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Snow profile interpretation for stability evaluation

Jürg Schweizer *, Thomas Wiesinger

Swiss Federal Institute for Snow and Avalanche Research, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland

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Abstract

Snow profile interpretation is part of the every day work of any avalanche forecasting service. Snowpack information is crucial for assessing such things as the probability of a skier triggering an avalanche in between storms or the probability and size of natural avalanches during and after storms. However, profile evaluation is considered an art. There are few standard procedures and most forecasters have their own method. Some expert systems have been developed to interpret snow profiles but their knowledge base is not documented. The avalanche forecasting service in Switzerland has to analyse about 110 snow profiles recorded by its observers twice a month. This task is presently quite time-consuming, and the results are not fully consistent. Therefore, part of the decision-making process of some experienced forecasters at the Swiss Federal Institute of Snow and Avalanche Research was explored. Based on this broad experience, each parameter observed in a snow profile with a stability test has been described in view of stability evaluation. A tentative snowpack stability rating scheme is proposed for dry snow conditions in transitional or intermountain climate zones. The principal criteria are: rutschblock score, hardness, presence and type of weak layers, grain type and size. It should help the forecasters in the future to more consistently interpret snow profiles.

Keywords: Avalanche forecasting; Snow stability evaluation; Stability tests

1. Introduction

Snow stability evaluation is considered as the essential element of avalanche forecasting (McClung and Schaerer, 1993). The best data for stability evaluation are observations on avalanche occurrence and snow profiles, preferably combined with a stability test like the rutschblock (RB) test (Föhn, 1987). Snow profile interpretation is therefore part of the everyday work of avalanche forecasters, and supplements the indirect method of assessing avalanche danger based on contributory meteorological factors (Atwater, 1954). Mellor (1968) has described how forecasters make qualitative and subjective assessments of snow profiles, drawing on training and experience to recognize combinations of conditions which have produced avalanches in the past. Having identified potentially dangerous snowpack structures, the forecasters follow the developments to determine whether the potential instability is being aggravated or whether stabilizing changes take place. The method of using direct evidence, i.e. data obtained by observation of the snow structure and by stability tests, is especially important for the forecasting of delayed action avalanches. The forecaster's objective is to detect weak layers, crusts, etc. overlain by a

* Corresponding author. Tel.: +41-81-417-0164; fax: +41-81-417-0110.

E-mail address: schweizer@slf.ch (J. Schweizer).

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potential slab structure, to follow their changes with time, and hence to assess current stability and the probability of release in the near future.

In Switzerland, the avalanche warning service at the Swiss Federal Institute for Snow and Avalanche Research (SLF) operates an extensive observation program. About 80–90 observers provide snowpit data twice a month. About 50 observe a profile in a level study plot and approximately 40 do the same on a slope. The slope profiles with a rutschblock test are frequently the most valuable information available to assess snowpack stability. Together with about 20 profiles taken by the forecasters themselves, a total of about 110 profiles has to be analyzed by the warning service every 2 weeks in order to derive a pattern of snow stability for the whole area of the Swiss Alps. Each profile is assigned to a stability class: very poor, poor, fair, good and very good. For instance, during winter 1999–2000, forecasters analyzed 1119 profiles (734 from flat study plots and 384 from steep slopes, most of them with a rutschblock test, very few with a compression test). This process is quite time-consuming and presently, the results partly depend on the view of the forecaster in charge since there is no rating scheme.

To improve the process of profile analysis we reviewed stability evaluation, explored the decision making process of experienced forecasters and derived some general guidelines on how to interpret dry snow profiles. The aim of the paper is therefore to describe the elements to consider for the profile and stability test interpretation and then give a description of each of the five stability classes with the help of these elements. We will primarily focus on loading by skiers since skier triggering contributes to about 85% of all avalanche fatalities in the Swiss Alps (Schweizer and Lütschg, 2001).

2. Snow stability

Snow stability is the ratio of strength to stress (skier, new snow, etc.) on a weak layer or interface. Stability evaluation means to assess the probability of avalanche release for the snow conditions under consideration. Although the danger scale used in Europe is based on snow stability (Meister, 1995), snow stability is only very generally described. In Canada, there exists a stability rating. It attempts to define classes that can be verified by observation, data or experiments (McClung and Schaerer, 1993; CAA, 1995).

