SNOW MECHANICS AND AVALANCHE FORMATION: FIELD EXPERIMENTS ON THE DYNAMIC RESPONSE OF THE SNOW COVER

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Abstract. Knowledge about snow mechanics and snow avalanche formation forms the basis of any hazard mitigation measures. The crucial point is the snow stability. The most relevant mechanical properties – the compressive, tensile and shear strength of the individual snow layers within the snow cover – vary substantially in space and time. Among other things the strength of the snow layers depends strongly on the state of stress and the strain rate. The evaluation of the stability of the snow cover is hence a difficult task involving many extrapolations.

To gain insight in the release mechanism of slab avalanches triggered by skiers, the skier's impact is measured with a load cell at different depths within the snow cover and for different snow conditions. The study focused on the effects of the dynamic loading and of the damping by snow compaction. In accordance with earlier finite-element (FE) calculations the results show the importance of the depth of the weak layer or interface and the snow conditions, especially the sublayering.

In order to directly measure the impact force and to study the snow properties in more detail, a new instrument, called rammrutsch was developed. It combines the properties of the rutschblock with the defined impact properties of the rammsonde. The mechanical properties are determined using (i) the impact energy of the rammrutsch and (ii) the deformations of the snow cover measured with accelerometers and digital image processing of video sequences. The new method is well suited to detect and to measure the mechanical processes and properties of the fracturing layers. The duration of one test is around 10 minutes and the method seems appropriate for determining the spatial variability of the snow cover. A series of experiments in a forest opening showed a clear difference in the snow stability between sites below trees and ones in the free field of the opening.

1. Introduction and Motivation

Snow avalanches belong to the major natural hazards in mountainous regions. Thousands of avalanches fall down during winter time without causing any damage. However, in the European Alps about 150 people are killed each year by snow avalanches. Avalanche protection is hence a necessity, among other things because the Alps are becoming more and more one of Europe's most attractive play grounds. There exist basically two possibilities to reduce the avalanche hazard: permanent measures such as constructing snow fences and land-use planning, and temporary measures such as closure, avalanche control and avalanche warning. Both measures require fundamental knowledge about snow mechanics and avalanche formation.

Snow, an ice-air mixture, is a granular or porous material that is highly compressible. The resulting deformations are often largely irreversible. Under ideal-

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ized conditions snow can be considered as visco-elastic fluid (Brown, 1979; Salm, 1982). However there exists no universal constitutive relation that is applicable under all conditions for solving practical problems. According to the problem snow is usually considered as either a linear elastic or a linear viscous body. The time scale of the load is decisive. Whereas under shock waves snow behaves elastically (Brown, 1981; Johnson *et al.*, 1992), the deformation of the snow cover behind a snow fence can be modeled using a linear viscous constitutive relation (Bader *et al.*, 1989). Most field and laboratory experiments concentrate on either slow deformations or very fast ones, due to explosions. For the understanding of slab avalanche formation an intermediate time scale and probably both types of behaviour seem to be important. Additionally the snow cover is typically of a layered character (Colbeck, 1991). Both the vertical layering and the mechanical properties of the layers itself vary substantially in space and time.

Whether a snow slab avalanche occurs or not depends on the mechanical properties of each snow layer and additionally on the variation of the mechanical properties within the layers; it is a question of snow stability. Simply stated, when the stress overcomes the strength (compressive, tensile or shear) the slab fails. However the strength of a certain snow layer depends on the stress state, the stress rate, the strain and the strain rate. Neither the stress state nor the strength are known in detail, especially not in natural conditions. From laboratory experiments it seems clear that the snow strength depends on the strain rate such that for small strain rates the snow follows the ductile behaviour and the strength may increase, however that for large strain rates the snow deforms in the brittle way (Narita, 1980; Fukuzawa and Narita, 1993). Snow falls represent the case of slow, quasi-static loading and hence the snow deforms mostly ductile. Explosives or a skier (dynamic loads) produce large strain rates and hence the snow exhibits brittle behaviour. The load conditions seem to be decisive. The variation of the shear strength within a weak layer or interface plays an important role for the understanding of natural avalanche formation (McClung, 1987; Bader and Salm, 1990). The existence of superweak zones as a prerequisite for avalanche formation was postulated. The artifical release of slab avlanches was described by Johnson (1980).

