Measurements on Skier Triggering

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Keywords: snow mechanics, slab avalanche, avalanche formation, dynamics loads

ABSTRACT
The forces induced by a skier (or snowboarder) within the snow cover were measured in situ with load cells for different snow cover conditions and for different load cell (weak layer) depths within the snow cover. The different steps of dynamic loading that are applied doing a rutschblock test were studied. The results show the importance of the weak layer depth (the thinner the slab the easier triggering) and in particular of the type of sublayering of the snow cover, i.e. of the slab properties. Bridging effects by hard layers are recognized. Skier penetration has to be considered. The stress increased strongly but non-linearly with rutschblock loading steps. For certain snow conditions the measured impact is of the same order of magnitude as typical shear strength values measured by pulling shear frames. The dynamic loads are applied within fractions of seconds. Provided that deformations are large enough (depending on slab thickness and slab properties), the skier's impact induces a brittle failure within a weak layer or interface.

INTRODUCTION
About 20 skiers, snowboarders and mountaineers are killed each year in the Swiss Alps (10 year average). In most cases the victims triggered the fatal avalanche themselves. They represent more than 90 % of all avalanche victims. This portion is typical for most mountainous regions in Europe and North America. The skier seems to be a very efficient trigger, despite his small static load. The skier's impact has to be considered in stability evaluation and avalanche forecasting.

The skier's load was introduced in the evaluation of the stability index by Föhn (1987). The numerical modeling by Schweizer (1993) showed that the layering of the slab seems to be crucial for skier triggering. Schweizer et al. (1995a,b) studied the stress distribution in the layered snow cover and in particular the response of the snow cover in the case of dynamic loading. Since field measurements strongly depend on weather and snow conditions during the course of the winter, measurements have to be done over a couple years to meet different snow cover conditions. This article represents a summary and update of the previous results (Schweizer et al., 1995a,b).

METHODS
The skier's impact is measured with load cells buried in the snow cover. The dimension of each of the five identical load cells is 0.5 x 0.5 m, giving an area of 0.25 m^2, the thickness is 5 cm and the density about 400 kg/m^3 (Schweizer et al., 1995a). Within the load cell four cantilever type transducers measure the normal and shear force. Additionally, temperature and cell inclination are recorded. We presently use a data acquisition system with a scan frequency of 2 kHz, giving a time resolution of 0.5 ms (Camponovo, 1995).

We started the experiments during the winter 1993-94 and up to now we performed about 60 experiments. The measurements were realised in the flat terrain of the study plot of the Swiss Federal Institute for Snow and Avalanche Research (SFISAR) at Weissfluhjoch, 2540 m a.s.l., above Davos, Switzerland. To measure the skier's impact in the flat terrain is reasonable, because we are primarily interested in the snow cover response.

The best way to ensure realistic measuring conditions is to put the load cell onto the snow surface just before a snow fall. During winter 1994-95 we did a lot of experiments with buried