One of the best stability tests, in particular to assess skier triggering, is the rutschblock test described by Föhn (1987). Jamieson and Johnston (1993) have shown some of the limitation of the rutschblock test. Schweizer et al. (1995) have pointed out what in particular to consider when interpreting RB tests: the type of release and the quality of the fracture plane. The type of release is described as the "whole block," most of the block, i.e. in most cases "below the skis" or only a minor part of the block such as "only an edge." The quality of the fracture plane is rated as "clean," "partly clean" or "rough." It is also mentioned that the test is unreliable for assessing the strength of weak layers close to the surface, and that in the case of deep instabilities the cohesion of the overlaying slab has to be taken into account. Furthermore, it is strongly recommended to always combine a stability test with a snow profile, since only by doing so, the communication of stability test results becomes possible.

Independently, Johnson and Birkeland (1998) proposed a system to rate the shear quality observed during a stability test similar as proposed by Schweizer et al. (1995), and applied in the expert system by Schweizer and Föhn (1996). Johnson and Birkeland (1998) describe three levels: clean shear, mostly smooth shear (average) and irregular or rough shear.

Although a snow profile, even when completed with a stability test such as the rutschblock test, is not sufficient to derive a final stability assessment, it is nevertheless usually the most important information, in particular in times of rather low avalanche activity. However, one has to keep in mind that any snowpit data is representative only for a certain area of usually the same aspect but there might be a (unknown) spatial correlation to a larger area with similar conditions.

There has been only a few attempts to systematically and objectively approach profile interpretation. Mostly, snow profile interpretation is demonstrated based on examples (McClung and Schaerer, 1993). LaChapelle and Ferguson (1980) tried to develop a quantified stability analysis through an objective evaluation of snowpack structure. To discriminate stable and unstable measurement parameters within snow layers, a clustering technique of pattern recognition was used that was able to successfully categorize profiles into stable and unstable profiles with an accuracy of 86%. It seems that the subsequent study (Ferguson, 1984) did not corroborate this surprising result. Ferguson (1984) quantitatively analyzed snow profiles from stable and unstable slopes. A multivariate statistical analysis using cluster analysis and pattern recognition techniques were employed. However, using statistical methods to easily differentiate between the 78 stable and the 78 unstable profiles proved to be difficult. The clustering patterns showed a relatively tight group of unstable profiles which were efficiently modeled with linear combinations of parameters. This was embedded in an amorphous group of stable data whose divergent pattern made modeling difficult. Ideally, a simple discriminant function between stable and unstable categories would be an optimal forecasting tool to determine the instability of an unknown snowpack. However, the imbedded cluster of unstable data would require a fabricated, nonlinear, multidimensional discriminant function to surround the class. Therefore, it seems that the analysis has never been used to finally develop a successful forecasting tool. Because unstable data was more tightly clustered than stable data, it was possible to derive a reasonable model of unstable snowpack profiles. It proved to be in general easier to describe instability than stability.

Numerical avalanche forecasting has rarely included snowpack and stability information. McClung (1995) describes an expert system that was developed for profile interpretation. The fact that interpreting profiles taken by others is not frequently an important task might be the reason why expert systems developed for snow profile interpretation are not widely used on a daily basis.

The forecast by the French Safran–Crocus–Mepra model chain (Durand et al., 1999) is based on the stability interpretation of calculated (modeled) snow profiles. It is the only forecasting model that is based on snowpack stability.

Schweizer and Föhn (1996) have included stability information in their statistically based models for regional avalanche forecasting. They also drafted a first scheme on how to assign a snow profile with a stability test to a certain class of snow stability (Schweizer et al., 1992). Snow stability was defined as a measure of how much load a given snowpack could sustain when it would be loaded by a skier, by new snow, or by wind-driven snow. The classification was primarily based on the rutschblock test result, the existence and type of weak layers and the type of hardness profile as proposed by deQuervain and Meister (1987).

Schweizer and Lütschg (2001) described characteristics of the snowpack structure of skier triggered avalanches. Their findings will be used to reassess the reasoning and the importance of certain parameters. One of the important results in their 90 profiles from skier triggered avalanches is that a weak layer was found in only about 50% of the cases. In the majority of the cases, the failure was described as interface failure. Interface failures are significantly more difficult to find although Schweizer and Lütschg (2001) showed that there is usually a distinct difference in grain type and size, and hardness. A similar study by Schweizer and Jamieson (2001) corroborates the above results and shows that important snowpack characteristics in view of skier triggering are independent of the climate zone.