There exists no instrument or method which is fully appropriate for directly measuring the snow properties that are relevant for avalanche formation: compressive, tensile and shear strength. All of them are destructive. Widely used is the Swiss rammsonde giving an index for the cohesion. Shear frame or scissometer measurements are performed to get an index of the shear strength. From hundreds of shear frame measurements it is known that the shear strength of a weak layer (e.g. a buried layer of surface hoar) or interface is typically of the order of 1 kPa or even less (Föhn, 1993). The shovel and the rutschblock tests are used both by scientists and practitioners to qualitatively assess the stability of the snow cover. The rutschblock test is actually one of the best means to dynamically test the snow stability, more exactly to assess the shear strength (Föhn, 1987). Weak layers or interfaces, a prerequisite of a dry slab avalanche, can easily be found. Furthermore the test is done with the typical load: the skier that is one of the most important triggers of slab avalanches at all. However it is a qualitative test, needs about 20 minutes to perform and it is not easy to find an appropriate test site. Finally the spatial and temporal variability of the snow cover represents a strong limitation to any snow cover test.

We concentrate on the study of the stress state and the response of the snow cover in the case of the dynamic loading. FE calculations considering the snow cover as a layered compressible elastic half space and the skier as a static line load showed the substantial impact of the skier on the snow cover (Schweizer, 1993). It seems hence very probable that a skier will directly induce brittle failure. To verify this assumption the impact of the skier was measured in situ. The skier represents the most significant dynamic load to be considered in practical applications such as avalanche warning. The aim of the study is to gain insight into the release mechanism of slab avalanches triggered by skiers and to finally improve the avalanche warning by an expert system which analyses the snow stability on the basis of snow pit data.

However, in order to study the mechanical properties of the snow cover in detail the experiments with the skier are not perfect. It is both more appropriate and more convenient to have a well defined impact. Rammrutsch, a new instrument for testing snow cover stability, was developed; it combines the properties of the rutschblock with the defined impact properties of the rammsonde. The aim is to study the spatial variability of the snow cover in starting areas of slab avalanches. The measurements with the new instrument are performed in and near forest openings. The presence of two different snow covers allows to measure if it is possible to discriminate different snow stabilities: below the trees and in the free field in the opening. Due to the well defined impact force and to the deformation measurements in the snow cover it should also be possible to improve the constitutive relation needed for further FE calculations.

2. Methods

In order to study the skier's impact a load cell was developed measuring both the normal and the shear force. The cell has an area of a 0.25 m^2, a thickness of 5 cm and the density is 436 $kg\,m^{-3}$. The forces are measured by four small cantilever beam load cells. Additionally the temperature is measured (Figure 1). A Campbell data logger provided the data acquisition working at about 22 Hz; the data resolution is hence 46 ms.

The best way of assuring natural measurement conditions is to put the load cell onto the snow surface just before a snow fall. However this limits the number of experiments. So it was tried to carefully fit in the load cell from the side or to cut out a snow block, to place the load cell and to reset the snow block onto the load cell (Figure 2). It was not yet possible to compare the results of load cells which

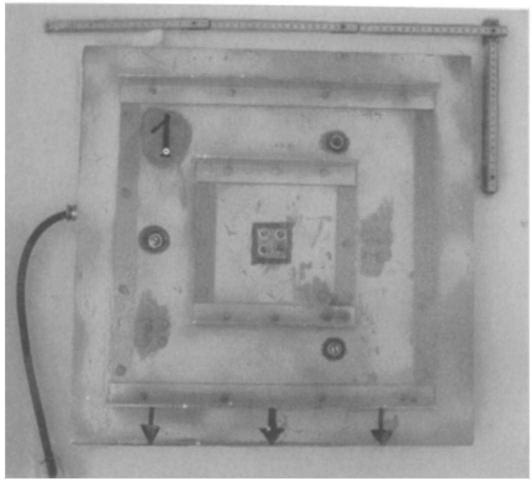

Fig. 1. The load cell for measuring the skier's impact. Size is 50 x 50 cm^2. Circles indicate the three cantilever beam load cells to measure the normal force. In the middle (square) the component of the shear force parallel to the arrows is measured.

have been naturally snowed in and those placed into the snow excavating a block. Usually we set up three load cells at the same time under the same snow cover conditions to control the representativity of the experiments. The load process by the skier follows the procedure of the rutschblock test. We performed five steps of loading: standing atop, standing atop a second time, weighting several times, jumping several times and finally jumping several times without skis.

