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Skier triggered slab avalanche release - some practical implications - *Déclenchement des avalanches de plaques par les skieurs : quelques implications pratiques*

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ABSTRACT

To understand the release of dry snow slab avalanches triggered by skiers is crucial for regional avalanche forecasting services as well as for the backcountry skier. Numerous observations of fracture line profiles (at the margin of natural/artificial avalanches or at Rutschblock test sites), Finite Element (FE) calculations and field experiments were performed to get insight in the release mechanism of slab avalanches triggered by skiers.
The skiers impact on the snow cover was measured with load cells at different depths within the snow cover for various snow conditions. Different steps of dynamic loading were considered. As in the previously performed FE-calculations, besides the depth of the weak layer or interface, the sublayering proved to be most important. Hard layers play an important role. Depending on the snow cover configuration the skiers impact is of the same order of magnitude as the strength of typical weak layers derived from shear frame measurements. The results corroborate the idea that the skier is able to trigger the slab avalanche, by directly initiating a brittle fracture within a weak layer or interface.
Based on this work the practical implications for the stability evaluation are discussed. In particular the potential and some of the limitations of the Rutschblock test are described.

RÉSUMÉ

Il est de prime importance pour les services de prévision avalanche ainsi que pour le skieur de randonnée de comprendre les mécanismes de déclenchement de plaques de neige seiche par un ou des skieurs. L'analyse de nombreux profils relevés dans les zones de fracture d'avalanches naturelles et accidentelles ainsi que lors de test du bloc glissant, des calculs par éléments finis et des expériences réalisées in situ permettent de mieux comprendre les mécanismes de déclenchement de plaques par le skieur.
L'impact du skieur sur le manteau neigeux a été mesuré à l'aide de jauges de contrainte appropriées en plusieurs profondeurs pour différentes conditions d'enneigement. Les mises sous contrainte passent progressivement de statiques à dynamiques. Comme l'avaient montré les calculs par éléments finis, outre la profondeur de la couche ou de l'interface faible, la stratification joue un rôle prédominant et en particulier des couches dures. Suivant les conditions d'enneigement, l'impact de skieur est comparable à la résistance au cisaillement mesurée avec un cadre de cisaillement pour les couches faibles typiques. Ces résultats confirment donc l'idée que le skieur est à même de déclencher une plaque en provoquant directement une fracture cassante au sein de la couche ou de l'interface faible.
En nous basant sur les résultats de ces travaux, nous discutons des conséquences pratiques pour l'évaluation de critères de stabilité et en particulier des points forts et des certaines faiblesses du test du bloc glissant.

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INTRODUCTION

During the winter season 1994/95 there were 20 avalanche fatalities in the Swiss Alps; this is less than the 30-year-average of 28 avalanche fatalities. Nearly one third of the fatalities happened within three days at the beginning of the year 1995 (January 3 to 5). From these three days we know about 7 dry snow slab avalanches triggered by skiers (probably many more were triggered without any victims); 12 skiers were caught, 9 were buried and 6 of them were killed; in particular one avalanche in the east of the Swiss Alps, near the Swiss-Austrian border, caused 4 fatalities and on the same day (January 3) 4 skiers were killed nearby in Austria.

On January 3, 1995 a 4-day snowfall period ended and the weather got fine. Within these 4 days the total depth of new snow was about 90 to 120 cm in the northern parts, 30 to 80 cm in the central parts and 10 to 30 cm in the southern parts of the Swiss Alps. Before this snowfall period there was hardly any snow up to 2000 m a.s.l. At 2500 m a.s.l. the average snow depth was about 50 cm; so skiing conditions until end of December were rather bad. The snow cover typically consisted of weak layers of faceted crystals with some crusts in between and on southern slopes also at the surface. According to the new snow depth the avalanche hazard was estimated to be *high (4)* in the northern parts, *considerable (3)* in the more central parts and only *moderate (2)* in the most southern parts (European 5 degree danger scale). Typically all avalanche accidents following the snowfall period happened in the more central or adjacent southern parts of the Swiss Alps where the new snow depth was only moderate and the avalanche hazard considerable (Fig. 1).

