The 2008-2009 exceptional snowfalls in the Italian Alps: threshold sum approach and analysis of the SNOWPACK model stability indices

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ABSTRACT: The 2008-2009 winter season has been characterized by exceptional snowfalls in the Italian Alps: it has been one of the 3-4 snowiest seasons since 1930. Six heavy snowfalls have determined the formation of several avalanches, many of which with a return time of 20-30 years.

The Avalanche Forecasting Centre in Arabba is responsible for assessing the avalanche risk in the territory of the Veneto region (Italy). In this centre the avalanche forecasting activity is supported by the research activity in order to improve and to ease the experts' job. Since 2004 it has been piloting the use of the SNOWPACK model and starting from December 2008 a new tool called Yeti NIK has been introduced to view manual snow pits. The peculiarity of this tool is its ability to assign a specific critical value to each layer in a snow pit. Threshold values are obtained according to the guidelines described by Schweizer and Jamieson (2008). The purpose of this method is to transform snow profile interpretation into a semi-quantitative scientific process.

In this paper the threshold sum approach has been applied to both the manual profiles and the model outputs in order to compare critical snowpack parameters obtained from these different methods.

Subsequently the stability indices automatically supplied by the model proved to be reliable and the evaluation of the most critical days of winter 2008-2009 have been presented with this new experimental approach.

KEYWORDS: Avalanche forecasting; Snow stability evaluation; Snowpack stratigraphy; SNOWPACK model.

1 INTRODUCTION

The interpretation of snow profiles and data on stability, which many consider to be an art form rather than a technique, is the key to determining the stability of the snow pack in order to calculate avalanche danger (Schweizer and Wiesinger, 2001).

Defining 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 instabilities in space and time relative to a given deformation energy level. Among the various ways to approach the matter, the conventional or synoptic approach is the commonest one, and it is used by Italian avalanche forecasting offices. It is mainly based on the skills, experience, and scientific knowledge of the forecasters (Cagnati, 1994). This approach was described by LaChapelle in 1980, and it has not been significantly modified since. Individual forecasts are based on field data, which are divided into categories. The most important data, which must weigh most heavily in the forecast, are those defined as low-entropy: for example, the direct observation of avalanches or *in situ* stability tests. In cases in which such observations are not available, or in order to confirm the indications given by them, higher-entropy data are used, such as data arising from the study of snow pack characteristics. Lastly, meteorological data are used (LaChapelle, 1980).

Over the last few years, efforts have been underway to improve this synoptic approach, in order to reduce the model's main weaknesses, including the limited objectivity of the interpretation of snow pack profiles, the spatial and temporal resolution of data, and the unavailability of data under high avalanche danger conditions.

The "Threshold sum approach" (Schweizer et al., 2004; Schweizer and Jamieson, 2007; Schweizer et al., 2008) is a proposal to make the interpretation of snow pack's stratigraphic profiles more objective. It is based on the identification of six critical variables, to be sought within the snow pack's layers, whose destabilizing role has been proven. These six variables are: failure layer grain size, difference in grain size between two adjacent layers, failure layer hardness, difference in hardness between two adjacent layers, failure layer depth, and failure layer grain type. The threshold values for the Swiss Alps are summed up in table 1.

The SNOWPACK model has been used by the Arabba Avalanche Centre since 2004 in support of its avalanche forecasting activities. This tool is very useful, since it aims to improve the spatial and temporal resolution of the infor-

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mation available to forecasters, especially on days when manual data collection is impossible due to high avalanche risk. During the 2007-2008 winter season, its simulations were verified in the Dolomites, resulting in a reliability of 72% (Monti et al., 2009; Monti, 2008).

The model reproduces the stratigraphy of the snowpack using data from automated snow and weather stations, and forecasts the changes induced by ongoing metamorphisms (Lehning et al., 1999; Bartelt and Lehning, 2002; Lehning et al., 2002a,b). Along with the stratigraphic profile, the model also formulates two stability indexes: the skier stability index and the deformation stability index. The former identifies the level where an avalanche provoked by a skier's excess weight is most likely, combining information regarding shear strength and information on structural instability (Schweizer et al., 2006). The latter identifies the level where the stress from the slower consolidation of the snow pack due to a rapid increase in load, for example after a new snowfall, is concentrated (Lehning et al., 2004).