From February to April 1994 we performed experiments under three different snow conditions: in cold, rather loose snow, in "warm" (-1 to -3 °C) snow and in generally warm snow but with a hard refrozen layer of several centimeters thickness at the surface. Except in one case where the load cell was set on a slope, the experiments were realized in flat terrain in the SFISAR study plot at 2540 m a.s.l..

The so-called rammrutsch is designed to (i) average the properties of the snowpack over an area which could be considered as a representative elementary volume, (ii) to reduce the influence of temperature and weather – the time for one measurement should be less than ten minutes – (iii) automatically detect weak layers in the snow pack, without detailed inspection of the profile, (iv) exactly quantify the forces applied to the snowpack. Because no instrument could be found which fulfills the above requirements, a new instrument was built. The rammrutsch (Figure 3) consists of an aluminium plate with the dimensions of 50 $\times$ 50 cm^2. A guiding rod is attached in the centre of this plate with a twodimensional joint. The guiding rod serves to lead the impacting weight. After a vertical column of snow with the same horizontal dimensions as the plate has been cut out of the snow pack over its whole depth, the snow is impacted first statically with 50 N (later refered

Fig. 2. Setup of the experiment to measure the skiers impact. A snow block was cut out (left in front), the load cell was set 38 cm below the snow surface (center) and the block will be reset onto the load cell.

as "static impact"), then dynamically by the fall of the weight from 5, 10, 20 and 40 cm. The fall of the weight from 40 cm height is repeated until the pile fractures, if it has not done so before. The instrument applies with this setup a normal and a shear stress at the same time, the ratio is dependent from the inclination. The deformation and deformation rates are measured indirectly from the video sequences, as discussed in the following (Figure 4). The fracturing and movement of the pile during the impacts is observed using a video camcorder. From the processed video images the movement of the snow pile during the rammrutsch experiment can be analysed. Figure 5 shows a cropped digitized video image with 159 $\times$ 216 pixels from the evaluated sequence. From a sequence of 25 video fields (representing 0.5 s) the movements of the snowpack was reconstructed. The black measuring marks were automatically segmented from the original image. Four of the markers (the leftmost and rightmost ones) were fixed points, the other five were fixed in the snowpack and therefore moving. The centre coordinates of these areas were first determined in the image coordinate system and then with an affine transformation put in a "world" coordinate system. The world coordinate system has the y'-axis vertical and is scaled to metric units.

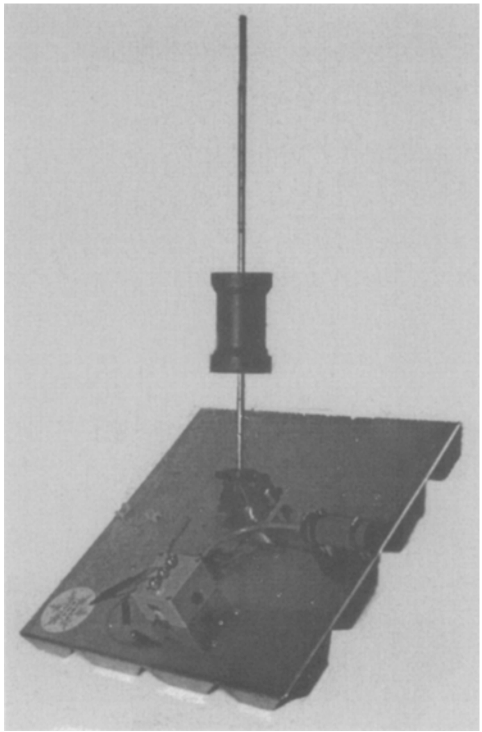

Fig. 3. The rammrutsch instrument. The dimension of the plate is 50 × 50 cm^2. The lamp on the frontside is switched on after the weight hits the joint.

