SNOW AVALANCHES

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Contents

Summary

Snow avalanche is a snow mass coming into a motion, sliding and rushing down a slope. They arise when the snow looses its stability due to an overload on slopes, where snow has precipitated in heavy snowfalls and snowstorms, and due to an occurrence of weakened layers in the snow cover induced by the snow re-crystallization, its melting or a rain penetration inside the thickness. Avalanches arise on every mountain slope where average thickness of snow cover exceeds 30-40 *cm*, the slope steepness is greater 15° and the slope relative height is larger 40-50 *m*. An avalanche flow can proceed on both a vast area of even slope, as well as in narrow troughs and channels. The head of the avalanche moves faster than its main body because the snow cover on the lower slopes gives way on impact with the avalanche head. The maximal avalanche speed measured falls within a range of 40-50 $m{\cdot}s^{-1}$.Snow thickness formed in the zone of accumulation ranges from 5 to 30 *m*, and sometimes this thickness can amount to many kilometers. The distance of an avalanche run varies from several tens of meters to 10-20 *km*, but it is mostly equal to 0.5-1.5 *km*. Dust avalanches have specific features as they are a mixture of dry snow and air of very small density They are followed (or accompanied) by a snow-dust cloud, and sometimes with a shock-wave of air that can cause destruction outside the main zone of snow deposition. Avalanches have a huge impact force, i.e. from 5 to 50 $t{\cdot}m^{-2}$. Potentially hazardous zones for avalanches display a number of characteristic signs, by which such places can be recognized in both winter and summer. To reduce damage from avalanches, a number of measures are undertaken: a) a choice of non-hazardous areas (with respect to avalanching); b) warning of people and organizations located in mountains; c) artificial avalanching of snow on a slope so as to stabilize the snow cover; d) building of anti-avalanche constructions. The basis of operational and preventative measures to combat avalanches lies in forecasting of

potential avalanching. Forecasting is based on the use of data which records the physical state of snow thickness on slopes, as well as on meteorological conditions favorable for avalanching, including processes of the atmosphere circulation under which avalanches arise.

Introduction

The ***Snow avalanche*** is a mass of snow under motion, sliding and rushing down a steep mountain slope. Under natural conditions they arise due to disruption of the snow stability on a slope which has been affected by meteorological phenomena, as well as processes running inside the snow mass and on conditions of relief and vegetation, which together form a complex of avalanche-inducing factors.

Among the permanent factors of avalanche-formation are relative altitude, inclination, slope exposure, character of relief forms, surface roughness, etc. Variable factors are snowfall and its intensity, type of snow falling, rain, wind and its duration and strength, the air temperatures and its changes, solar radiation, snow temperature and the presence of free water within it, the state of older snow and its thickness, the existence of loose snow layers , crusts on the snow surface, snow-drift sites, crevices, etc.

A large volume of snow and sufficiently steep slopes are necessary for an avalanche to occur. The most dangerous condition is a snow cover on slopes with a gradient from 15° to 45°. On more gentle slopes snow-cover layers gradually and does not become dangerous, whilst on the very steep slopes it is not held and falls immediately by small portions, during the snowfall, and thus it is not allowed to build up into layers and become dangerous.

An isoline of the greatest background thickness of snow cover of about 30 *cm* is usually taken as a lower boundary of possible formation of snow avalanches. The lower limit of avalanche speed is conditionally taken as 1 $m \cdot s^{-1}$, whilst the upper one has not been confirmed. Whilst in motion, an avalanche is capable of increasing its volume through entraining new snow masses into itself.

The first study into avalanches was made in the Alps as early as in the middle of nineteenth century. The governmental Avalanche Commission was organized in Switzerland in 1932 as it was necessary to protect the growing railroad network, which had thread its way throughout the Alps, from the threat of avalanches. . Soon afterwards, the well known mechanics specialist professor R. Haefeli headed a small research group which started a thorough investigation of avalanche problems in the region of Weisfluhjoch, above the town of Davos. In 1942, a new building had been built in place of a wooden hut on the Weisfluhjoch at an altitude of 2700 *m.* It was built for the Swiss Federal Institute of Snow and Avalanches which is now a leading world center in the study of avalanches. At present, snow avalanches are widely investigated in many European countries as well as in Russia, Canada, USA, Japan, India, China and a number of countries in Central Asia.

1. Formation of avalanches

1.1. Stability of snow on a slope

The snow cover on a slope, being acted on by external forces, will remain in equilibrium for a limited time only. Its stability is broken by the influence of snow subsidence, both shear and sometimes floating, that causes the appearance of crevasses, snow slides and avalanches. Accurate calculation of snow stability on a slope is rather complicated, therefore simplified calculation procedures are usually used. Equilibrium condition of a loose dry and disconnected snow on a slope can be expressed by the equation $\alpha = \varphi$, where α is the angle of inclination of the snow surface (or of the slope if they are parallel), and φ is the angle of internal friction in the snow.

