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Skier-Triggered Avalanches

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ABSTRACT

Skier-triggering is one of the most frequent mechanism in releasing avalanches. This is due to the high effectiveness of skis in deforming of snow cover which properties are of great importance for the formation of avalanches. In the first part of this paper the causes of the formation of avalanches are described and the snow cover transformations induced by the movements of skiers are outlined. The example of two avalanches released by skiers in the Eastern Alps helps to evaluate the impact of skiers on the stability of snow on a slope, and that in the context of other "natural" factors. On the basis of the obtained findings, the conditions under which an avalanche may get released by the movements of skiers were evaluated.

Key words: skier-triggering, avalanche

1. Introduction

Avalanches are one of the characteristic processes in mountain regions. The formation of this process was, till the middle of the 20th century, conditioned mostly by natural impacts, intentional or unintentional release of avalanches by humans occurring only exceptionally. The rapid development of modern society after the Second World War has changed this situation. The destructive impact of emissions on forests that during centuries stabilized mountain slopes and prevented snow cover from sliding down started to manifest in European mountains. Deforestation was accompanied by an increased frequency of avalanches, especially in the Alps. In order to limit the increasing risk of avalanches, anti-avalanche barriers were built in the threatened regions, and in many places avalanches were released artificially by blasting.

During the last few decades, the occurrence of avalanches is more and more frequently due to another anthropogenous factor – to the movement of man in mountains. The rapid development of tourism in mountain regions causes an annual increase of the number of avalanches and of their victims. In the most visited mountain regions of Europe and North America, the victims among mountaineers, skiers and snowboarders represent about 90% of the total number of the persons killed by avalanches (Camponovo, Schweizer 1996). This high percentage is due to the lack of discipline and experience of many visitors to the mountains, but also to the exceptional effectiveness of skis in releasing avalanches. In spite of a small static load, this sport equipment causes relatively considerable deformations of snow cover.

2. Formation of avalanches

Differently from the other gravitation conditioned geomorphologic processes, avalanches are formed only under certain external preconditions as a result of a series of complex processes. In the cases where these external preconditions are met, other factors may appear and become the proper cause of the formation of an avalanche.

2.1. External conditions for the formation of avalanches

The basic condition for formation of avalanches is a combination of favourable relief conditions and a certain meteorological situation. Among relief indices, the slope inclination is particularly decisive. The papers indicate that avalanches are the most frequently formed on slopes with an inclination between 20 and 50° (Vrba 1964). This so-called critical inclination is given for the place of shearing, that is for the starting part of the avalanche trajectory. On milder slopes, avalanches get released only exceptionally and only when other external conditions are favourable (especially wet snow). On slopes that are steeper than the upper limit, the critical inclination is generally not suitable for the formation of avalanches. Fresh snow does not hold on these slopes, so that a continuous and sufficiently thick snow cover does not accumulate there.

Another important factor is the slope profile. While in slopes of concave shape pressure is exerted in the snow cover, in convex slopes tensile stress, which is one of the critical quantities influencing the stability of snow cover (see further), is increasing inside the snow cover. The shearing zone of the majority of spontaneous snow slides is therefore situated in that part of the slope that has a convex-shaped profile. The stability of snow cover is also influenced by the slope articulation and by the character of its vegetation cover. All sorts of unevenness and relief obstacles increase the anchoring of snow cover and impede the movement of snow. On the contrary, formation of an avalanche is facilitated by smooth relief, as for instance rock plates, debris fields or free grass slopes. On grass canopies, it is also important whether the grass is mown or not. According to Vrba (1964), the adhesion of snow cover to mown grass reaches the value of 102 kg/m^2, while to unmown grass only 37 kg/m^2.

The slope exposition to the prevailing air circulation and sun exposition is decisive for stocking of the snow or for the speed of the snow cover diagenesis. The specific relief forms are glens. Usually they have “smooth rock bottom and because of their relative height they cross several belts with different climatic conditions and by that with different quality of snow. Dark rock lining the glen absorbs more heat than the white snow. The heat spreads to the bottom of the glen and snow melts from below and sublimates” (Procházka 1979).

Besides the relief dispositions, the sliding of avalanches is influenced by the development of weather. Weather is generally determined by the climate of the individual region that is given by geographic positions and altitude. There re also meteorological factors, mainly snow and rainfall, direction and speed of the wind and air temperature, that influence the possible occurrence of an avalanche situation.

The principal determining factor is the intensity of snowfall. If the falling snow accumulates in a layer thicker than 2.5 cm per hour (Atwater 1954), a balance of forces is not established inside the snow cover and the snow begins to move. It also depends on the quantity of the fallen snow: the greater the thickness of the fallen snow, the higher the probability of a spontaneous release of an avalanche is.

Rainfall is another important factor. Rainwater increases the mass of snow, which leads to a breaking of the balance inside the snow cover. At the same time, water affects the links formed between snow particles during the process of sinterization and the snow progressively loses its cohesion. In addition, when the rain lasts a longer time, a certain position in the snow profile might get saturated by water, which causes a change of water regime. The water from the space between the snow particles progressively expels air and finally isolates it into small particles (Colbeck 1974). It results into a significant decrease of the cohesive forces between snow particles.

Another important meteorological factor is the wind that carries away the unconsolidated snow and deposits it in leeward positions. Snow accumulates when the particles transported by wind lose their speed because of turbulent streaming behind the edge of leeward slopes. Overdrifting of snow forms huge drifts or overdrifts, the shearing of which usually starts an avalanche. On windward slopes, the wind transforms the surface of the snow cover into hard but brittle plates under which incoherent loose or flowing snow may remain. The wind mechanically also directly affects snow crystals, rounds them and diminishes thus their cohesion.