3. Results

3.1. Skier's Impact

Figure 6 represents a typical example of the skier's impact for the three typical load steps: standing atop, weighting and jumping. The load cell was set 24 cm below the snow surface. The snow cover consists of 13 cm of new snow (mean density: 160 $kg\,m^{-3}$) followed by a layer of fine grained snow (mean density: 230 $kg\,m^{-3}$). During the experiment the snow above the load cell was substantially compacted (about 2.5 times). After standing atop the penetration depth was 8 cm, after weighting 10 cm and after jumping 18 cm; so finally the skier was standing 6 cm above the load cell. The mean density of the remaining snow layer was 480 $kg\,m^{-3}$. In this case the skier (weight: 700 N) induced the following additional maximal normal stresses for the different load steps: 300 Pa for standing, 800 Pa for weighting and 2400 Pa for jumping. Considering the skier as a line load on an elastic half space an additional normal stress of about 1 kPa can be calculated for a depth of 24 cm (Föhn, 1987). However in order to compare the results of the experiments to the calculated values the penetration depth has to be taken into

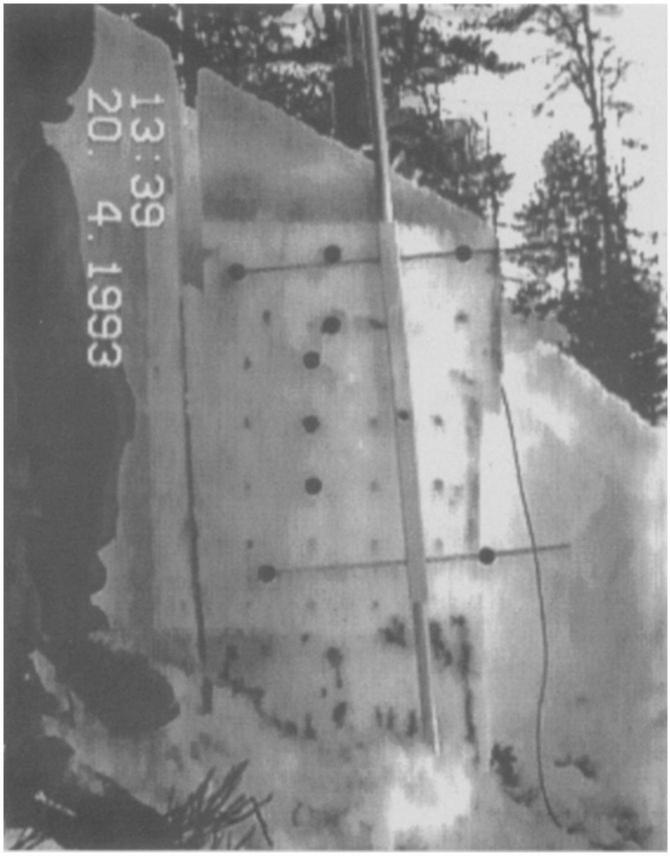

Fig. 4. The rammrutsch instrument in action. The weight at the surface is well visible. The top 25 cm of the snow pile are in movement because the weak layer has been fractured by a 40 cm impact.

account. In the above case the thickness of the effectively overlaying snow layer is reduced accordingly to 16 cm for standing atop, 14 cm for weighting and 6 cm for jumping. Hence measured values of the normal stress correspond to even larger values of the calculated stress. The effect of bridging seems to be large. Due to the layering a substantial part of the impact force seems to be transmitted to the sides and not in the depth. Part of the impact energy is used for snow compaction. As the load step of weighting was best reproducible and represents the typical dynamic impact of a skier, the values from all experiments for the weighting are given in Figure 7 together with the calculated values due to a static line load. The data can be grouped according to the three different snow conditions. The largest impact was measured in the case of the well consolidated, warm snow. Whereas in the case when the layer of refrozen, previously slightly moist, snow forms the uppermost snow layer the impact of the skier is insignificant in the deeper layers. Furthermore