If we take the distribution of a snow cover and its density along a longitudinal profile as homogeneous, so the equilibrium condition of a layer of dry connected snow on an unlimited inclined plane is written as

$$T = \rho z \sin\alpha,$$

where T is the limit of the snow shearing strength, ρ is the snow density, z is its thickness down to the surface on which sliding will occur. In this case the snow is considered as a plastic medium whose mechanical properties do not allow the essential processes of flow and development over time. With these assumptions the equilibrium formulas are used to estimate a stable dry snow condition, on a slope under rapid accumulation of snow. Due to the high rate of growth in the snow mass, and bearing in mind a negligible limit of shearing strength at or near the lower zones of the fresh snow cover, an unstable state will rapidly develop, causing avalanches of short-term development.

The above formula can be complicated through the introduction of additional conditions such as: contour forces, or resistance of the snow to compression in the lower part of the snow mass whilst in motion, or forces related to the thermal compression and the snow expansion, etc. The thickness of the snow stratum, under which the conditions of balance are met, is called the critical thickness of snow on a slope. It is easily determined from the above formula. For the case under consideration, a ratio of the limit of snow strength to a shear at the dangerous contact, to the tangential stress is the coefficient of the snow stability on a slope.

In the study of avalanches, the coefficients of snow stability on a slope are used for the prediction of those avalanches with short-term development. In the course of a long development of snow cover, weak inter-layers appear within it. In such cases, the conditions of limit balance for certain parts of the snow cover are set at the interface "weakened horizon - above-laying snow". Avalanches formed under such conditions are known as avalanches of long development. The location and size of such sites, with limit balance, depends on of the underlying surface profile, and the density and thickness of snow cover. On such sites the stress is redistributed leading to a concentration of extension stresses at the upper part of the site, and compression on its lower boundary.

When a mass of snow develops into an unstable state it breaks away in the zone where the extension stresses are concentrated and shears off in the zone of compression stresses. A line of the avalanche breaking-off runs in this place. On average, its length is greater, by a factor of five, than the width of the snow cover on a site which is developing into an unstable state. It can vary from 2.5 to more than 10 times greater. For a convexo-concave, longitudinal profile of slope, which is typical for mountain countries with a smooth mild relief forms, the position of the breaking-off line and the sites of snow limit balance is relatively stable. For concave and concavo-straight longitudinal profiles of slope, typical for countries with the alpine relief forms, the position of the breaking-off line and the sites of snow limit balance is not stable.

1.2. Factors of the avalanche formations

Heavy avalanches arise usually after abundant snowfalls lasting for many days which overload slopes. The avalanche hazard appears after a snowfall with an intensity of 2 $cm \cdot h^{-1}$ or greater and lasting continuously for at least 10 hours. Fresh snow is frequently loose and free-flowing like sand. This "wild" snow easily causes avalanches. The hazard of avalanches greatly increases when snowfalls are accompanied by strong wind. During a snow-storm the "snow flags" are waved over steep ridges—this means that the snow is transported from the windward slope to the leeward side where dangerous snow 'benches' develop; these can fall down at any moment and thus cause a snow avalanche.

With a strong wind a snow 'slab' is formed on the snow surface which is a dry hard layer of fine-grained snow of large density—about 400-600 $kg \cdot m^{-3}$. The snow slab consists of tightly packed snow crystals and sometimes reaches a thickness of several tens of centimeters. It is caused by the fact that mechanically or wind packed snow, and in addition the quick sublimation of moisture takes place on the snow surface being accelerated by the wind effect. As a result, a dense thick layer of a specific grade of snow is formed on the slopes, under which some cavities frequently appear. Suddenly, the snow slab is broken, and its separate blocks subside and start to glide down along the underlying loosened snow, and an avalanche arises.

In the absence of snowfalls the snow gradually '"matures", and the danger of avalanching increases. Processes of metamorphism run continuously through the body of snow. Any snow cover has viscoelastic properties: it can flow, like a liquid, or contract without destruction, like a solid body. Sometimes forces of adhesion are entirely absent from snow, and sometimes it is so tightly cemented that it reminds one of stone.

With time the snow thickness settles, resulting in its solidification. But in individual layers a loosening takes place, and it is exactly these weakened layers which are the source of the avalanche hazard. Weakly connected crystals of a deep hoar are formed in such layers allowing the overlying layers of compact snow to slide. The deep hoar corrodes the lower layer of snow cover, and the upper thickness turns out to be suspended and ready to fall on the slightest trigger, thus forming an avalanche.