On the southwards exposed slopes, the impact of sunshine is important. The sun warms the snow cover and, in combination with night frosts, gives birth to sliding surfaces on which the freshly fallen snow cannot hold. The effect of direct sun radiation is higher in old wet snow, because of its relatively low albedo (Photo 1). While fresh snow cover reflects 90 and more percent of sun radiation, the albedo of wet snow decreases approximately to 60% (Armstrong, Ives 1976).

The air temperature creates conditions for avalanches sliding by its impact on the qualities of the snow cover. Generally, the temperatures in the range of –5 to –10 °C lead to a consolidation of snow cover and to the binding of its different layers (Milan 1977), whereas the temperatures above 0 °C or long lasting strong frosts create optimal conditions for the formation of avalanches (see the following chapter).

2.2. Proper conditions for the formation of avalanches

The causes of the formation of avalanches must be searched for in the physical, stratigraphic and mechanical properties of snow cover. Primarily, these properties are given by the character of the falling snow that may occur under different forms and shapes. The snow cover then gets its secondary properties by a progressive metamorphosing after falling on the earth.

The basic shapes of snow crystals depend on temperature and the degree of saturation by water vapour in the free atmosphere where they are formed. Their formation is described in the paper by Hanousek, Spusta and Soukup (1981). The least stable are the flat star-shaped crystals (dendrites) formed in calm weather, in temperatures inferior to –10 °C and in a low relative humidity. Their mean mass is 4.10^{-5}g and, after falling, they form the so-called "downy snow". In higher temperatures (–5 to –10 °C) and in average relative air humidity, needle, prism and plate-shaped snowflakes are formed which form powder snow. Because of its low density (0.05 to 0.1 g/cm^3), this snow is easily transported by the wind and after its compacting forms a brittle snow cover that breaks into compact plates. If the temperature approaches the freezing point and the air has a high relative humidity, the wings of dendrites are covered by icing. The density of snow reaches 0.1 to 0.2 g/cm^3. In temperatures above 0 °C, mixed precipitations fall and the resulting snow cover is heavy (its density reaching 0.2 to 0.3 g/cm^3).

The higher the total quantity of water in snow precipitation (ratio of water and snow), the more quickly the weight of snow increases in comparison with the cohesion, which increases the probability of the formation of an avalanche. On the contrary, the content of available water in snow precipitations cannot be, from the viewpoint of avalanche formation, explicitly considered either positive or negative. Though it increases the cohesion of snow cover, at the same time it enables an increased deposition of snow by wind which may lead to mechanical overloading of the snow cover and to the consequent sliding of an avalanche (Atwater 1954).

After landing on the earth, the snow progressively settles down to reach 10% of its original volume (Kinosita 1967). Settling down is caused by the movement of snow particles into the empty space (surrounding the particles) and by the thermodynamic instability of snow mass (Perla 1980). In addition, under the impact of wind, temperature, sun radiation and pressure of overlying snow layers, the snow crystals metamorphose. The metamorphosis velocity is directly proportional to the environmental temperature and is the most important factor determining the mechanical properties of snow cover. Regarding the air temperature, the metamorphosis progresses in three different ways (Hanousek, Spusta, Soukup 1981):

1. If the air temperature is above the freezing point, the snow particles repeatedly melt and freeze. The snow particles having initially complicated shapes get progressively rounded and transformed into snow grains. The density of snow progressively increases and firn is formed. If the firn absorbs a higher quantity of water, for instance during spring rains, water fills up the spaces between individual grains and affects their mutual links. It finally results in slides of heavy wet snow with a highly destructive effect.

2. In a stable air temperature reaching –5 to –10 °C, snow particles evaporate and thus progressively transform into fine spherical grains (the so-called destructive metamorphosis in a constant temperature below the freezing point). This transformation consists in egalization of a high surface tension due to a disproportion between the surface and the mass of the snow particle. The water evaporated from the snow particle under the form of vapour moves through the free space among snow particles across the surface of snow grains and through the snow mass. The transport of water vapour results in a reinforcement of mutual links (cohesion) between individual grains (Perla 1980). This process, called sinterization, is the most intensive after the snowfall when the shape of snow particles is the most complicated and the free space between the snow particles

the largest. With the progressive rounding of snow particles and reduction of the free space between the particles, the intensity of sinterization diminishes. As a result of destructive transformation, the snow settles down, binding forces increase and the snow cover gets stabilized.

3. The third type of metamorphosis (the so-called constructive metamorphosis by temperature gradient) occurs only under exceptional meteorological situations. It supposes a relatively thick snow cover (at least 100 to 120 cm), long-lasting frosts (air temperature below –10 °C) and a relatively high temperature of earth under the snow (0 °C or only a few degrees below the freezing point). Because of the high temperature gradient in snow cover, the lower snow layers sublimate, water vapour rises up through the snow and when reaching colder horizons it crystallizes again. However, crystallization does not occur on connecting lines between individual snow particles, but on the surfaces of snow crystals. In the course of metamorphosis, the snow crystals therefore increase but do not get connected, which leads to an increase of instability of the snow cover. The newly formed crystals (the so-called cavity hoarfrost) have the shape of hexagonal pyramids, are hollow and have only very little cohesion. The cavity hoarfrost itself or in mixture with round firn (the so-called moving snow) significantly disturbs the stability of the snow cover and thus forms an ideal sliding surface for sliding of the overlying layers.

