days when a snow profile was observed. The avalanche danger level (red line) is given as a number from 1 to 4, corresponding to Low, Moderate, Considerable and High. The avalanche activity index (bars) for the region of Arabba is shown based on the following classes: 0: no avalanches recorded; 1: small natural avalanches (loose snow avalanches) recorded; 2: natural avalanches of medium size recorded; 3: many natural avalanches of medium size recorded; 4: single natural large size avalanche recorded; 5: many natural large size avalanches recorded.

The last period discussed here started with a snowfall between 6 and 7 February 2009. 50 cm of new snow were recorded in the study area, where already 30 cm of new snow had been recorded on the two days prior to that period. Above tree line strong southerly winds caused significant snowdrifts. The precipitation ended on 8 February 2009, which coincided with the highest activity of large avalanches. The instabilities were due to several buried surface hoar layers and layers of weakly bonded faceted crystals located 70–90 cm below the snow surface.

3.2. Comparison between manually observed and simulated stability information

3.2.1. 28 November–2 December 2008 and 10–12 December 2008

Nine manually observed snow profiles were available for this period, four from the study plot PORD and five from the study plot near the AWS MORN. The profiles from MORN are shown in Fig. 4. On 27 November 2008 the structural instability in the deepest part of the snow cover is already visible in the simulated and the manually observed profiles.

The manual profile of 4 December 2008, recorded after the first snow storm, shows well bonded layers in the central and top part, but some potentially critical layers with persistent grain types in the lower part of the snowpack. In the simulated profile roughly the same structure is shown. Moreover a weak layer of buried surface hoar at a height of 35 cm is simulated. The existence of the surface hoar layer was confirmed by numerous observations indicating that the surface hoar grew during the nights of 25–27 November 2008 and was subsequently covered by new snow.

For the manually observed and the simulated profile of 4 December 2008 the structural instability was similar (Fig. 4). Sources of instability were weak basal layers and a layer of buried surface hoar as correctly simulated by SNOWPACK.

On 10 December 2008 about the same stability information can be derived from the manually observed and the simulated profiles: the weakest parts of the snowpack were still the basal layers (Fig. 4). In the SNOWPACK profile a weak layer is shown just a few centimetres below the surface. We have no indication that this weak layer existed

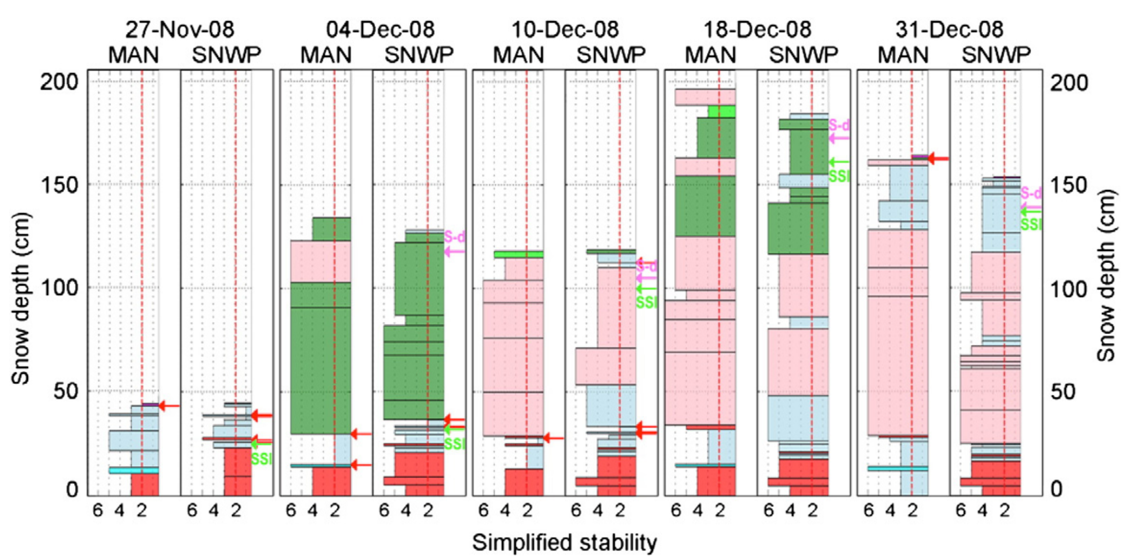

Fig. 4. Simplified snow stability profiles at the Monti Alti di Ornella station for 27 November, and 4, 10 18 and 31 December 2008. For each date, the manually observed profile is shown on the left, the simulated profile on the right; same representation as shown in Fig. 2b. In addition, in the simulated snow profiles, the depths of the potential failures layers based on the stability indices (SSI, S_d) provided by the model are shown by arrows.