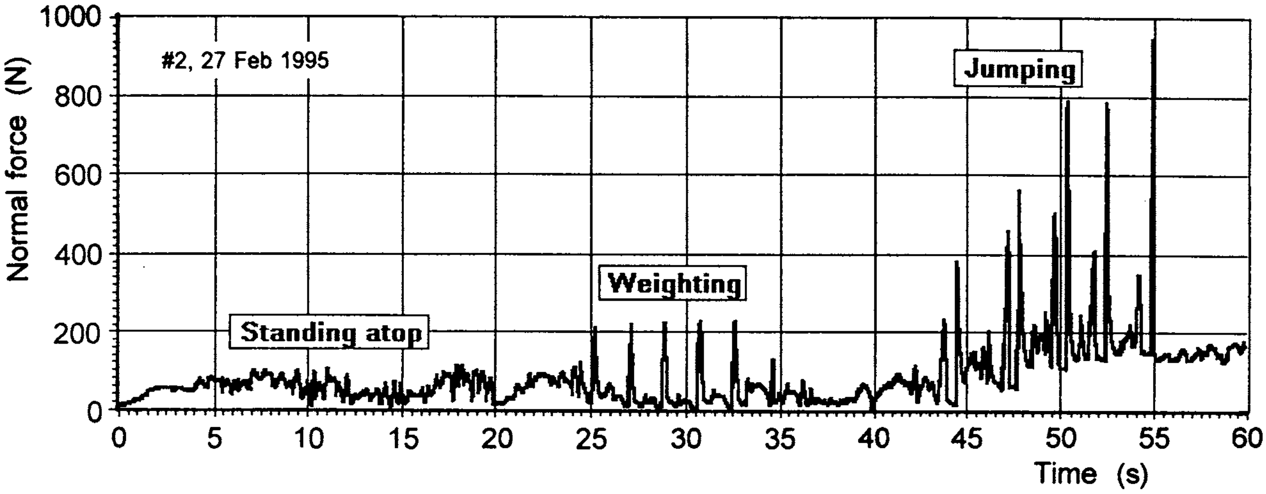

Fig. 1. Normal forces measured within the snow cover due to skier's impact for the tree load steps: standing atop(left), weighting (middle) and jumping (right).

load cells, in order to increase the number of experiments. A snow block was cut out, the load cell placed, and then the snow block carefully reset onto the load cell. No significant differences could be found between the two placement methods for the snow conditions found (Schweizer et al., 1995b).

For each experiment the load procedure by the skier follows partly the procedure of the rutschblock test: (1) standing atop, (2) weighting several times (four or five), (3) jumping several times. Usually a single load cell was loaded centrally and the different load steps were applied successively. For each loading the recording time was 20 s.

Before each experiment the snow thickness on the load cell and during the experiments the ski penetration for each load step was measured, so that the depth of the load cell relative to the skier is well known. The difference in penetration depth between two loading steps may yield information about the energy absorbed for compaction. Each set of experiments was completed with a snow cover profile, including snow density, grain shape, grain size, snow temperature, snow hardness index (hand hardness) and liquid water content.

RESULTS

An example of an experiment is shown in Fig. 1 and described in detail in the following. On 21 February 1995 the load cell (#2) was put onto the snow surface. Two days later the cell was covered with a few centimetres of new snow. During the following snowfall period 59 cm of snow were accumulated on the load cell; the cell was loaded on 27 February 1995. For the load step standing atop the average additional normal force was about 90 N. The penetration depth was 27 cm, so that the distance between the load cell and the skis was reduced from 59 to 32 cm. For the load step weighting the measured additional force was about 220 N (mean of five peaks) and the mean peak width 0.20 s. The additional penetration depth was only 3 cm and the distance between skis and load cell decreased to 29 cm. Between each weighting the value of the additional force of the load step standing atop is not reached, because weighting caused a snow compaction concentrated just below the ski binding, so that the snow surface below the skis got concave and the contact between skis and snow got worse during standing (Fig. 2). The same happened for the load step jumping, but this effect is not visible, because jumping increased the ski penetration additionally (from 29 to 21 cm), so that the load for standing increased as well. The maximal additional load was about 380 N for the first jump and increased to about 920 N (fifth jump). This increase is not only the result of the depth decrease, but also of the better force transmission due to snow compaction. The impact occurred in a very short time (mean peak width 0.05 s). Typical for jumping is the double peak, shown also in Fig. 1. The first, smaller peak is due to the weighting done just before the jump.

Fig. 3 shows the impact for different snow conditions. For the experiment performed on 20 February 1995 the snow layer above the load cell was characterised as soft snow (partly new snow/decomposing particles/rounded grains), mean density: 180 kg/m^3 and mean hand hardness index: fist to 4 fingers). For the second experiment (28 March 1996) there was a crust near the surface and below soft snow with thin crusts in between (mean density: 210 kg/m^3 and hand hardness index of crust: pencil). The initial depth was for both experiments 35 cm. The final depth was 11 cm for the soft snow conditions and 18 cm for the hard snow conditions. The decrease of the measured additional normal forces in hard snow for the load steps standing atop and weighting is large, 60 % and 80 %, respectively. There are two reasons for the decrease. First, the force transmission, hard layers have a bridging effect. The impact is spread out within the hard layer, and effect into depth is reduced. However, hard layers spread the impact over a larger area than soft layers. Second, there is less ski penetration in hard snow than in soft snow. The larger effective depth means smaller impact forces at the weak layer (load cell) depth. Because the crusts were broken after the first jump, the decrease is less important for jumping (less then 20 %) and is primarily due to the different effective depth.