3. Methods

Stability evaluation based on snow profile and stability test interpretation means essentially to seek for signs of instability (McClung, 2000), rather than stability. One of the advantages of this pessimistic approach is that the signs of instability are easier to interpret and extrapolate. The presence of an instability always is a clear indication for caution to be applied, whereas the absence of instability is more ambiguous, partly because of the site-specific nature of the observation.

Snow profile interpretation is largely experience-based. Therefore, no rigorous method can be given below. We used different approaches.

When interpreting a snow profile, the following measured or estimated parameters are available: snow depth, layering (stratigraphical order and thickness), grain type, grain size, hand hardness, liquid water content (dry, moist, etc.), snow temperature, ram

Table 1
Questions 1 to 9 were asked for each of 14 snow profiles that had to be interpreted by 10 experienced forecasters/researcher of SLF

	Questions
1	Do you relate the following parameters rather with stability or instability? (ram profile, hardness profile, rutschblock, grain type and size, liquid water content, snow temperature)
2, 3	Do you recognize weak layers or interfaces? How many?
4	Do you rather expect skier triggered or natural avalanches?
5	Might a single skier trigger a slab?
6	Is there a slab structure favouring triggering?
7	Does the snow temperature profile have a stabilising or weakening effect on potential weak layers?
8	What is the type of hardness profile?
9	How would you rate the profile? (very poor, poor, fair, good, very good)
10	Which parameters do you consider as important in general when interpreting snow profiles? (ram profile, hand hardness profile, rutschblock score, grain type and size, snow temperture, liquid water content, weak layers/interfaces)
11	How important do you rate the following parameters when interpreting a rutschblock test? (slope angle, snow depth, RB score, slab thickness, slab hardness, type of failure, type of fracture plane)

Questions 10 and 11 were of general nature and had be answered only once. Questions were given in simplified form.

hardness (not always), density (not frequently), RB score, slab thickness, information on type of RB failure, e.g. whether the whole or only part of the block was released, or whether the failure plane is smooth or undulated.

To quantify the experience on how to interpret a snow profile based on the above parameters, we did a survey. We asked 10 experienced forecasters and/or researchers at SLF a series of questions (Table 1) on 14 snow profiles from the Swiss Alps —nearly exclusively consisting of dry snow. The emerging problems or discrepancies were then discussed and conclusions reached.

Furthermore, we used a previously developed scheme by Schweizer et al. (1992), and the general knowledge, e.g. as described in McClung and Schaerer (1993). Finally, we referred to some recent results on the snowpack characteristics of skier-triggered avalanches (Schweizer and Jamieson, 2001).

The first draft of the derived stability rating scheme was then tested and improved by applying it to about 100 randomly chosen snow profiles.

4. Results of questionnaire

The evaluation of the questionnaires showed that in general, the agreement on the stability rating of the profiles is relatively high between the different forecasters. The subsequent discussion revealed that, however, their reasoning is often quite different. We will only present the results of the general questions 10 and 11. In 78% of the cases the forecasters and/or researcher rated the profiles within half a level of the verified stability rating (Fig. 1). Fig. 2 shows that most forecasters do consider many parameters when interpreting a snow profile (question 10 in Table 1). Seven out of the 10 forecasters do consider four or five of the seven proposed parame-

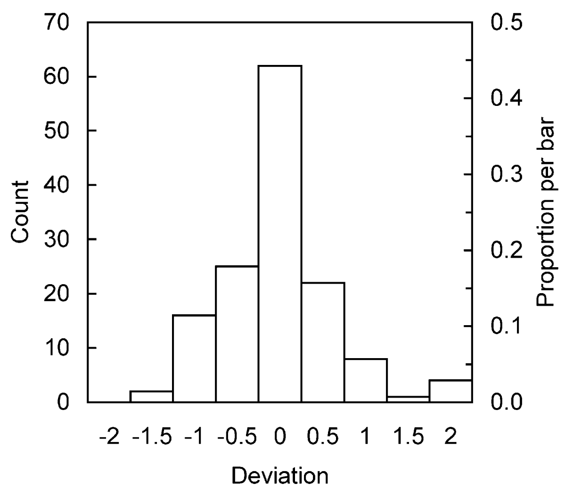

Fig. 1. Deviation of the stability rating of the 10 forecasters and/or researchers compared to the verified stability rating for the 14 profiles evaluated ($N = 140$).