What happened? Probably two things; there seems to be a social aspect and a snow cover aspect. First, it might be that due to the avalanche warning people kept out from the regions with a lot of new snow and a high hazard and went skiing in the other regions; secondly, in the regions with only a moderate amount of new snow, the probability for skier triggered slab avalanches is higher than in the regions with a lot of new snow; there, numerous spontaneously released avalanches were observed, the situations stabilized rather fast and finally the weak layers were deep, so that induced forces are small and skier triggering is less probable.

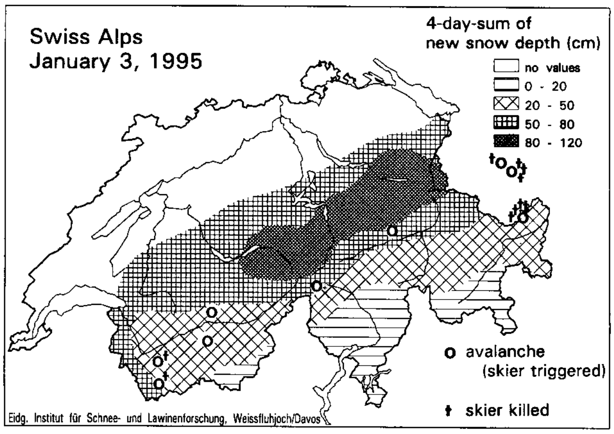

Fig. 1. 4-day-sum of new snow depth at January 3, 1995 and locations where avalanches were triggered by skiers during January 3 to 5, 1995 in the Swiss Alps.

In the regions with only 30 to 50 cm of new snow the conditions for triggering were perfect: a slightly consolidated layer of new snow on a very unfavourable old snow cover with different weak layers. Before the snowfall, skier triggering was not very probable; the layers of faceted crystals were rather cohesionless; skier's forces could not spread out, although in December some Rutschblocks were easily triggered due to a collapse of the basal layers. After the snowfall, the fracture was in most cases within the old snow cover not at the interface between old snow and new snow, probably since the air temperature was relatively high at the beginning of the snowfall and decreased during the storm.

This episode not only shows the importance of studying skier triggering and transfer of the results to practice but also, it confirms the very old rule that winter periods or regions with a snow depth below the long term average are more dangerous regarding skier fatalities than periods or winters with a lot of snow. In the winter season, 1994/95 both sides of the rule were

confirmed: 15 of the total 20 fatalities occurred at the beginning of the winter in December and during the first half of January; in the following 4 months there were fortunately only 5 fatalities; the maximum snow depth, in most regions, exceeded the long term average.
Föhn (1987a) introduced the stability index S' considering the skier's effect. As the skier is a substantial additional load, the snow stability may largely decrease when a skier passes (e.g. Schweizer, 1991). Jamieson and Johnston (1995) improved the stability index and tried to use it operationally as forecasting index.
To remember, it is generally believed that slab avalanches start with a shear fracture; so besides steep terrain two requirements must be met for dry snow slab avalanches to occur: a weak layer or interface and an additional shear stress which overcomes the shear strength of the weak layer and which produces a large rate of deformation in the weak layer so that the layer fractures in the brittle way (McClung and Schaerer, 1993).
In the following, we will discuss some results of experiments we have performed to measure the skier's impact and try to come to some conclusions about skier triggering and stability evaluation by Rutschblock tests.