2 OBJECTIVES

The 2008-2009 winter season, which was characterized by exceptional snowfalls throughout the southern Alps, provided an important opportunity for testing the new techniques for interpreting snow pack stability. The objective of this work is to analyze the most significant events from this past winter through the "Threshold sum approach" (Schweizer and Jamieson, 2007), applied both to manually-collected profiles and to the SNOWPACK model's simulations. Due to the way that the Veneto regional administration collects data, information on stability tests is unavailable. It was thus impossible to verify avalanche occurrence through the combined analysis of critical values, shear failure type, and the results of the rutschblock test, as suggested by Schweizer et al. (2008).

Finally, we propose a simplified visualization of the snow pack profile, which is not limited to hardness trends, but also gives an idea of layer stability, calculated through the verification of the presence of critical variables.

3 METHODS

The area chosen for our experiments is the upper Cordevole basin, in the area adjacent to the Arabba Avalanche Centre (Belluno, ITALY).

The events we examined, characterized by significant avalanche activity, took place between the months of December and March; they are all situations that rate a 4 (high danger level) on the European avalanche danger scale (Meister, 1995). Evaluations of actual stability conditions, taken as reference conditions for this study, were carried out by the Arabba Avalanche Centre's forecasters using the conventional or synoptic approach, upon which rests the study of snow pack's manual profiles, avalanche events, and weather conditions. A total of 20 manual profiles, whose critical values were determined, were compared with the profiles obtained by SNOWPACK. All of the manual profiles come from the two recording stations located in the upper Cordevole basin: the Monti Alti di Ornella station, at 2250 m a.s.l., (from whence the other model simulations come) and the Passo Pordoi snowfield (2142 m a.s.l.).

Variable Critical range	Manual	SNWP
Difference in grain size (mm)	≥ 0.75	≥ 41%
Failure layer grain size (mm)	≥ 1.25	≥ 0.6
Difference in hardness	≥ 2	≥ 1
Failure layer hardness	≤ 1	≤ 2
Failure layer grain type	Persistent	Persistent
Slab thickness or failure layer depth (cm)	18…94	18…94

Table 1. Critical ranges of variables in calculating the stratigraphical threshold sum

3.1 *Threshold sum approach*

In winter 2008-2009, the Arabba Avalanche Centre began experimenting with a new version of the Yeti software for viewing profiles. This version calls for the automatic assignment of critical variables for each contact point between two layers of the snow pack. Each interface can thus have a degree of criticalness between 0 and 6; this score is calculated by adding the various critical characteristics of the two layers that are coming into contact. In addition to this automated modality, in the present work we also calculated the degree of stability for each single layer. The critical values were assigned to each single layer by evaluating the characteristics of the layer itself and comparing them with those of the layer immediately underneath it. For the bottom layer, which touches the ground, the critical values of difference in hardness and in grain size are always assigned (Fig. 1).

3.2 *Threshold sum approach applied to SNOWPACK*

In order to apply the threshold sum approach to the SNOWPACK model, it was necessary to manually transcribe each single profile illustrated by the model in a manner compatible with the Yeti software. Another problem then emerged: adapting the threshold values of the critical variables to the values calculated by SNOWPACK. The model simulates snow crystals as spheres, and calculates their average radius, while manual measurements measure the length of the major axis of the average grains that are most representative of the sample (Cagnati, 2003). In order to determine the size value above which SNOWPACK crystals can be considered dangerous, we performed a statistical calculation using data from all the profile layers examined.

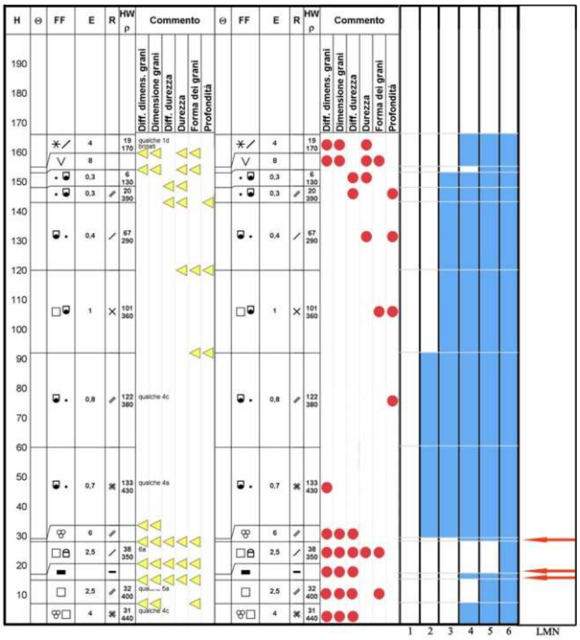

Fig. 1. Manual profile of the Monti Alti di Ornella station on 15-01-2009. From left to right, we can see: the automatic formulation produced by the Yeti software, where critical values are assigned to the interfaces (triangles), critical values assigned to the individual layers (spheres) and the simplified view of the stability of the profile with arrows indicating the weakest interfaces.