Stability and consistence, humidity and granularity are the decisive snow features for the formation of avalanches. Special attention must be paid to the stratification of snow cover. In general, snow cover consisting of layers with similar structure is more stable than snow mass with individual layers of visibly differentiated structure. Snow cover with a well-developed sliding horizon in its profile is the least stable. This term includes in general hard and coherent snow positions, or possibly a smooth surface of the underlayer, in which the overlying layers of snow cannot anchor well. The sliding horizon is generally the limit between the neighbouring snow layers formed under different meteorological conditions. In the snow profile, there can also be present a position of unstable snow which is the result of the deposition of brittle snow crystals (for instance cavity hoarfrost) or of leaching of rain or melt water. Because of insufficient cohesion of snow cover and of the sliding horizon, or the unstable snow layer, only a small impulse is sometimes sufficient to start an avalanche. Some researchers (Moskalev 1967) even consider a defect of an unstable snow layer as the most frequent cause of avalanches.

2.3. Impulses starting avalanches

An avalanche starts to move at the moment when the integrity of the snow cover is affected. Immediate impulses able to start an avalanche are, according to Atwater (1954), the following:

1. mechanical overload (deformation force outgrows binding forces of snow cover)
2. shearing (fall of an overhang, rock, snow from a tree, skier)
3. change of temperature (rapid rise of temperature reduces cohesive forces, a decrease increases the tension in the snow cover)

4. vibrations (acoustic impulse provoked by thundering, shooting, explosion; impact wave due to overflight of a plane).

2.4. Mechanism of avalanches

Snow is a multiform and unheterogenous system characterized by high compressibility and thermodynamic instability. Because the mechanical properties of snow cover can only be defined with difficulty, the process of the releasing of avalanches is not yet known in detail. In a simplified way, the mechanism of release of avalanches is described with the help of the model of force effects in a viscose-elastic matter (Kinosita 1967, Brown et al. 1973).

In the snow cover deposited on a slope, there acts the weight component G that decomposes the shear component S acting in a parallel direction with the slope and the compression component K (acting in the direction perpendicular to the slope). The resulting deformation force D affects the snow cover in the direction of the slope. If there were not binding forces between snow particles in the snow cover, the deformation force would depend only on the angle of the slope inclination, on the thickness of the snow cover and on its density.

However, because the snow mass is a complex system with viscose-elastic properties (its behaviour depends on temperature, density and degree of metamorphosis), the individual force components are compensated by friction force. The shearing component is compensated by its mutual adhesion that is defined as adhesion of snow cover to the relief or to the nieghbouring layers. Adhesion depends on the kind of underlayer and on the quality of neighbouring layers (hardness, size of grains). Poor adhesion is characteristic, for instance, for powder snow on an ice layer or hard firn on a layer of moving snow. Another phenomenon egalizing force effect is mutual cohesion of snow crystals or grains (Houdek, Vrba 1954). Favourable conditions for the formation of avalanches exist in incoherent layers (soft unconsolidated snow), but also in highly coherent layers. They are not flexible and elastic and may thus crack more easily and provoke the sliding of a plate avalanche. The fissures in snow plates themselves are on the contrary a positive phenomenon because they separate and reduce the tension in snow cover.

If the above mentioned force components are balanced, the resulting deformation tension is nil and the snow cover is stable. The higher the thickness or density of the snow cover, the greater the deformation force is in the sense of the slope line. Because of the elastic qualities of snow, at first only a flexible deformation of snow cover occurs. If the thickness or density of snow exceeds the critical limit or if the levels of adhesion or cohesion decrease, the elastic deformation changes into a fragile one. A fissure appears in the snow cover and the snow begins to slide. According to Perla (1980), the fissure may spread at a velocity close to that of sound (100 m/s), but also relatively slowly (1 m/day).

The role of force components on the deformation force depends on the stratigraphic characteristics of snow cover. If in the snow profile there is a very unstable position (for instance cavity hoarfrost), the decisive part is played by shear component. The effect of the compression component grows with the homogeneity of the individual layers of the snow profile.

3. Skier-triggered avalanches

Avalanches are triggered by skiers mainly during winter months, especially when the snow is dry. A higher occurrence of anthropogenously released dry snow avalanches is due to the fact that this type of avalanche is influenced by the mutual relation of rigidity and tension in snow cover which is the result of static load. The changes of tension are most frequently caused by snow cover overload by the weight of freshly fallen snow. Because of the low cohesion of dry snow, only a small impulse, as for instance the crossing of a skier, is sufficient to destabilize it.

Differently from dry snow avalanches, the formation of wet snow avalanches is mainly conditioned by changes in the rigidity of snow cover (Armstrong, Ives 1976). This type of avalanche occurs independently of the further load of snow cover and the possible impact of a skier is thus minimal. Even if an avalanche gets released by the crossing of a skier through wet snow, the primary factor of the formation of wet snow avalanches is the rigidity of snow cover.

3.1. Examples of skier-triggered avalanches

Dachstein, 4th April 1994

An avalanche was released beneath the Grosser Gosaugletcher glacier at the place called in the map Kreidenbachtiefe. This place is situated at the northern margin of a relatively broad valley bottom, at about 300 m above a pronounced relief edge beneath which the valley steeply falls to the Hinterer Gosausee Lake.

The avalanche was torn in a shallow amphitheatre-shaped relief depression deepened into a round relief elevation. The elongated depression is approximately 300 m long and, at its widest, about 100 m. The slope of the relief depression has in its upper part, where it links up to the above-mentioned elevation, a concave profile. During its further course, the slope inclination at first progressively increases to reach approximately 20° and then, in the lower (concave) part of the depression, decreases again. The lower margin of the depression mouths at the above-mentioned relief edge. Because of its position and shape, the relief depression is a natural snow catchment area.