MEASUREMENTS OF THE SKIER'S IMPACT IN THE SNOW COVER

Methods

During the winter season 1993/94 and 94/95 we performed 21 and 22 experiments respectively with load cells (Schweizer et al., 1995) to measure the skier's impact in the snow cover, most of them in the study plot of the Swiss Federal Institute for Snow and Avalanche Research (SFISAR) at Weissfluhjoch 2540 m a.s.l.. A few experiments were done on a slope, but as the principal aim was to study the dynamic response of the snow cover, most experiments were performed in flat terrain. For the second period the data acquisition was substantially improved (Camponovo, 1995).
One experiment consists of a series of load steps subsequently performed on the same load cell that was buried or set on the snow surface prior to a snowfall. The different load steps, following the Rutschblock procedure, were: standing atop, weighting and jumping (Föhn, 1987b) (Fig. 2).
For each load step the normal and the shear force were recorded during 20 s with a sampling frequency between 0.7 and 2 kHz. During the experiments the penetration depth and/or the thickness of the snow layer between skier and load cell were measured. Special attention was given to the snow cover conditions: after each set of experiments a snow cover profile was performed, including grain shape, grain size, snow hardness index (hand hardness), snow temperature and snow density (Fig. 4). Whereas during the winter season 1993/94 measurements for different snow cover conditions could be realized showing the substantial effect of the layering, in the winter 1994/95 mostly new snow conditions were found.

Fig. 2. Loading step of jumping; to show the configuration the load cell was partly digged out. The load cell was originally 32 cm below the snow surface, during jumping the distance between skier and load cell reduced to 11 cm. For scale: the load cell's dimension is 50 cm.

This had the advantage that the two possibilities to set a load cell (by cutting out a block or by laying it on the snow surface prior to a snowfall) could be compared. No significant differences could be found provided that there was no thin hard layer or crust in the snow cover.

Results

An example of the measured normal force for the three different loading steps is shown in Fig. 3. The load cell (#3) was laid on the snow surface on February 21, 1995; between February 23 and 27, 82 cm of new snow were recorded in the study plot. Measurements were taken on March 1, 1995; due to settlement the load cell was finally covered with a layer of 48 cm partly fine grained snow (mean density about 180 kg/m^3) (Fig. 4). Sampling frequency was 1.3 kHz. Standing atop produced an additional impact of 110 N (weight of the snow cover and offset: 310 N); the penetration depth was 11 cm; to the end of the load step the skier was standing on one ski only, hence the penetration depth and the normal force slightly increased. In the middle of Fig. 3 the load step of weighting (5 times) is shown, the mean maximal additional normal force is 210 N, the mean peak width is 0.21 s; the penetration depth was 17 cm. Since the new, low density snow (Fig. 4) on top has mainly be compacted just below the ski binding the contact area (ski tracks) got more and more concave, so that there was no more contact just below the binding while standing after the first weightings; hence between the single weightings the value of the additional force of the load step standing atop is no longer reached. This effect is even more pronounced for the load step of jumping (Fig. 3, bottom) where hardly any difference can be seen between standing atop and easing the burden during the jump. Whereas during the several weightings the penetration depth did not significantly increase it increased substantially from jump to jump; accordingly the static load (between the peaks) increases and the peak value increases from 410 N (first jump) to 1150 N (fifth jump); the distance between skier and load cell was finally reduced to 17 cm; the mean peak width is 0.037 s. However, the increase is not only due to the smaller thickness of the overburden layer but also due to a better transmission of the forces due to the compaction.