In order to obtain the critical difference in grain size between two layers, we calculated the incidence on the average grain, in percentage terms, of the threshold value determined for manual profiles. We used the following equation:

$$\Delta_{\%}=\frac{\Delta_{OBS}}{X_{mOBS}}*100 \qquad (1)$$

Where $\Delta_{\%}$ is the percentage difference, Δ_{OBS} is the critical difference in mm, and X_{mOBS} is the average grain value observed in manual profiles. Therefore, in order to calculate the critical range in the difference in critical size between grains from two layers produced by SNOWPACK, we must verify that:

$$\Delta_{s\%}\geq \Delta_{OBS}$$

where

$$\Delta_{s\%}=\frac{|X_{1snw}-X_{2snw}|}{X_{1snw}}*100 \qquad (2)$$

With $\Delta_{s\%}$ indicating the percentage difference between two adjacent layers.

Finally, we performed a qualitative analysis of the hardness values calculated by SNOWPACK, in order to obtain the most adequate suitable critical values.

In Table 2, we summarize the critical ranges used both for manual and simulated profiles.

Variable Critical range	Manual	SNWP
Difference in grain size (mm)	≥ 0.75	≥ 41%
Failure layer grain size (mm)	≥ 1.25	≥ 0.6
Difference in hardness	≥ 2	≥ 1
Failure layer hardness	≤ 1	≤ 2
Failure layer grain type	Persistent	Persistent
Slab thickness or failure layer depth (cm)	18…94	18…94

Table 2. Critical ranges used to evaluate both manual profiles and simulated ones.

3.3 Simplified viewing of the profile

Simplified viewing of the stability of a profile uses information from the study of critical variables, combining data on critical ranges both in layers and in interfaces. This makes stability trends in the various layers intuitive and easy to understand. The interfaces - along which shearing is more likely - can be identified thanks to the arrows on the side of the profile. In the profiles of the SNOWPACK simulations, the points where the two stability indexes take on the lower value are easily identified, again by arrows (Fig. 1).

4 RESULTS

For reasons of space, we decided to describe only two of the four cases we examined; the first, which took place between January 19th and 22nd, and the second, which took place between February 6th and 8th. For each date, we summarize the snow and weather conditions, along with actual stability conditions, and we compare images of the classic snow pack profile with those of the simplified stability profile.

4.1 January 19-22, 2009

The first period of heavy avalanche activity we analyzed was brought on by the snowfall of January 19-22, 2009. During this period, the snow pack was made up of thick intermediate and superficial layers of angular crystals, and a thick surface hoar layer. Faceted grains were the result of the cold spell during the first decade of January, while surface hoar mostly formed during the night of January 15, 2009.

The first avalanches began to fall along the steepest slope in the late afternoon of January 20th. However, most avalanches fell during the early afternoon of Tuesday, January 21st: from 12:30, numerous medium-sized avalanches began to fall from slopes at all exposures (Valt and Pesaresi, 2009).

Four profiles of the snow pack (two for each snow field), both before and after the moments of greatest instability, are available to study this event. The manual and SNOWPACK profiles both clearly describe the situation. The model correctly identifies the point in the profile where stability is lowest, although with the critical variables method proposed above, the snow pack appears generally less consolidated than it actually is according to manual profiles. This discrepancy does not make it impossible to identify the point of instability, but it does make it more difficult to differentiate, prior to the snowfall that caused the events, between stable and unstable conditions. Keeping the above in mind, we can attest to the fact that this situation is well interpreted by the threshold sum method, both for the SNOWPACK model and for manual profiles (Fig. 2).

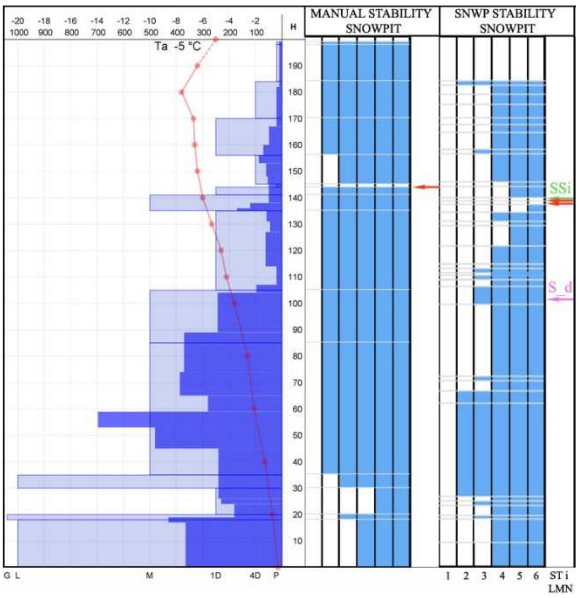

Fig. 2. 28-01-2009 snow stability situation at the Monti Alti di Ornella station. From left to right: hand hardness and ram hardness (darken) profile; manual and SNOWPACK simplified stability profile. The instability is clearly induced by a thin surface hoar layer at 140 cm of depth. This situation is well described by both manual and simulated profiles.