The weather created favourable conditions for the release of an avalanche. Till 1st April it had radiation character. It was sunny with daily temperatures above the freezing point and with heavy frosts during the nights and it was calm. This stable weather lasted at least one week. The old snow had the character of firn because of repeated melting and freezing. On 2nd April, a front was passing over the Dachstein massif bringing intensive snowfall. The temperature fell to –4 °C (measured at Adamek Huette, 2196 m a.s.l.), the air was humid. In the afternoon of the following day, the thick snowing ceased, the sky was progressively getting bright. The night of 4th April was bright with temperature inferior to –10 °C. Early in the morning, a strong wind began to blow and stabilized the surface layer of snow profile. It was windy also during the day of 4th April, but the wind was getting milder. The sky was bright.

During snowing accompanied by the progressing front, some 50 to 60 cm of powder snow fell and some 120 to 150 cm of snow accumulated in leeward positions.

The avalanche was released by a skier on 4th April at about 1 p.m. at the moment when he was crossing the upper part of a shallow relief depression in the place at the end of the convex part of the slope. The slope inclination was in this place not even 20°. The avalanche was not released by shearing off by skis but by developing of the shearing line roughly 2 to 3 m above the trace of the skier, that is in the convex part of the slope where tension is concentrated. The fissure spread very quickly and the avalanche was released immediately. Because of a relatively compact surface layer of snow (due to strong wind), the released snow mass had plate character. The released snow moved relatively slowly and stopped in the concave part of the depression. In the shearing area the tongue was 8 to 10 m wide, on the slope then 35 to 40 m wide. The length of the tongue was 120 to 130 m. At the margin of the tongue, parts of the affected skier's equipment were excavated from a depth of 110 cm.

The snow cover was characterized by the following profile (Fig. 1): the surface layer (A) had been consolidated by wind and had thus roughly middle density and cohesion. Under that layer there was powder snow which had fallen under calm weather with temperatures inferior to –5 °C. It was characterized by low density and a small degree of sinterization, that is by low internal cohesion. This layer (B) was approximately 40 cm thick. The layer of powder snow laid on a thin crust (C) formed by repeated melting and freezing of the surface of the old snow. Because of the minimal cohesion of powder snow, sufficient cohesive forces did not form between the fresh snow and the crust, so that the crust constituted an ideal sliding surface. The lowest layer in the snow profile was old snow (D) consolidated by long lasting settling down and sinterization. It was characterized by a high density and stability.

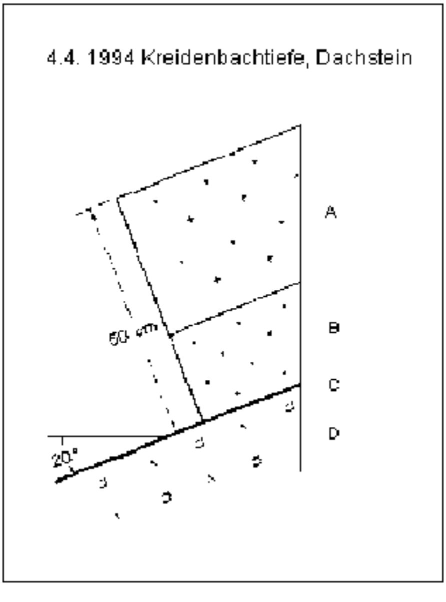

Figure 1: Profile of snow cover in the Dachstein region.

The above-mentioned situation clearly shows that the fall of the avalanche was largely determined especially by weather conditions and that it occurred under the combination of several favourable conditions: 1. The skier traversed the convex part of the slope where the snow cover is exposed to the highest tensile stress. 2. The avalanche was preceded by intensive snowfall (about 1 m of freshly fallen snow). 3. The fresh snow was not sufficiently anchored to the old snow. This case confirmed the fact that fissures spread quickly in dry snow cover. According to Perla and Martinelli (1975) this is caused by a low density of snow and by the ensuing feeble binding forces between individual snow particles.

Ötztal Alps, 31st March 1998

An avalanche was torn away in the Taschachtal Valley at the place where the front of the Taschachferner glacier turns to the north. The avalanche was released when skiers were traversing the eastern slope of the Urkundkopf Mountain (2898 m) approximately 30 metres above the place where the left lateral moraine branches off the slope (Photo 2). The valley slope is only sligthly articulated there and very steep. From the margin of the glacier to the foot of rock walls at 2500 m a.s.l., it has the form of large rock plates the consistence of which is disturbed only by several protruding rock outcrops. In the place where the avalanche got torn away, the slope inclination is 50 to 55°.

Fresh snow fell in the Ötztal Alps region several days before the release of the avalanche. From 28th March, the weather stabilized and it remained unchanged till the end of the week. It was bright and calm with maximum daily temperatures in the shade oscillated just below the freezing point. Because of the progressing season, the solar radiation was already considerably intense, so that the snow exposed to the sun was already starting to melt before noon. The sun was high in the sky, so that the duration of sunshine was longer even at less favourably situated sites. The slope where the avalanche was released was exposed to sunshine from the morning to 2 p. m.

The profile under the snow cover was relatively simple (Fig. 2). Down to a depth of 40 cm, there was no position of unstable snow. Because of the long-lasting metamorphosis, this layer (A) had in its entire thickness the same structure and was characterized by a higher density and cohesion. Under that layer, there was old frozen snow (B) which was very compact and stable. Its surface was hard and smooth, locally with a protruding rock underlayer. In spite of the considerable differences in the structure of both layers, their mutual cohesion was higher than the cohesion of layers B and C in the Dachstein profile.