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as it was not observed in the field. However, as the overlying slab was thin, this discrepancy had no effect on the overall stability estimate. The profile observed on 18 December 2008 (MORN) (Fig. 4) suggests that stability had improved. This finding is confirmed by the profile from the PORD study plot observed on 23 December 2008 (not shown). Finally, on 31 December 2008 both manual and simulated profiles indicate a stable situation. In the manually observed profiles the basal layers were weaker than in the simulated profile. However, the number of structural variables in the critical range was still sufficiently low to indicate the weakness.

During the same period, the SNOWPACK stability indices did not provide any useful information (Fig. 3a). In fact, the minimum of the SSI was located in the lower part of the snow cover (at about 33 cm) until 7 December 2008, roughly in agreement with observations, but its value was too high indicating rather stable conditions. After 8 December 2008 the SSI was located just below the depth of ski penetration, which indicates that the stability information provided by the SSI is not useful (as the location, just below the ski penetration, is an artefact of the model) (Fig. 3a). The same holds for the deformation index S_d that usually indicated an instability very close to the surface (Fig. 4).

3.2.2. 19–22 January 2009

The conditions before the avalanche cycle are described by the snow profile of 15 January 2009 (MORN) (Fig. 5). The manual profile shows that due to the cold and dry conditions in early January most of the snowpack consisted of layers characterized by mixed formed and faceted crystals. In the simulated profile the faceting is less pronounced. However, the stability that can be derived from both the simulated and manual profile is fairly similar (Fig. 5). The lower and central parts of the snow cover were rather well consolidated. The hardness of the layers very close to the ground was lower, but the number of variables in the critical range was not sufficient to classify theses layers as unstable.

In both, the manually observed and simulated profiles, the layer of buried surface hoar, at about 20 cm below the surface that subsequently caused the instability, is clearly shown (Fig. 5). In the SNOWPACK simulation the hardness of the buried surface hoar layer was slightly higher than the one of the adjacent layer consisting of faceted crystals. Consequently, the critical variables describing the interface properties were assigned to the layer of faceted crystals. Nevertheless, the unstable part of the snow cover was clearly identified by the model.

In the manual profile of 28 January 2009 (MORN) the layer of buried surface hoar was observed (as it had been two days earlier in the profile recorded at the PORD study site) and was still the major concern even though overall snow stability had substantially improved as is reflected in the avalanche danger rating and in the avalanche activity index (Fig. 3a,b).

The SNOWPACK model suggested a distinct return to rather stable conditions. In the simulated profile of 28 January 2009, the weakest part was still the one surrounding the layer of buried surface hoar, but the number of variables in the critical range was not sufficient to indicate unstable conditions as was previously the case in the simulated profile of 21 January 2009 (Fig. 5).

Also, the SNOWPACK skier stability index worked well in so far it correctly identified the layer of buried surface hoar as source of instability; the value of the SSI was critically low right in the period of major avalanche activity (Fig. 3a). On the other hand, no useful information was provided by the S_d index.

3.2.3. 6–8 February 2009

The snow conditions before the snow storm are described by the manual profile of 4 February 2009 (MORN) (Fig. 6). As for the period discussed earlier, in the manually observed profile more kinetic growth forms (in the central part of the snowpack) are shown than in the simulated profile (the same was observed for the manual profile recorded at PORD). However, the difference had no effect on the stability evaluation. The middle to upper parts of the simulated snowpack were slightly less hard than the corresponding parts in the manually observed profiles. On the other hand, the basal layers in the manual profiles were softer than the corresponding layers in the simulated profiles. The layer of buried surface hoar that had caused the previous instability was still observed as well as simulated.

Two profiles were observed in the days following the peak of avalanche activity: 11 February (MORN) and 16 February 2009 (PORD). Two layers of buried surface hoar were found in the profile observed at MORN (Fig. 6) and considered as the cause of instability; the same layers were recorded at PORD (not shown). The simulated profiles did not show any layers of buried surface hoar, but rather a series of layers with low hardness. These layers had originated from the transformation of surface hoar layers and from new snow layers deposited in early February.