4.2 February 6-8, 2009

Starting in the night between February 6th and 7th, snowy weather brought an additional 50 cm of fresh snow to the study area, on top of the additional 30 cm that had fallen between January 31st and February 3rd. Precipitation was accompanied by strong southerly winds, leading to heavy accumulations of snow, especially above the tree line. Precipitation ended during the morning of Sunday, February 8th, which is when the largest avalanches took place.

Once again, four profiles of the snow pack (two for each snow field), both before and after the moments of greatest instability, are available to study this event. The analysis of the critical variables of the manual profiles reveals that instability was caused by buried layers of surface hoar; one at a height of 165 cm (degree of stability: 0) and another slightly more stable layer at 135 cm (degree of stability: 1).

SNOWPACK, however, did not see any dangerous layer of buried surface hoar , but rather a series of very weakly consolidated layers, deriving both from the transformation of surface hoar layers and from metamorphism affecting the snow fallen during the first few days of February. The most unstable layer is identified at a depth of 135 cm. The situation that best agrees with reality is that depicted by SNOWPACK, since the main shearing events took place around 135 cm, and while surface frost was indeed present within the snow pack, it was already in a state of advanced transformation.

The stability indexes produced by the model do not provide any useful indications for evaluating actual stability (Fig. 3).

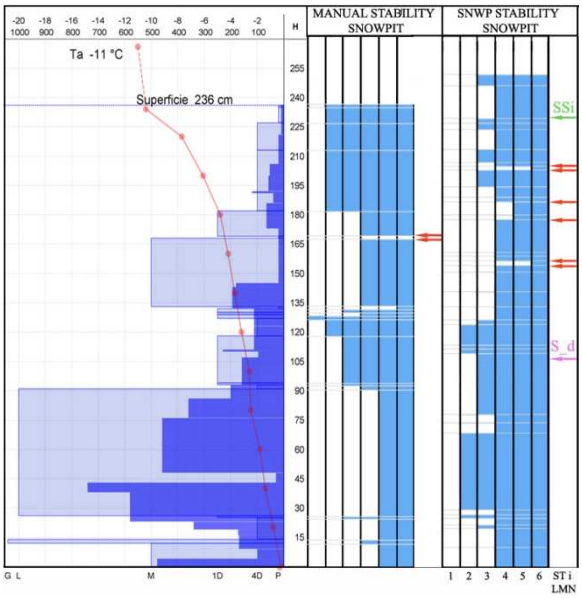

Fig. 3. 11-02-2009 snow stability situation at the Monti Alti di Ornella station. It shows how in the manual profiles the instability is assigned to a layer of surface hoar, while in the SNOWPACK simulation the instability conditions are triggered by a sequence of low consolidated layers.

CONCLUSIONS

The threshold sum approach is a very valid tool for interpreting snow pack profiles. The proposal to combine the study of critical ranges for each single layer with the same analysis for interfaces would allow for a complete stability analysis. The graph depicting the simplified stability profile can be understood quickly and intuitively. It also sums up, in a single graph, information on 6 snow pack parameters, and not just hardness trends, as the classic simplified profile does. The application of the threshold sum approach to the SNOWPACK model gave excellent results. Nevertheless, more work is needed in order to identify the critical variable parameters best suited for simulations. This work is necessary both for grain size variables and, especially, for hardness variables. With the help of this method, the model becomes very useful especially during times when the high risk of avalanches makes it impossible to perform measurements in the field; this was the case for most of December 2008. In operational terms, the main problem associated with the use of the SNOWPACK model is its limited ability to distinguish unstable from stable days. Nevertheless, its continuous and constant use on the part of an avalanche forecaster who is well aware of general snow and weather trends makes SNOWPACK a valid tool for helping determine avalanche risk, especially when combined with the threshold sum approach.

The analysis of stability indexes supplied by the model confirmed that they indeed function correctly only in cases of instability generated by evident conditions, such as a covered surface layer of frost, or new, significant snowfall (confirming the work of Nishimura et al., 2005; Monti, 2008). In all ambiguous situations, their interpretation is more problematic.

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