The avalanche got released at 2.20 p. m. and that by the second of a couple of skiers traversing the slope. The first skier was leaving in the snow about a 30 cm deep trace and by his movement, as his whole body weight was being alternatively transferred to one or to the other ski only, still further released the snow and slided on the sliding surface. When the second skier passed, he further weighted down the snow mass which had already been cut away. This mass, in a width of three metres, started to move in one place and quickly slid down the slope. The avalanche trajectory remained narrow (about 50 m) for its whole length, with its maximal width at the foothill when the avalanche stopped against

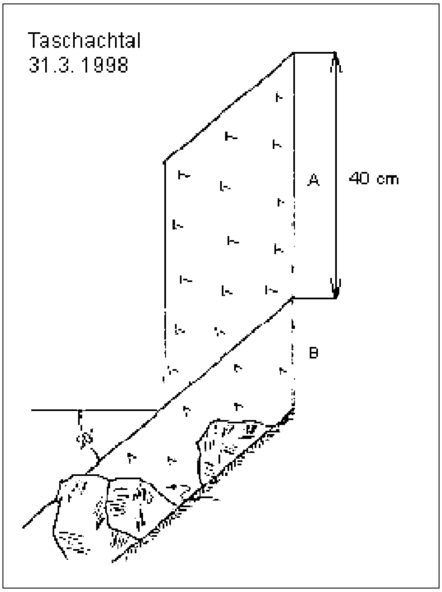

Figure 2: Profile of snow cover in the Ötztal Alps.

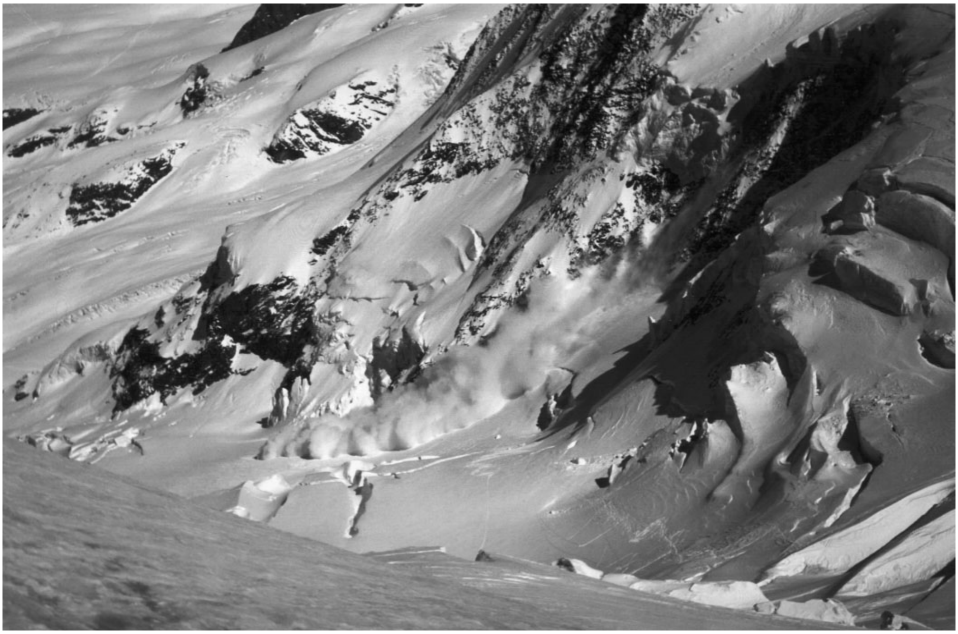

Photo 1: An avalanche in the northwestern slope of the Lyskamm 4527 m (The Pennine Alps, Switzerland) was released shortly after the noon as the direct sunshine hit the upper part of the slope. (Photo Z. Engel)

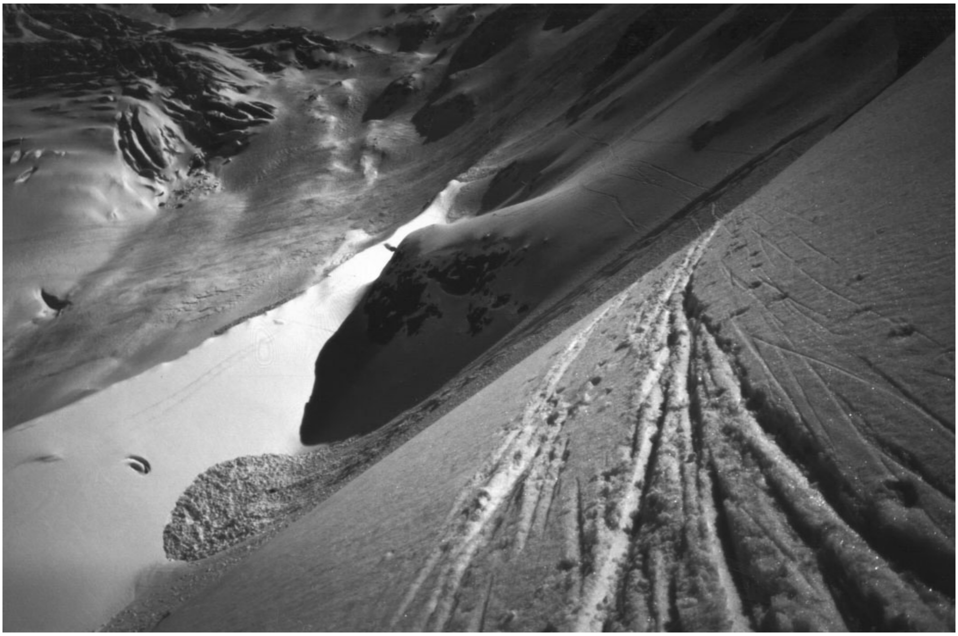

Photo 2: An avalanche in the Taschachtal Valley, the Ötztal Alps (31st March 1998). (Photo Z. Engel)

the outer slope of the parallel oriented lateral moraine. In the depression between the valley slope and the moraine, the avalanche accumulated in the form of a 15 to 20 m wide and 8 m high cone. The shape of the snow accumulation was influenced by the moraine mound that did not allow the typical elongated avalanche cone to develop but caused the snow to flow to the sides.