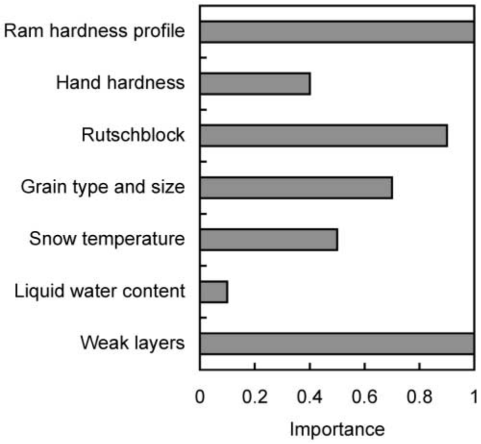

Fig. 2. Relative importance of parameters for profile interpretation (1: very important, 0: not important) (Table 1).

ters. Liquid water content is hardly considered, except in spring situations, similarly the snow temperature. Snow temperature is considered to check whether dry snow conditions prevail, but none of the forecasters does explicitly use the snow temperature in dry snow conditions for stability evaluation. A few take into account the effect of future changes of temperature on snow stability. The low importance of the hand hardness is rather surprising but explained by the fact that in Switzerland, most profiles include the ram hardness. Since the hand hardness is a more subjective measure, the ram hardness is preferred. The three parameters that are considered most are the ram hardness profile, the RB score and the existence and type of weak layers.

The answers on question 11 (Table 1) show a similar result. Again, each of the forecasters considers many parameters when interpreting a ruthschblock test (Fig. 3). The ones that were most homogeneously rated as important are the RB score, the slab thickness and the type of fracture plane. High, but having a somewhat less consistent rating has the type of release (whole block, below the skis, only an edge).

5. Description of parameters

Based on the above mentioned elements of experience, we describe each of the parameters observed in a full snow profile in view of stability evaluation. We focus on dry snow conditions as mainly found in intermountain and transitional climate zones. Peculiarities of maritime or coastal climate zones are not considered.

5.1. Grain type

Weak layers of skier-triggered avalanches typically consist of surface hoar, faceted grains or depth hoar (e.g. Föhn, 1993). These grain types are generally rather large and have plane faces. The number of bonds is relatively low, making layers of these grain types weaker than others (Jamieson and Johnston, 2001). They are also called persistent (i.e. thermodynamically relatively stable) (Jamieson, 1995) and tend to gain strength slowly. The grains in persistent weak layers that have been buried for some days or even weeks become rounded and are less critical, but frequently still show clean shears.

Melt-freeze crusts and ice lenses tend to stabilize the snowpack provided they are thick enough. However, they also can be gliding surfaces as long as the bonding of new snow to the crust is insufficient. In spring, wetting of these impermeable layers may cause a reduction of friction (Fierz and Föhn, 1995).

In certain situations, the bonding within new or partly settled snow layers is poor during or immediately after a storm, in particular during cold heavy snow storms. In that case, failures occur within a

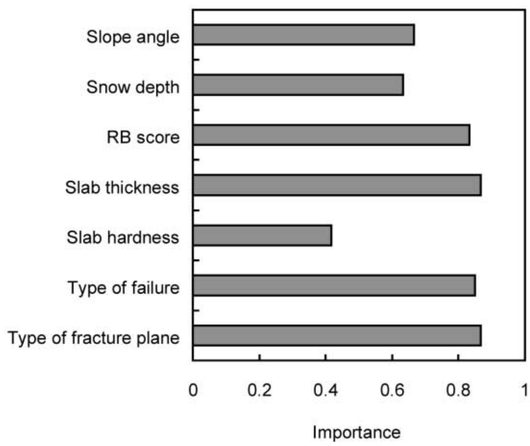

Fig. 3. Relative importance of parameters for RB interpretation (1: very important, 0: not important) (Table 1).

layer of new snow, or partly decomposing and fragmented precipitation particles.

Rime and graupel are rarely observed to form weak layers. Graupel is formed at relatively high temperatures. Although it survives in the snowpack once it is buried quite long, graupel has been mainly observed as weak layer shortly after deposition on a smooth crust.