As for the period in January, the manually observed profile of 16 February 2009 (PORD) indicated an unstable situation (the layer of buried surface hoar was still present) that was not reflected in terms

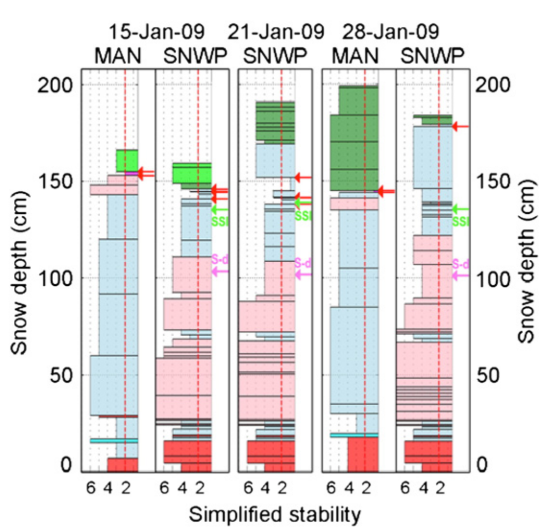

Fig. 5. Simplified snow stability profiles at Monti Alti di Ornella for 15, 21 and 28 January 2009. On 21 January 2009 when the avalanche activity peaked no manual profile was recorded.

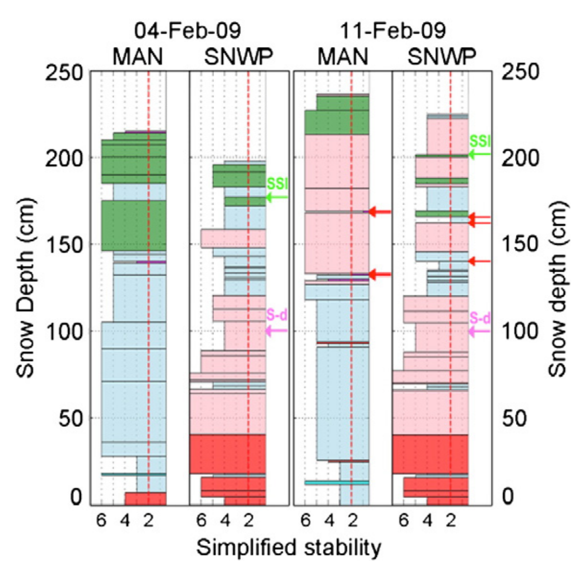

Fig. 6. Simplified snow stability profiles at Monti Alti di Ornella for 4 and 11 February 2009.

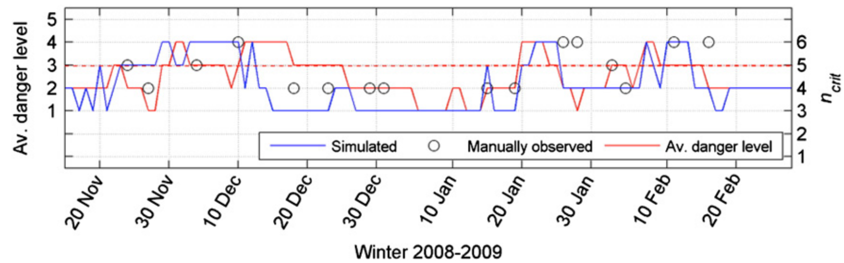

Fig. 7. Maximum number of variables in the critical range n_{crit} assigned to anyone layer in a given profile (manually observed and simulated). The dashed red line indicates the critical value of threshold sum according to Schweizer and Jamieson (2007) and the avalanche danger level 3: Considerable.

of avalanche activity or danger level (Fig. 3b). Again, the SNOWPACK model seems to more properly simulate the increase in weak layer strength than can be derived from the manual snow profile.

The stability indices given by the model did not provide any useful information. Throughout the period the depth of the SSI was just below the depth of ski penetration (where the stress induced by a skier is largest); we therefore conclude that its value is not related to a true weak layer (Fig. 3a).

3.3. Stability evolution during the winter 2008–2009

To more quantitatively analyze the threshold sum approach applied to manually observed and simulated profiles, we compared the maximum number of critical variables to the avalanche danger level. Fig. 7 shows the maximum number of variables in the critical range found in anyone layer in a given profile, either manually observed or simulated, in comparison to the verified danger level for the period 15 November 2008 to 28 February 2009. We used the SNOWPACK simulation performed on a daily basis at 09:00 am with input data of the AWS at MORN. The layers within the first 18 cm of the profile were excluded from the analysis Schweizer and Jamieson (2007). Fig. 7 suggests that SNOWPACK started to provide useful stability information once the snow depth had reached about 50 cm (28–29 November 2008) (Fig. 3a). In the middle of December both the manually observed and the simulated profiles showed a return to rather stable conditions before the danger level decreased, i.e. the danger level may have lagged behind. The development after the avalanche cycles in January and February 2009 suggests that in the simulated snow stratigraphy, the weak layers gained strength whereas this trend was often not reflected in the manually observed profiles.