The factor of the snow's temperature was largely involved in this avalanche. The slope was exposed to direct solar radiation for almost 7 hours that increased the snow temperature to 0 °C. The surface of the snow cover was melting and water was penetrating into deeper positions of the snow profile. The snow cover was thus being enriched by water in liquid state, which is one of the conditions for the formation of so-called wet avalanches. The water was soaking through the snow down to the layer of the old snow, the frozen surface of which acted as an impenetrable boundary. The rapid melting and saturation of snow cover by water was accompanied by a decrease of binding forces between snow grains which disabled the release of any possible tension by slow elastic deformation.

In comparison with the first described case, the snow cover in Taschachtal underwent a different development. A several-day sinterization had increased its density and the number of bonds (binding forces) between individual snow particles. The shearing stress due to deterioration of the snow cover by the passing skiers' was thus not sufficient to cut away the avalanche. But the further load increased the deformation force to the extent that the friction forces were no longer sufficient to compensate the shearing tension and the snow began to move. In this case, the avalanche tore away directly in the trace.

3.2. The impact of skiers on the formation of avalanches

When a skier moves in a straight direction, he leaves a straight trace behind him. This trace not only disturbs the integrity of the snow cover (under favourable conditions it can cut the snow profile down to the sliding layer) but also, at the same time, increases the

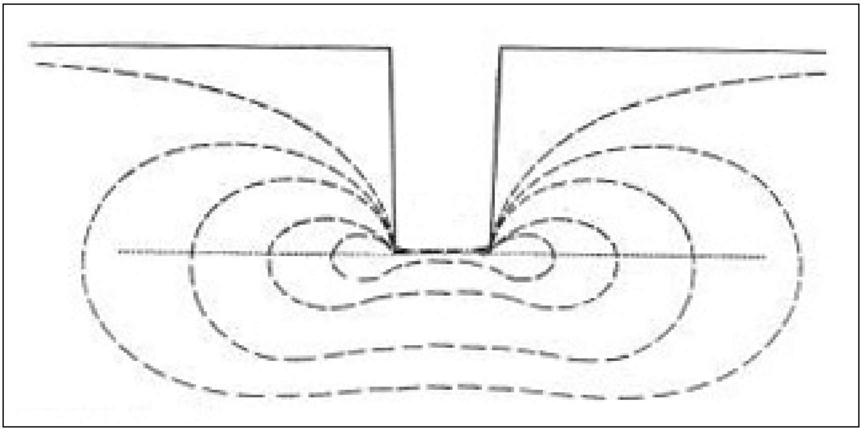

Figure 3: Schematic illustration of tension in the neighbourhood of a cutting in the snow cover. The dashed line depicts the isolines of the tensile stress, the line in the axis of the picture indicates the level of increased shearing stress.

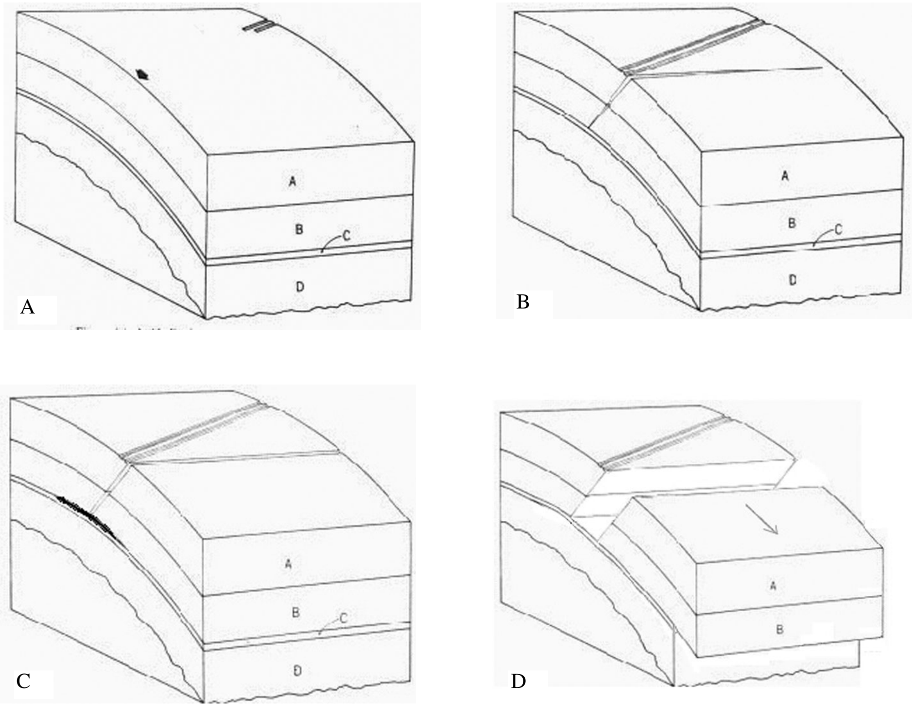

Figure 4: The course of release of an avalanche by a skier (modified according to Sommerfeld 1969).

compression and the shearing tension in the neighbouring snow mass (Fig. 3). If the snow mass is homogenous, the compression tension is highest in the proximity of the lower part of the cutting and its level decreases outwards into the neighbouring snow mass. The shearing tension concentrates in homogenous snow cover to the level of the lower part of the cutting where there is a level of increased shearing stress. This level is relative to the inclination of the snow cover, and the binding forces frequently get affected by it and the snow layers get sheared away when a position of unstable snow occurs in the snow cover, the shearing movement occurs right there.