5.2. Grain size

The larger the grains the lower the number of bonds per unit volume (other factors being equal), in particular in combination with persistent grain types. On the contrary, layers consisting of small grains rather indicate strength. Significant differences in grain size from one layer to the other are usually unfavourable.

5.3. Existence of weak layers or interfaces

The lower stability the more prominent weak layers/interfaces are present. In a profile rated as good, there are only moderately prominent or inconclusive potential weak layers present. The absence of weak layers/interfaces points toward very good stability. With increasing stability weak layers become more unlikely, whereas weak interfaces become more likely. Interface failures frequently involve a crust. The strength of bonding of the adjacent layers to the crust can hardly be judged from a snow profile unless it is supplemented with a stability test. However, a sign of instability has to be interpreted if facets are found above or below the crust.

5.4. Hand hardness index

Weak layers are usually soft, mostly hand hardness “fist,” sometimes “fist to four fingers.” Although the hand hardness is rather subjectively estimated, it is relevant to look for difference in hardness, because hardness differences are frequently associated with weak layers or interfaces. In general, decreasing hardness with increasing depth is an indicator of instability. Yet, any hardness difference of two steps of the hardness scale has to be critically assessed. Critical weak layers are frequently sandwiched between harder layers. Hard layers such as crusts are most frequently found in the case of interface failures. In general, large gradients of hardness between two layers are more critical than small differences, and frequent changes of the sign of the gradient are unfavourable. Thick layers of low strength consisting of faceted crystals or depth hoar in the uppermost part of the snowpack frequently have not sufficient cohesion to represent potential slab layers, even with a prominent weak layer directly below. The same situation can occasionally be found during storms.

5.5. Snow temperature

In dry snow conditions the snow temperature alone does not reveal potential instability, and snow temperature seems to be of limited value. None of the forecasters and/or researchers questioned could give conclusive rules on how snow temperature should be rated. Sometimes it is used to assess the stability trend given a certain temperature gradient, layering and expected trend of air temperature evolution. However, snow temperature in a dry snowpack is important for assessing the effectiveness of skier triggering and the propensity of fracture propagation (McClung and Schweizer, 1999). The analysis by Ferguson (1984) suggests that unstable snow is colder than stable snow. However, we have compared the slab temperature of 105 stable with those of 83 unstable snowpacks and found no statistically significant difference. When the snowpack tends to get isothermal, snow temperature becomes more important again for evaluating wet snow instability. Of course, changing air temperatures affecting snow temperature have a distinct effect on snow stability, but this is a different subject (Armstrong, 1983).

5.6. Liquid water content

The amount of liquid water is not measured but estimated. Until the snowpack is not (or not at least partly) isothermal, the amount of liquid water is hardly considered relevant for instability assessment in generally dry snow conditions. Rain on snow events are not considered.

5.7. Ram profile

The ram profile shows the vertical distribution of penetration resistance or ram hardness of the snowpack. The resolution is limited, so that thin layers whether hard or soft, are frequently missed. Soft layers of at least 5–10 cm thickness can be detected, however, and such features as a weak basal layer due to depth hoar can easily be seen. This is important to assess in order to know whether an avalanche due to a failure in the upper snowpack might sweep out deeper layers of the snowpack, which could lead to a much larger avalanche. Slab structures can usually be recognized as well.

The hardness profile is characterized as one out of 10 types of profiles (Fig. 4). The general shape is considered. When classifying a hand hardness profile, thin crusts for example are usually neglected. DeQuervain and Meister (1987) have given a first classification. The profile types 1–5 all have a weak base, whereas the profile types 6–10 are well consolidated at the bottom. The profile types 1, 5, 7 and 9 indicate potential instability. Profile types 6 and 10 represent in general stable conditions, whereas types 2, 3, 4 and 8 cannot be assigned definitely, but all show some potential, but depending on the conditions, usually less critical weakness.

The presence of a weak base of depth hoar is not conclusive on its own. Most profiles have a weak base due to our transitional to partly continental type of climate. If the profile is well consolidated in its middle part (belly-shaped profile in combination with a weak base), this points to good or very good stability.