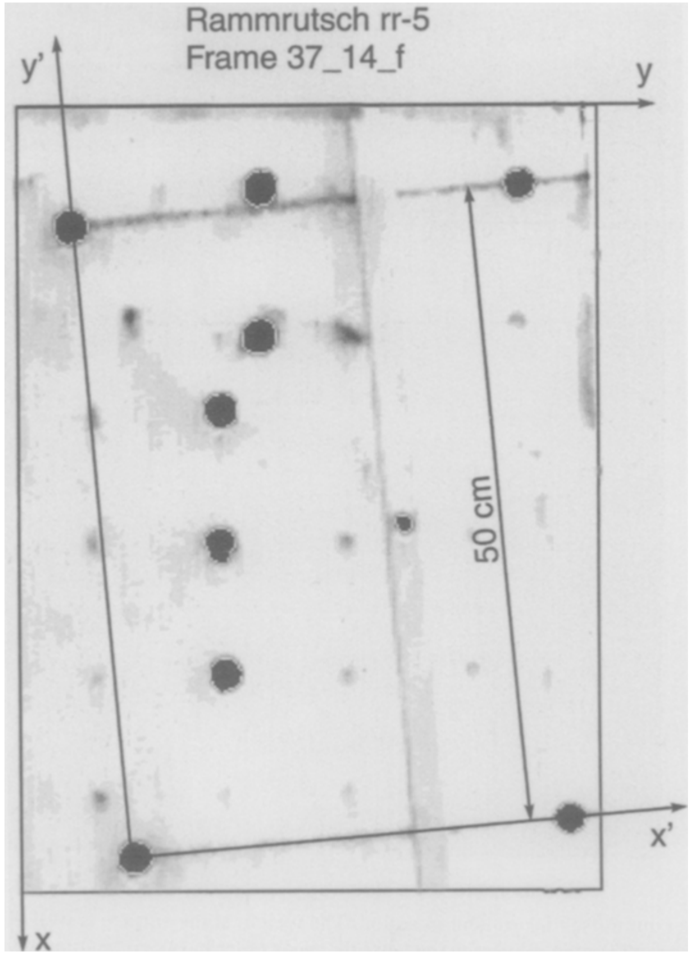

Fig. 5. Cropped digitized video field with the original image coordinate system x-y and the transformed world coordinate system x'-y'. The reference markers are the black markers at the four corners. The fractured zone is below the second marker counted from the top.

there is a clear tendency towards lower values with increasing depth below the snow surface. The experimental values of the dynamic impact (weighting) by the skier are of the order of the calculated static load. That means that, compared to the calculated static stress, the additional dynamic impact is mainly compensated by the energy loss due to the irreversible compaction of the surface layers and due to the bridging effect. Edge effects and the areal stress distribution have not yet been investigated.

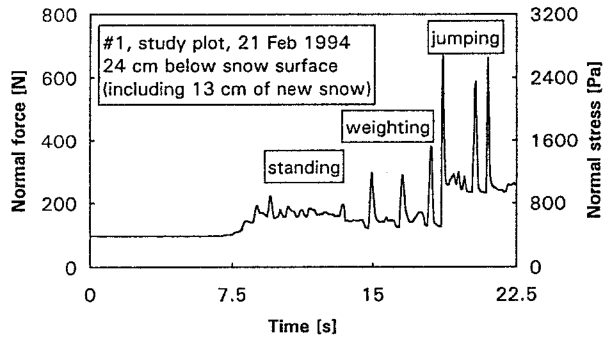

Fig. 6. Normal forces and stresses 24 cm below the snow surface for three typical load steps (standing, weighting and jumping) of the skier's impact, compiled from three subsequent experiments.

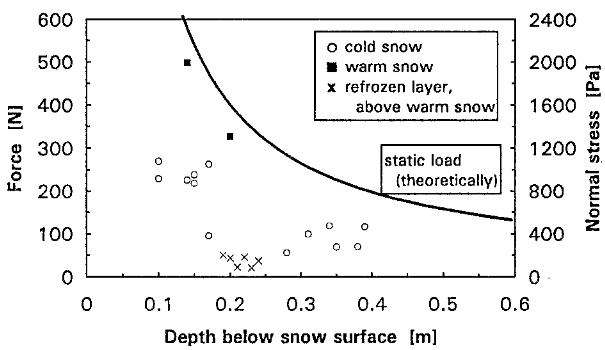

Fig. 7. Additional normal stresses measured vs. depth below snow surface. Results for the load step of weighting are given. For comparison the calculated normal stress of a skier, represented as a static line load, is shown.