The course of release of an avalanche by a skier is clear from the pictures a-d of Fig. 4 (the snow profile is described in Chapter 3.1) and was reconstructed with regard to theoretical considerations by Sommerfeld (1969). When a skier crosses the slope, the snow cover is most affected on its surface and that in the place where the slope has a convex profile (arrow in Fig. 4a). When the tensile stress exceeds the limit of elasticity of the snow cover, a fissure appears in this place (Fig. 4b). The fissure is getting vertically deeper in the snow cover and gets enlarged into sides. The deeping progressively slows down in the layer B because of its feeble coherence. Because the bond between the layers B and C is feeble and because the layer C is at the same time very compact, the tensile stress is not transferred into layer C but spreads under the form of shearing stress along the limit of both layers (marked in black in Fig. 4c). If the shearing disturbance spreads to a large area, layer B loses its adherence and begins to move (Fig. 4d). In the case that the tension in the snow cover is not sufficiently high, the shearing disturbance does not occur and the snow remains in place.

The direct impact of a skier on the load of snow cover (Föhn 1987) – is relatively small according to research carried out in the 1990's. According to Föhn (1992), it is under certain snow conditions comparable with the static load due to the snow cover and reaches the values of 500 to 1000 Pa. Campano and Schweitzer (1996) measured values going from 90 N (standing skier) up to a load exceeding 1000 N (springing skier). The results of these measurements show what is significant for release of an avalanche by a skier. It is, above all, the depth in which the unstable snow layer is situated in the snow profile (impact of load decreases with depth) and the mechanical characteristics of the snow cover (the hard surface layer prevents the skis penetrating to a greater depth and transfers the load on to a larger area).

The above mentioned cases make it clear that the density of snow cover is very important for the release of an avalanche by a skier. While in the first described case, when the snow was soft and little consolidated, the avalanche was released immediately, in the second case, the hard snow cover did not allow a rapid transfer of deformation into deeper layers of the snow profile. The probability of the release of an avalanche by a skier in snow cover formed by older snow of higher density is thus lesser than in the case of fresh snow with low density.

An increase of air temperature and the ensuing warming of the snow cover in the second described case also shows the significance of the factor of snow temperature, mentioned for instance by McClung (1996). The given case indicates that, from the short-term perspective, the increase of temperature reduced the coherence of the snow cover: while the crossing of skiers across the avalanche slope was without problems shortly after the noon, some three hours later (that is at the time of the maximum daily snow temperature amplitude) the movement of skiers in the same place released an avalanche.

4. Conditions for the release of an avalanche by skiers

In spite of complicated conditions of formation of avalanches, it is possible to clearly define situations favourable for the release of an avalanche by a skier. It is important to observe trends in the development of the snow cover, which are decisive for the stability of the snow. Similarly, both in spontaneous avalanches and in the cases of sliding of snow released by skiers, basic external conditions must be fulfilled, that is sufficient quantity of snow on a slope of critical inclination.

When evaluating the conditions for the release of avalanches by skiers, it is necessary to consider many factors that can be divided into the factors of relief and snow stability. Regarding relief factors, the probability of the release of an avalanche increases when a skier moves on steep slopes, mainly in the convex parts of these slopes. Because of the qualities of snow cover, the leeward slopes are particularly susceptible to the release of avalanches. In a closed mountain valley, the upper parts of the windward slope (where the snow cover is the most cohesive) are the most secure for the movement of skiers. Selection of articulation and character of the slope can minimalize the possibility of release of an avalanche. The least avalanche-susceptible slopes are those separated by transversal steps with uneven subsoil. Trees also represent an important stabilization factor.

The factors of snow stability are more complex and directly influenced by weather. The probability of a skier releasing an avalanche greatly increases shortly after an intensive snowfall. If the other factors remain unchanged, the probability of release of an avalanche decreases with progressing sinterization - while the cohesion of snow increases exponentionally, the tension increases only linearly (Perla, Martinelli 1980). The drifting of snow is also important: snow transported by the wind is very unstable in leeward positions.

In new snow, the thickness of snow cover and the character of the snow (shape and cohesion of snow particles and the specific weight of the snow) are especially decisive. The stability of old snow depends mainly on its mass and on the cohesion of its individual layers. If in the snow profile there is a layer of unstable snow, the possibility of the release of an avalanche decreases with the depth of this layer. The impact of a skier is also limited by the mechanical qualities of the snow, especially by the resistance of its surface layers.

On critical slopes, the daytime and snow temperatures play an important part in the anthropogenous release of an avalanche. Optimal conditions do not occur at the moment of the maximum air temperature, but with a certain delay. This is due to a higher absorption of solar radiation by the snow cover, which occurs because of decreasing albedo during the day. While at noon when the air temperature is maximum the skier may securely cross the slope, later in the afternoon his movement in the same place may release an avalanche.

5. Conclusion

The most significant findings obtained by studying the above-mentioned skier-triggered avalanches can be summarized by the following points.

1. Ski cutting reduces the stability of snow cover in two ways. It affects its integrity and increases the compression and shearing stress in the neighbouring snow mass. This finding conforms to the mechanism of the release of avalanches proposed by Sommerfeld (1967).

2. Comparison of both situations indicates that the probability of release of an avalanche by a skier depends on the density (and age) of the snow cover. In soft and little consolidated snow, deformation penetrates into deeper layers of the snow profile and it is more probable that it may also affect a layer of unstable snow.