The small number of manually observed profiles did not allow a statistically sound comparison between manually observed and simulated profiles. In 5 out of 16 cases the two types of profiles were classified differently (stable instead of unstable, or vice versa). Analyzing the 5 cases of disagreement, in 3 cases (26, 28 January 2009 and 16 February 2009) where the manually observed profiles were rated as unstable and the simulated profiles as stable, the stability derived from SNOWPACK better corresponded to the avalanche danger level. As mentioned earlier the difference is probably due to the fact that in the model the weak layers gained strength more quickly than reflected in the manually observed profiles. In one case (4 February 2009) SNOWPACK overestimated stability; though the weak layer was simulated as observed in the study plot, it was covered by less than 18 cm of new snow in the simulated profile so that this weak layer was not considered for the instability analysis. As mentioned earlier we always excluded this part of the snowpack from our analysis. The location where the manual profile was observed, received more new snow producing a thicker slab and thus a more critical situation which is in accordance with the increase of the avalanche danger (from moderate to considerable). Finally, the disagreement on 27 November 2008 is related to the fact that SNOWPACK has difficulties to provide useful stability information whenever the snowpack is thin.

The stability classification derived from both the manually observed and the simulated profiles was each compared to the verified danger level (Table 2). The classification accuracy for manually observed and simulated profiles is relatively poor (56% in both cases). In the case of the simulated profiles the evaluation can be extended to the period of 15 November 2008 to 28 February 2009 ($N=106$) (Table 3). The accuracy increases to 72%, but the prediction of the unstable situations (POD) remains fairly poor (53%).

For the simulated profiles, the average number of structural variables in the critical range (n_{crit}) was 4.7 on "unstable" days when the avalanche danger level was 3 or higher ($N=47$), and 3.4 on the "stable" days when the avalanche danger was Low (1) or Moderate (2) (Table 3). The difference is statistically significant (*U*-Test, $p<0.001$), i.e. n_{crit} was clearly related to the avalanche danger level — or to stability in general. On the other hand, the SSI provided by SNOWPACK had no discrimination power.

4. Discussion

Three periods of snow instability in the 2008–2009 winter season were analyzed by means of the threshold sum approach and the simplified stability visualization applied both to the manually observed and simulated profiles. The 16 manually observed profiles collected before and shortly after a period of high avalanche activity were compared to the corresponding simulated snow profiles. Despite a number of limitations, our preliminary analysis already allows one to assess the usefulness of the method for avalanche forecasting.

The newly developed simplified stability representation sums up, in a single graph, information on six structural variables; it is hence not only based on the ram or hand hardness as it is the case with the classical profile representation. The main feature of the proposed visualization is its intuitive readability. The avalanche forecasters can interpret it at the first glance since the representation is similar to the classical hardness profile, which they are familiar with. The new graphical visualization is superior to the standard visualization, where the structural variables are indicated by symbols only (Fig. 2).

Adjusting the threshold sum approach so that it can be applied to profiles simulated with the snow cover model SNOWPACK model, provided satisfactory results and facilitates the comparison between stability information derived from simulated and manually observed stratigraphy. Moreover, stability estimates derived from simulations were more sensitive to variations of stability than those derived from manually observed profiles.

The maximum number of variables in the critical range assigned to anyone layer in a given simulated profile was clearly related to the degree of avalanche danger suggesting that the threshold sum approach applied to simulated snow stratigraphy provides useful information. On the other hand, the classification accuracy was limited. However, the accuracy is comparable to (and even better than) the one that can be obtained with manually observed profiles. In fact, Schweizer and Jamieson (2007) related the number of structural variables in the critical range to profile stability estimated by using the method proposed be Schweizer and Wiesinger (2001) and found a classification accuracy

Table 2
Comparing stability derived from snow stratigraphy (manually observed and simulated profiles) to the avalanche danger level.