Fig. 2. Skier and load cell after load step jumping. The load cell was partly dug out to show the measurement configuration. Notice the concave snow surface due to compaction. For scale: the load cell's dimension is 50 cm.

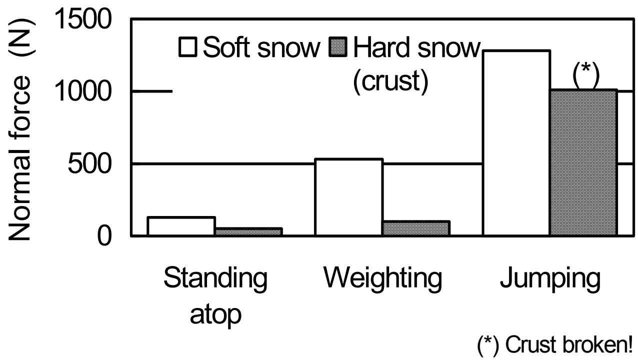

Fig. 3. Maximal measured normal forces for different layering of the snow cover for the three load steps. The experiment with soft snow (partly new snow/decomposing articles/rounded grains, mean density: 180 kg/m^3 and mean hand hardness index: fist or 4 fingers) was performed 20 February 1995 and the initial depth was 33 cm. The one with hard snow (crust above soft snow, mean density: 210 kg/m^3 and hand hardness index of crust: pencil) performed on 28 March 1996 and the initial depth was 35 cm.

Fig. 4 shows the results of the experiments performed during the last two winters (1994-95 and 95-96) in soft snow (partly new snow/decomposing particles/rounded grains; hand hardness index: fist or 4 fingers). The mean normal forces for standing atop, weighting and fifth jump are given together with calculated values for a static line load (500 N/m) on a homogeneous one layer snow cover (Schweizer, 1993). The dynamic load step weighting seems best to correspond to the calculated static load, whereas standing atop and fifth jump are smaller and greater respectively.

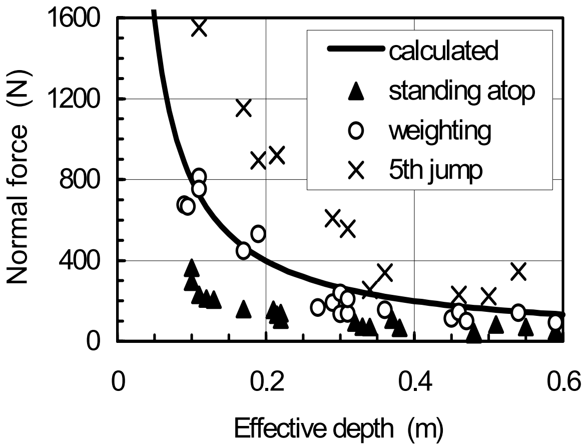

Fig. 4. Effective depth (distance between skis and load cell) vs. maximal measured normal forces within soft snow for the load steps standing atop, weighting and fifth jump together with calculated static normal force for a line load (500 N/m). Assuming normal and uniform loading of the load cell (area 0.25 m^2) the normal stress would correspond to four times the normal force.

DISCUSSION

The measurements show the importance of the weak layer depth. The impact substantially decreases with increasing depth, explaining why triggering points are often observed near rocks or to the margins of a slope, where snow depth is smaller and additionally the snow cover weaker in general.

In particular for the load steps standing atop and weighting the type of sublayering of the snow cover is more important, or at least as important, as the weak layer depth. Hard layers cause a bridging effect, which distributes the skier's impact over a larger area, but less efficient in depth. Ski penetration is directly related to layering (surface hardness) and is important as well, because the effective weak layer depth decreases with increasing ski penetration, thereby increasing stress. However the large variety of snow cover conditions makes it very difficult to derive simple rules.

Measurements done by the ski manufacturing industry and for biomechanical studies indicate that the dynamic load of skiing (snowplough and parallel turning) is most comparable to the impact measured on the snow surface for the load step weighting. For short turns and fast skiing the impact is greater and similar to the measured one for jumping. As shown in Fig. 4 the calculated static load due to a line load correspond to the measured impact for weighting and can therefore simulate the impact for skiing, however does not account for layering.