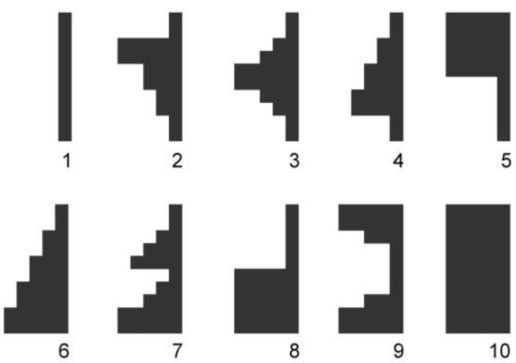

Fig. 4. Classification of ram hardness profile.

5.8. Density

Critical layers are less dense than the surrounding layers. However, density measurements of distinct thin layers are usually not available. Density does not directly show instability. Density is used to calculate the load on a weak layer, but unless there is no strength measurement this is again of limited value. In general, dense (warm) snow on loose (cold) snow is unfavourable, but this is usually recognized by the hardness or grain size difference.

5.9. RB score

RB scores of 1–3 are clear signs of instability (Föhn, 1987; Jamieson, 1995). Scores 4 and 5 indicate transitional stability. Scores 6 and 7 are generally associated with stable snowpacks. This rating is valid for test results where the whole block was released and the fracture surface indicates a clean shear. Partial release and/or not clean shears indicate correspondingly higher stability.

On a steeper slope a lower score is expected. However, the dependence on slope angle is rather low (Jamieson and Johnston, 1993). So there is no correction needed for RB tests done on slopes between about 30° and 40°. RB scores from slopes steeper or less steep than these limits might be adjusted by 1 step of RB score.

As a rutschblock is isolated from the surrounding snowpack, there is no peripheral strength. Therefore, a rutschblock can fail in a deep weak layer covered by a thick strong slab layer, but triggering a slab on a similar slope is still rather unlikely, except maybe at a shallow spot.

Layers close to the surface cannot be tested (shallower than about ski penetration) but need to be considered as well. Occasionally, during or very shortly after a snowfall the slab might not yet be cohesive enough so that the RB score tends to underestimate the situation in the near future.

In general, slab properties influence the RB test result, but it is not clear, e.g. how to assess the fracture propagation potential.

5.10. Layer thickness

A snowpack with many thin layers is in general rather more unstable than a snowpack that only consists of a few, relatively thick layers.

Weak layers can be very thin (millimetres), but are usually less than a few centimetres. In extreme cases the entire snowpack can be weak, and could therefore be designated as weak layer; but in general, if we talk about weak layers we have a layer of a few centimetres (about $\leq 3–5$ cm) in mind. The closer the weak layer is to the surface the more critical it has to be considered in view of skier triggering. However, if the layer is within about the first 15 cm, it is less critical. The most favourable range in view of skier instability is a weakness that

Table 2
Snowpack stability rating scheme for dry snow profileswith stability tests

Class of stability	Description
5: very good	No critical weak layers present. In general, well consolidated (ram resistance R larger than about 100 N), some soft layers (new snow or faceted crystals) near the top possible. Faceted crystals in the lower snowpack may be present, but with $R > 100$ N (“four fingers” or harder). The bottom is usually well consolidated as well, but occasionally a potentially weak base of large faceted crystals or depth hoar may exist, but is covered with a thick cohesive layer (at least 70 cm with $R > 200$ N). Profile type: 4, 6 and 10. Rutschblock score: 6 or 7.
4: good	Weak layers may be present, but not very prominent, e.g. showing no clean shear. In general well consolidated middle part with $R > 100$ N, or prominent hard crust of a few-centimetre thickness in the upper third of the snowpack. At the bottom a potentially weak base with large faceted crystals or depth hoar may exist, but is covered with cohesive snow (at least 50 cm with $R > 100$ N). The snowpack might fail if applying high stresses to interfaces or less well pronounced weak layers, or on top of the depth hoar base. Profile type: 2, 3, 4 and 6. Rutschblock score: 5 or 6.
3: fair	Weak layers are present, showing clean shears, but transitional scores (4, 5). Weak layers often consist of rounded persistent forms. Some soft layers with $R \approx 40$ N present (except new snow on top), but most of the snowpack is fairly well consolidated. Profile type: 2, 3, 4, 8, 9; occ. 7. Rutschblock score: 4 or 5; occ. 3, e.g. when overlain by thick strong slab.
2: poor	Prominent weak layers and/or interfaces are present, showing clean shears. Weak layers of surface hoar or faceted crystals, larger than 1 mm, or interfaces within the new or partly settled snow or new snow on crust. Hardness of slab is $R < 40$ N (“fist” to “four fingers”). Some well consolidated parts may exist ($R = 100\ldots300$ N), but the thickness of these layers is less than 30 cm. Profile type: 1, 2, 5, 7, 8 and 9. Rutschblock score: 2 or 3.
1: very poor	Prominent weak layers and/or interfaces are present. Thin weak layers of surface hoar or faceted grains, larger than 1–2 mm sandwiched between harder layers, or facets on crusts. The bottom is frequently weak, occasionally covered with only one cohesive slab layer. The ram resistance may be low from top to bottom ($R \approx 20$ N). In general, ram resistance above the weak layer is $R < 50$ N, often “fist.” There are no hard layers with $R > 150$ N present, crusts are usually thin and do not show up in the ram profile. Profile type: 1, 5, 7 and 9. Rutschblock score: 1 or 2.