3.2. RAMMRUTSCH: DEFORMATION MEASUREMENTS

An example of the results of the deformation measurements is shown in Figures 8 and 9. The experiment was performed on a slope of 32 degree inclination. The snow pack was slightly humid. The snow pile fractured after one fall of 40 cm height. A weak layer which was not visible in the snow profile was broken. Figure 4 shows the situation during the experiment. Figure 8 shows the precision of the fixed points and the movement of the flexible points. It is obvious that the top two points, the markers no. 7 and 8, where above the weak and broken layer and were moving synchronously for about 180 ms, then no. 8 was stopped by a transverse bar of the fixed point. The standard deviation of the fixed points was 0.31 mm in x-direction and 0.44 mm in y-direction. The velocity of the marker no. 7 is shown in detail in Figure 9. The fracture of the weak layer, identified by direct observation above marker no. 6, led to a settlement of 0.55 cm with a very low horizontal movement. After this fracture, the total velocity of the fractured snow layer increased steadily from about 20 cm s^{-1} to 40 cm s^{-1}.

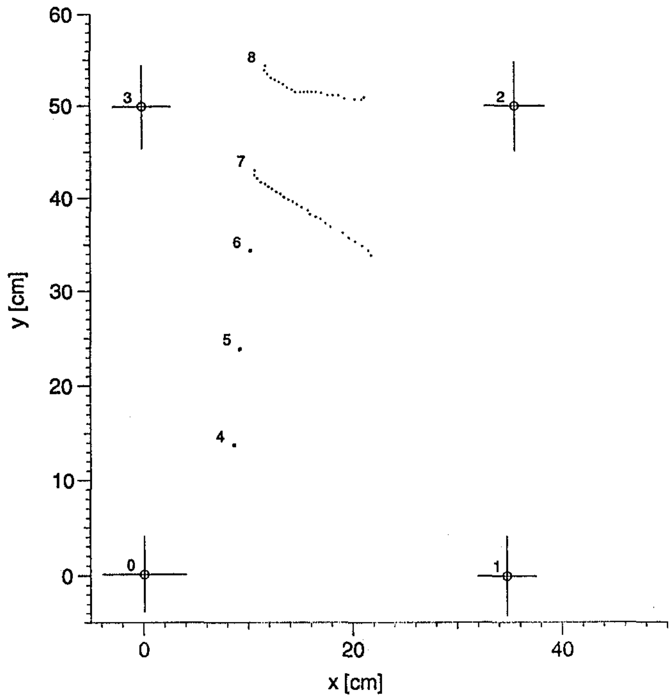

Fig. 8. Movement of the markers during and after the rammrutsch experiment. The uncertainty of the fixed markers is given by ten times the standard deviation. The fracture plane was 1 cm above marker no. 6.

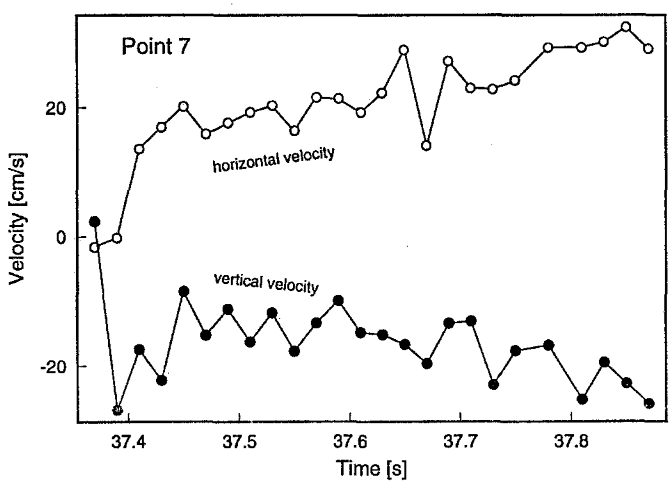

Fig. 9. Horizontal and vertical velocity of marker no. 7. The initial compaction of the fracturing layer is well visible through the high vertical velocity before second 37.4.