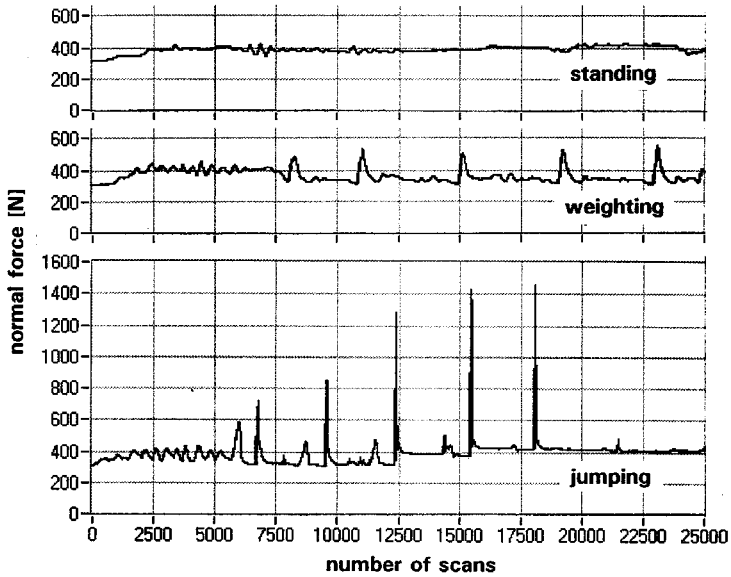

Fig. 3. Normal forces measured within the snow cover due to the skier's impact for the three load steps: standing atop (top), weighting (middle) and jumping (bottom). Sampling frequency is 1.3 kHz, total number of scans on horizontal axis (25'000) corresponds to about 20 seconds. (#3, March 1 ,1995)

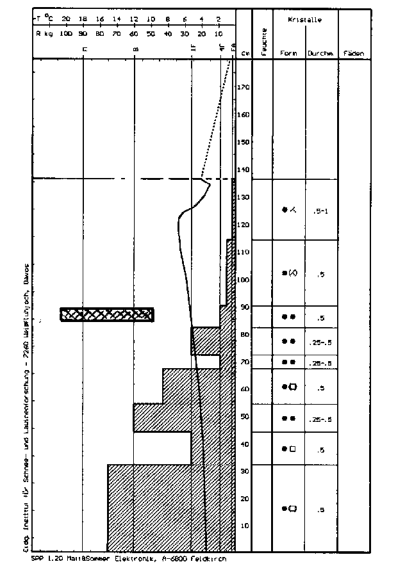

Fig. 4. Snow cover profile at March 1, 1995 in the study plot of SFISAR at Weissfluhjoch 2540 m a.s.l. (total snow depth: 256 cm)

Fig. 5 compiles all results of weighting from the season 1994/95. Snow conditions were quite similar, mostly new snow. Clearly visible is the decrease of the normal force with increasing depth. The solid line represents the calculated impact due to a static line load (assumed to be 500 N/m) on an elastic homogenous one layer snow cover. The difference to a band load of 10 cm is negligible as soon as the depth is greater than about 10cm. The dynamic load step of weighting is best reproducible and seems to correspond to the calculated static load. The difference is probably due to the layering.

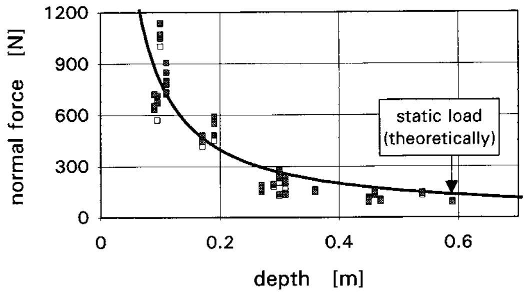

Fig. 5. Measured dynamic (weighting) and calculated static normal force vs. depth below snow surface. Assuming uniform loading of the load cell (area: 0.25 m^2) the normal stress would correspond to four times the normal force.

CONCLUSIONS - DISCUSSION OF PRACTICAL IMPLICATIONS

The measurements of the skier's impact in the snow cover showed the substantial dynamic load that the skier represents. The results generally coincide with former FE-calculations (Schweizer, 1993).

A typical value for the additional shear stress (load step of weighting, effective depth about 30 cm, slope angle 30°) is 500 Pa; Föhn (1993) found the shear strength of typical weak layers to be about 500 to 1000 Pa. The value of the additional force and the duration of the peak strongly supports the observation that the skier easily may overcome the shear strength and the critical strain rate to induce brittle failure and fracture of weak layers or interfaces. The damping due to snow compaction (energy dissipation) is less relevant than the dynamic character of the load, but significant differences could be found depending on the sublayering. Hard layers are good transmitters in particular for shear forces; weak layers transmit the forces directly downward, but on a small area and slightly reduced due to snow compaction. Very hard thin layers (i.e. crusts) spread forces at the snow surface; then hardly any impact is measured in deeper layers of the snow cover, i.e. safe skiing in spring time after a clear cold night, when the snow surface could refreeze.