		Observed	
		"Stable" (danger level ≤ 2)	"Unstable" (danger level ≥ 3)
Forecasted	Manually observed profiles		
	"Stable" ($n_{crit} \leq 4$)	5	3
	"Unstable" ($n_{crit} \geq 5$)	4	4
	Simulated profiles		
	"Stable" ($n_{crit} \leq 4$)	6	4
	"Unstable" ($n_{crit} \geq 5$)	3	3

of only 47%. In both cases, stability was estimated without knowing the location of the weak layer which in principal is a difficult task.

With recent model developments, such as improving snow settlement, the SSI index provided by SNOWPACK seems to have lost its capability to pick the weak layer that originally motivated its introduction (Schweizer et al., 2006). Most of the time, the depth of the SSI was located just below the depth of ski penetration (Fig. 3a) which is unlikely in most cases and simply follows from the definition of the skier stability index. In addition, the value of the SSI had no discrimination power anymore.

It is known that the threshold sum approach generally overestimates instability (Winkler and Schweizer, 2009). This trend was less pronounced with our simulated profiles.

Whereas in this study a profile was classified as stable or unstable simply based on the characteristics of a single layer, it must be kept in mind that interpreting a snow profile is more complex (Schweizer and Wiesinger, 2001). Further developments are needed to supplement the present approach in order to achieve a more comprehensive stability estimate.

Some further limitations need to be pointed out: (i) the avalanche danger level summarizes the avalanche situation in a given region and is primarily valid in slopes of a certain elevation and aspect. Comparing local profile stability to regional danger level is questionable in principal and may introduce considerable uncertainty. However, as stability cannot be objectively measured, an appropriate target variable is in general lacking. (ii) The threshold sum approach was primarily developed for assessing instability due to persistent layers and it may not be suited to assess instabilities related to storm snow or surface warming.

5. Conclusions

We proposed a simplified snow stability visualization based on six snowpack parameters and tested our approach with both manually observed and simulated snow profiles.

The new profile representation sums up the stability information related to snow stratigraphy and facilitates a fast and intuitive interpretation of a snow profile. It helps not only to highlight the characteristics of the weak layer, but also the structural properties of the potential slab.

Table 3
Comparing stability derived from simulated profiles to the avalanche danger level for the period 15 November 2008 to 28 February 2009 ($N = 106$). Also shown is the average of the maximum number of structural variables in the critical range (n_{crit}) assigned to anyone layer within a simulated profile and the average of the minimum of the SSI. The p-value (Mann–Whitney U-Test) indicates whether the "stable" and "unstable" samples are from a different population (p-value < 0.001).

	Avalanche danger level		p
	1 and 2 ("stable")	3 and 4 ("unstable")	
Simulated profiles			
$n_{crit} \leq 4$ ("stable")	51	22	
$n_{crit} \geq 5$ ("unstable")	8	25	
n_{crit}	3.4	4.7	< 0.001
SSI	1.9	1.9	0.869

With adjusted threshold values profiles simulated with the numerical snow cover model SNOWPACK can be evaluated as well. The stability information derived from simulated profiles proved to be more sensitive to variations of stability than the stability derived from manually observed profiles. In addition a daily resolution can easily be obtained even during situations of high danger when manual observations are often impossible. The comparison of stability derived from simulated profiles to the avalanche danger level showed that this type of stability information was significantly related to stability — even though the classification accuracy is not very good (about 70%), but still in a range comparable to other methods. Preliminary results suggest that a stability estimate based on simulated snow stratigraphy may well be suited to complement traditional data used for avalanche forecasting.

As we considered only a limited time period and had to compare simulated point stability information to regional avalanche danger which is questionable from a methodological point of view, the proposed method needs to be further tested. Furthermore we suppose that it should be most promising to combine the threshold sum approach with other types of stability information provided by SNOWPACK. However, first the various stability indices, in particular the SSI, need to be thoroughly revised.

Acknowledgments

We acknowledge the help by Christoph Mitterer with SNOWPACK simulations and data analysis. We thank Tiziana Corso and Walter Cagnati who collected the profile data. Renato Zasso, Giorgio Barberis, Charles Fierz, Michael Lehning, Christine Groot Zwaaftink, Alec van Herwijnen and Andrea Pozzi provided various support and advice. We thank Garry Timco and an anonymous reviewer for helpful comments and suggestions.

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Please cite this article as: Monti, F., et al., A new method for visualizing snow stability profiles, Cold Reg. Sci. Technol. (2012), doi:10.1016/j.coldregions.2012.02.005

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Please cite this article as: Monti, F., et al., A new method for visualizing snow stability profiles, Cold Reg. Sci. Technol. (2012), doi:10.1016/j.coldregions.2012.02.005