3. Both the described cases show that if the snow cover offers favourable conditions for release of a plate avalanche (under hard and brittle surface, there is a layer of cohesionless snow), the shearing fissure is not immediately bound to the ski trace. On the contrary, under the conditions of harder, longer metamorphosing snow, the avalanche was released directly in the ski trace.

4. An analysis of the first described avalanche confirms the theoretic presumption of the accumulation of stress and the formation of a shearing fissure in place with convex slope.

5. In dry snow cover the shearing fissure spreads quickly, in heavy snow more slowly.

References

ARMSTRONG R. L., IVES J. D. (Eds, 1976): Avalanche Release and Snow Characteristics. – INSTAAR, Occas. Pap. 19, 256 p., Boulder.

ATWATER M. M. (1954): Snow avalanches. – Sci. Amer., 190, 1, 26–31, New York.

BROWN R. L. et al. (1973): A failure criterion for snow. – J. Geophys. Res., 78, 4950–4958, Los Angeles.

CAMPONOVO CH., SCHWEIZER J. (1996): Measurements on Skier Triggering.– Proc. of the Int. Snow Science Workshopñ96, October 6–11, Banff. 75–78, Revelstoke.

COLBECK S. C. (1974): The capillary effects on water percolation in homogeneous snow. – J. Glaciol., 13 (67), 85–97, Cambridge.

FÖHN P. M. B. (1987): The stability index and various triggering mechanisms. – In: B. Salm and H. Gubler, (Eds): Avalanche formation, Movement and Effects. Proc. Davos Symp. IAHS Publ. 162, 195–214, Davos.

FÖHN P. M. B. (1992): Characteristics of weak snow layers or interfaces. – In: Proc.Int. Snow Science Workshop, October 4–8, 160–170, Breckenridge.

HANOUSEK F., SPUSTA V., SOUKUP M. (1981): O práci a významu střediska lavinové prevence v Krkonoších. – Krkonoše 14, 2, 24–27, Praha.

HOUDEK I., VRBA M. (1954): Zimní nebezpečí v horách. – STN, 205 p., Praha.

KINOSITA S. (1967): Compression of snow at constant speed. – In: H. Oura, (ed.): Physics of Snow and Ice. Proc. Int. Conf. on Low Temperature Science, 1(2), 911–927, Sapporo.

MCCLUNG D. M. (1996): The Effect of Temperature on Fracture in Dry Slab Avalanche release. – J. Geophys. Res., 101, B10, 21907–21920, Los Angeles.

MILAN L. (1977): Nebezpečenstvo lavín. – Šport, 161 p., Bratislava.

MOSKALEV J. D. (1967): The stability of snow cover on mountain slopes. – In: H. Oura, (ed.): Physics of Snow and Ice. Proc. Int. Conf. on Low Temperature Science, 1(2), 1215–1222, Sapporo.

PERLA R. I. (1980): Avalanche release, motion and impact. – In: S.C. Colbeck, (ed.): Dynamics of snow and ice masses. Academic, 367–462, New York.

PERLA R. I., MARTINELLI M. (l975): Avalanche handbook. – Agriculture Handbook No. 489, U.S. Government Printing Office, 238 p., Washington.

PROCHÁZKA V. (1979): Základy horolezectví. – Olympia, 276 p., Praha.

SOMMERFELD R. A. (1969): The role of stress concentration in slab avalanche release. – J. Glaciol., 8, 451–462, Cambridge.

VRBA M. (1964): Sněhová akumulace v lavinové oblasti Modrého dolu v Krkonoších. – In: Opera corcontica, 1, 55–69, Praha.

LAVINY UVOLNĚNÉ LYŽAŘI

Résumé

Laviny patří k nejčastějším rizikovým geomorfologickým procesům horských oblastí. V souvislosti s rychlým rozvojem cestovního ruchu se v posledních letech výrazně zvyšuje počet lavin podmíněných pohybem člověka v horách. Mimořádně účinným prostředkem při uvolnění laviny je sportovní náčiní, zejména lyže, které navzdory malému statickému zatížení vyvolávají poměrně značné deformace sněhové pokrývky.

Změny, které vyvolává pohyb lyží ve sněhové pokrývce, byly popsány na příkladu dvou lavin uvolněných lyžaři na území Východních Alp. Vliv lyžaře na stabilitu sněhu na svahu byl hodnocen v kontextu s ostatními (přírodními) faktory. Na základě získaných poznatků byly odvozeny podmínky, při nichž může dojít k uvolnění laviny pohybem člověka na lyžích.

Z popsaných případů je zřejmé, že pravděpodobnost uvolnění laviny lyžařem závisí na hustotě (potažmo stáří) sněhové pokrývky. Měkkým a málo zpevněným sněhem proniká deformace do hlubších vrstev sněhového profilu, a může tak s větší pravděpodobností zasáhnout až na vrstvu nestabilního sněhu. Porovnání obou situací rovněž naznačuje, že pokud skýtá sněhová pokrývka příhodné podmínky pro uvolnění deskové laviny (pod tvrdým a křehkým povrchem leží vrstva nesoudržného sněhu), odtrhová trhlina není bezprostředně vázána na stopu po lyži. Naopak v podmínkách těžšího, déle metamorfovaného sněhu došlo k odtrhu přímo ve stopě po lyži. Pokud jde o vývoj odtrhové trhliny, v suché sněhové pokrývce se šířila rychle, v těžkém sněhu pomaleji. Rozbor první popsané laviny potvrzuje teoretický předpoklad hromadění napětí a vzniku odtrhové trhliny v místě konvexního svahu.