is buried between about 15 and 75 cm. If a layer of depth hoar on the ground is thinner than the terrain roughness, it is in general hardly critical, and likewise if a thick strong layer overlies the depth hoar layer.

Slab thickness can vary from centimetres to meters. The thicker and harder the slab overlying the weak layer, the more unlikely is skier triggering (other factors being equal). On the other hand, a thick slab on a weak layer may produce a spontaneous avalanche as the slab increases due to loading (snowfall, snowdrift).

Crusts are commonly found in the snowpack of the Alps. Thin crusts are mainly found in profiles rated as poor to fair, whereas thick crusts, providing strength, are more common in stable snowpacks.

6. Interpretation scheme

Based on the above description of instability, the following tentative and simplified scheme is proposed for stability evaluation based on snow profile and stability test data (Table 2). Not every criteria given for each stability class has to be fulfilled. Often, only a few of the criteria are fulfilled, but at the same time in two classes of stability. In that case the profile is assigned to the stability class for which the more important criteria are fulfilled, e.g. RB score usually overrules profile type. However, the RB score criterion given for each stability class is only fulfilled if the whole block was released and a clean fracture plane showed up. Otherwise the higher stability class has to be considered.

There are always exceptions that cannot be covered by the system in Table 2. The scheme is now operationally used and will then be reassessed. It is presently only applicable for dry snow slab avalanches with the skier as trigger in mind. In the spring, other parameters have to be considered, as well as for the case of naturally released avalanches.

The problem of snow profile interpretation is in general too complex to be simply summarized in a scheme as given above. But for our aim, it is useful to at least consistently rate the majority of the large number of profiles that have to be analyzed by the forecasters.

Furthermore, it has to be pointed out that for avalanche danger forecasting any stability rating should be completed with the depth of the potential instability. Only with this additional information the avalanche danger can be assessed.

7. Conclusions and outlook

Snow profile and stability data are the key to evaluate snowpack stability for avalanche forecasting. To improve snow profile interpretation, we explored the decision making process of experienced forecasters. Based on these results and on well established knowledge, a list of criteria has been developed to assign a profile to a certain class of snowpack stability. The derived scheme is to rate dry snow profiles from intermountain or transitional climate zones. The principal criteria are: rutschblock score, hardness profile, presence and type of weak layers, grain type and size. We followed a structured approach for snow profile interpretation (Table 2) but experience and judgement cannot be replaced. Any derived scheme will be tentative and incomplete. It needs to be further validated and improved during operational use. Despite its incompleteness, the developed stability rating system will help the forecasters to more consistently interpret the large number of profiles they receive for interpretation.

An expert system would be ideally suited for the complex, intuitive decision-making process of snow profile interpretation. This study might accordingly pave the way for the development of an expert system that will give a first guess on the stability based on a snow profile (modeled or observed), and that will finally be incorporated into the GIS system used for drafting the avalanche danger bulletin in Switzerland. This should provide a map of snow stability as an additional supporting tool for the forecaster. Superimposed onto the stability map, other snow and weather parameters might be shown to assess the temporal evolution of stability.

In the near future, new methods of measuring snowpack structure (Schneebeli et al., 1999) may substantially improve stability evaluation based on snowpack information, and give in addition useful information on the spatial variability of stability.

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