The fact that wind slabs are often triggered is explained by the stiffness of this snow layers (good cohesion); popularly said it is more easy to push and move a slab than a piece of cloth.

Since skiing probably best corresponds to the load step of weighting and the weighting to the calculated load due to a line load, the stability index including skier triggering (S') should be a good index. The measurements support the idea to take into account the penetration depth as proposed by Jamieson and Johnston (1995).

Preliminary results from the measurements indicate in accordance with the calculations that the areal impact is generally small, probably at the most one meter around the area the skier influences at the snow surface. However, this does not mean that distances (10 to 20 m) from skier to skier are ineffective, since it is not yet clear how far the repeated load within several seconds weakens the snow cover and what the time of relaxation is.

It is definitely clear and should be well known that the skier's impact decreases with increasing depth, i.e. the closer a weak layer or interface to the snow surface the easier the release. So generally the shallower the snow pack, the more probable is skier triggering; first reason: see above, second reason: weak snow layers are usually more often found in shallow snow covers. This explains why trigger points quite often can be found to the edge of a slope or around rocks. Visible rocks on slopes do not indicate stability. Furthermore, this means that windward slopes usually are relatively dangerous, in particular some days after a storm. Does this finally mean that the old rule to rather climb and ski ridges than concave slopes or bowls is wrong? No, if the risk of being buried under large snow masses is also considered.

Rutschblock test

Although the spatial variability of the snow cover reduces the validity of any stability test and turns the interpretation into a difficult task of extrapolation, stability tests present a lot of useful information, e.g. does a weak layer exist. Digging is still a necessity in stability evaluation. However, whereas the presence of a weak layer is a definite sign of instability, the absence of it in a snow profile or stability test does not imply that skiing in the area is everywhere safe. The result of a stability test is important, but it is always only part of the whole procedure of stability and risk assessment.

As difficult as the interpretation is the choice of the test site. It is generally said that the site should be representative for the slopes considered to be the most dangerous in the area. But first of all, the place should be safe, i.e. that the risk and the consequences of burial has to be estimated. Some points to consider: the slope should be small (slope angle at least 30°, rather about 35°), should look homogenous and undisturbed and should not be above rocks; it should not be convex (in the line of fall), but rather uniform or concave and there should not be a terrain depression below the slope so that a large burial depth is rather unlikely. The snow depth at the test site should be rather small to have easy triggering (see above). Test sites just below ridges are mostly not representative as due to wind effects (cornice formation) near the ridge the snow cover is often thicker and better consolidated than further downslope.

The measurements showed that the scale of loading (standing, weighting, jumping) is reasonable and represents a continuous, non linear increase of the additional load. Repeated weighting (e.g. three times) does not increase the load, but, it probably makes sense to ensure the correct performance, and, it might progressively weaken the snow cover, the repeated jumping substantially increases the impact, in particular if the surface layers may easily be compacted.

In general, it is not necessary to emphasize the degree of release in complete detail (e.g. release after second or third weighting), but more attention should be given to the type of release (whole block or only parts of it, most of the time only below skis) and the quality (significant sliding plane, type of snow crystals) of the weak layer or interface. These results are important for the stability evaluation. The fact that not the whole block is triggered indicates that the conditions for a shear failure are not very favourable. If the weak layer or interface is near the surface a correct performance (load in shear) is usually not possible and accordingly the test result is not reliable. If the weak layer or interface is deep down in the snow cover the cohesion of the overlaying snow has to be taken into account for the stability evaluation.

To get a good result, in particular to ensure a proper test in shear, the skier loading the block should stand only about 20 to 30 cm below the upper wall of the block, since the maximum additional force is 10 to 30 cm below the skier's position. To enable the correct performance we prefer the Rutschblock to the wedge (Rutschkeil).

The measurements and the calculations indicate that the influence of the slope angle on the test result is insignificant for practical applications, i.e. that an increase of 10° in slope angle could reduce the Rutschblock result by one degree at the most, in accordance with the Canadian results (Jamieson and Johnston, 1993). However, the strong non-linearity of the Rutschblock scale makes any kind of rule doubtful.

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