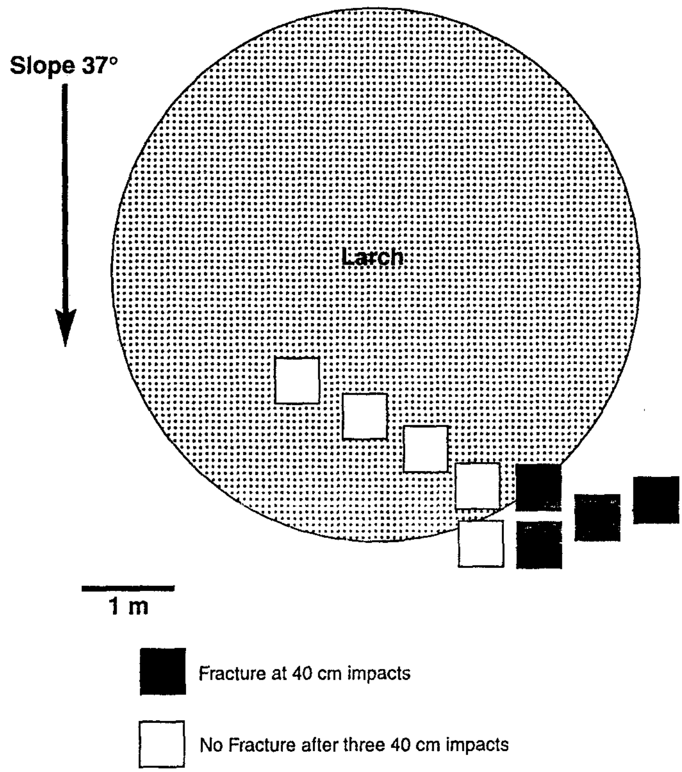

Fig. 10. Spatial variability of the strength of the snowpack under a larch. The dotted area indicates the crown projection. The black and white squares indicate the size of the rammrutsch plate (and the tested area). It is clearly visible that the stability is smaller outside the crown projection.

3.3. Rammrutsch: Spatial Variability of the Snow Pack

In order to test the ability of the instrument to detect spatial variations of mechanical properties of the snow pack the stability under a larch was investigated. The snowpack consisted mainly of rounded polycrystals. Only the basal layer consisted partly of cup crystals, typical of depth hoar. The fracture surface was always very near the base of the snowpack. Nine experiments with the rammrutsch were performed following the different steps of dynamic loading described above. Figure 10 shows the locations of the tests and the resulting distribution of snow stability. The test result (fracture or not) is given for each test. While the fracture occured after the first impact from 40 cm height, no fracture occured after 3 consecutive impacts from 40 cm height outside the crown projection. No additional impacts have been made, because after three impacts from this height the snow fractured just below the plate. A significantly higher stability was found in the area where the snowpack was influenced by the crown of the larch. Further tests will show the influence of the crown under different snow conditions.

4. Conclusions and Outlook

The field experiments on the dynamic impact of the skier showed that the skier is an efficient trigger of dry slab avalanches. The measured additional stress is of the same order as the strength of weak or very weak layers obtained by shear frame measurements. The impact decreases strongly with increasing depth. The variations found under different snow conditions corroborate the results of the FE-calculations. The slab hardness and sublayering is decisive. Hard layers at the surface transmit the forces to the sides, the effect on deeper layers is minor. Soft layers such as layers of new snow strongly attenuate stress — probably due to energy dissipation by snow compaction. The best transmission of the skier's impact was observed for well consolidated, warm snow. Under cold conditions the response was elastic (after snow compaction), whereas in warm snow a typical relaxation was observed after large impacts: the snow was deforming plastically. The additional stresses produced by the different degrees of loading (standing–weighting–jumping) do not increase linearly. This is important and helpful for the interpretation of the result of the rutschblock test. The importance of the irreversible snow compaction shows that this effect which is usually not considered in most FE calculations should be included in future simulations. In future measurements the skier's impact will additionally be measured directly at the snow surface. This will allow us to give a more quantitative interpretation of the response of the snow cover.

The deformation measurements during the rammrutsch experiment proved to be capable of measuring the slower processes of deformation and fracture. Additional instrumentation will be necessary for measuring the plastic and elastic shock waves of the impact. The rammrutsch instrument is also well suited to determine an index of the snow pack stability on a slope with a well defined impact energy. Weak layers are easily detected, similar to the rutschblock test. A significant result was the detection of differences in snow pack stability around a larch. Until now the snowcover stabilizing effect of larch trees was considered to be very poor, but already the statistical evaluation of avalanche starting zones in larch dominated forests (Schneebeli and Meyer-Grass, 1993) has indicated that this is not the case. Further experiments will be carried out to confirm this interesting result.

Both field experiments show the importance of studying the dynamic response of the snow cover. The dynamic behaviour of the layered snow cover under stress is definitely seen to be crucial for avalanche formation. However, field experiments always may only capture a special situation. Systematic studies are much more difficult to perform than in the cold laboratory. But the disadvantage of working in the field is compensated by the certainty to work under realistic snow conditions, especially with regard to the highly important layering of the snow cover.

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