The skier stability index has to be supplemented with slab properties (sublayering). To include ski penetration as proposed by Jamieson and Johnston (1995) is a first step towards an improved skier stability index.

For certain snow conditions the measured skier's impact is of the same order of magnitude as the strength of weak layer obtained by shear frame measurements, found to be typically 500 to 1000 Pa (Föhn, 1993). The dynamic loads are applied within fractions of seconds (0.03 to 0.3 s). Comparing our field measurements to laboratory test results (e.g. Narita, 1980) it seems most likely that a skier will cause (depending on snow conditions and slab depth) a deformation in a potential weak layer that is both, large and fast enough to start brittle failure.

Fig. 5 shows that the impact increases strongly, but non-linearly with rutschblock load steps. The substantial increase from step to step is reasonable since it gives the test more sensibility in the lower stability ranges. The differences arising from different snow cover layering and different weak layers depths explain much of the variation observed with stability tests and support the suggestions that the rather rough rutschblock scale is by far good enough and that the rutschblock score alone as a stability test result far from complete. As important is additional information on the depth, age and type of weak layer, on the type of release of the block (whole block or only a part of it) and on the snow cover (slab) characteristics at the test site. Only while considering all these information an extrapolation should be tried.

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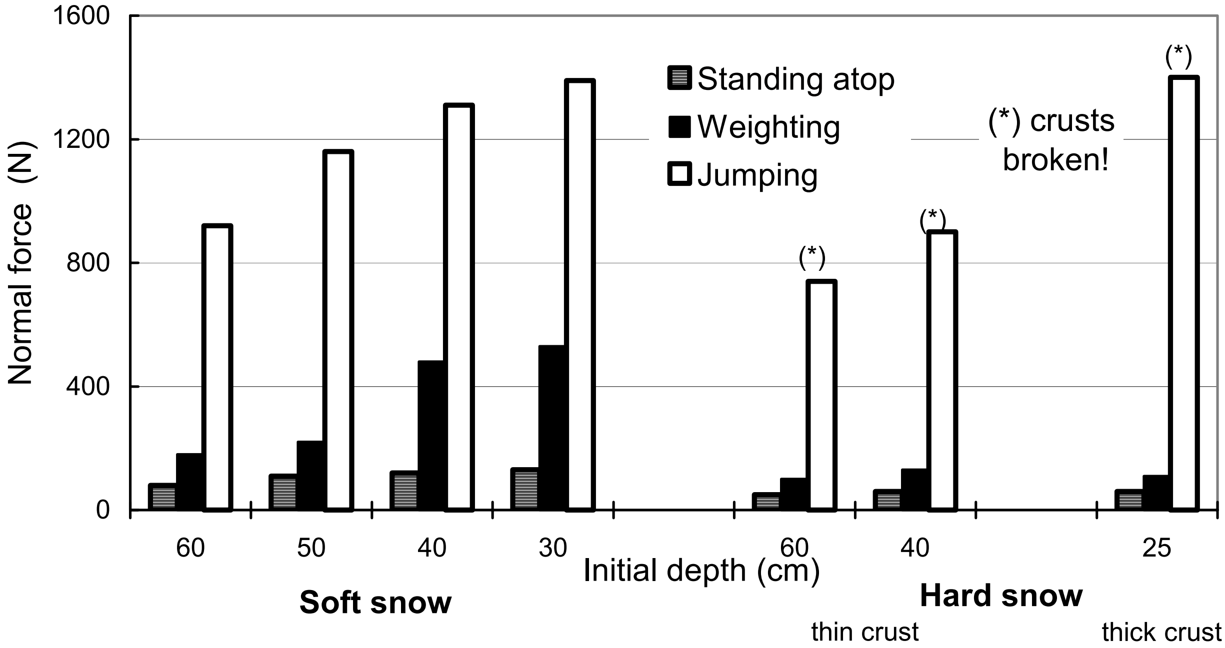

Fig. 5. Maximal measured normal forces for different snow cover conditions and different initial depth, for three load steps.