The state of the snow cover drastically changes when water develops within it. With a temperature rise the structure of the snow weakens, and the liquid water appearing in the snow then weakens it further. Underrapid melting or intensive rain, the structure of the snow mass quickly changes, and in such cases the grandiose 'wet' avalanche is formed. A wet avalanche falls in spring over vast territories, and sometimes they entrain almost all snow accumulated during the winter. They move as one, directly over the ground and stripping soil, stones, pieces of turf, shrubs and trees. These are very heavy avalanches often resulting in roadblocks, which prove difficult to remove. At full saturation of the snow cover after a melt or heavy rain the gravitational creeping of water-soaked snow masses begins over vast expanses. Such avalanches can come down on very gradual slopes with a gradient not larger than 20°.

Snow, lying on a slope, starts to move by action of gravity. However, other forces tend to keep it on the slope for some further time. Two forces are at work here—adhesion with underlying layers of the snow cover or with the ground and frictional force which is proportional to the weight of overlaying snow. Both forces act together, and they are called the shear strength. In addition, the snow cover located lower down the slope impedes the snow displacement, and the upper layer of the snow mass also tends to hold the snow by means of ties between the snow particles. The opposing forces do not remain constant over the course of time: as the snow thickness increases the gravity grows, and the other forces change in variable ways. The whole range of these changes can be explained by three groups of causes: snowfall or snowstorm, recrystallization of the snow mass, and the development of liquid water in the snow mass.

Firstly, a long-lasting snowfall or strong snowstorm overload the slope until such point that the forces holding the snow cannot contain the gravity component which tends to displace the snow, and thus an avalanche-hazardous situation arises. In the second case, the snow mass on the slope can remain constant whilst recrystallization processes run within it, thus weakening some layers and destabilizing the structure. In the third case, a quick melting of snow caused by a temperature rise or a rainfall penetration severely loosens the links between snow grains and thus attenuates the action of holding forces which cannot counteract the increasing gravity, and again the body of snow is ready to generate avalanches.

Despite a snow mass being ready to move, with regard to these forces, it cannot displace spontaneously. A first pulse is needed. Various factors can serve as such a trigger mechanism: sharp overloads, temperature fluctuations, the development of weakened layers in the snow, shearing and vibration. As such, avalanching can be caused by heavy snowfall or strong snowstorm, warming accompanied by the snow melting, warm rain soaking the snow-mass, layers of fragile crystals of deep rime in weakened layers, the cutting of snow by skis, vibration in the snow caused by sound or shock wave. This represents some common factors which act as trigger mechanisms, however there is a huge number of possible causes for avalanching, too numerous to mention here.

Snow on a mountain slope is almost always in a tense state. As a consequence of the deformation and destruction of ties between crystals in the snow cover, high frequency sounds are generated with an intensity of a hundreds kilohertz. A shift of great snow masses causes oscillations of another range of frequencies, which are similar to seismic ones, i.e. their intensity is about several tens of hertz. But a moving avalanche creates sounds at the frequency of radio signals, i.e. about 1000 *kHz*. This means that with a tense snow state, its readiness to movement as well as the avalanching itself can be detected by means of taking a radio bearing of it, i.e. remotely.

Sometimes earthquakes cause mass avalanching. On 25th March of 1978, an earthquake of 9 units of intensity took place in the West Tien Shan, and though calculations did not indicate an avalanche hazard, i.e. the snow should not loose its stability, avalanches formed over area of 700 km^2.

2. Classification of avalanches

If the speed of snow movement does not exceed 1 *m*/*s*, it is known as ***snow slide,*** or ***osov***: it usually slides down on a broad surfaced, mildly rugged slope, which has no deeply expressed eroded grooves. Snow avalanches periodically come down along the same routes. However they travel most frequently along avalanche channels—grooves down a slope. If the snow avalanche meets a scarp or a steep bend in the slope, the avalanche 'jumps' from such a place and travels for some time, rushing through the air. A 'Jumping' avalanche has great strength. For instance, in the Khibini Mountains a powerful avalanche jumped over a dam of 30*m* height and struck the constructions it was meant to protect.

The part of a mountain slope and valley bottom on which an avalanche forms, travels and comes to rest is called the *avalanche catchment*. The *avalanche site* or the *zone of avalanche origin* is situated above, and the channel and the *avalanche evacuation cone* is below. In the zone of origin an avalanche gains the required force, entrains the first portions of snow from the slope and quickly becomes a torrential flow sweeping away everything in its way. In the transit zone it rushes down the slope, increasing its mass along the way, and breaking bushes and trees in its way. But gradually the slope flattens out, the avalanche movement is decelerated, and the snow masses are piled in the form of the avalanche evacuation cone. The *zone of avalanche deposition* is formed here, sometimes it flows on for a distance up the opposite slope of the valley.

The speed of an avalanche reaches 100-350 *km*/*h*, and hundreds of thousands or millions of cubic meters of snow are involved in its movement. The thickness of snow formed in the zone of deposition ranges from 5 to 30 *m*, and sometimes such thickness can reach many tens of meters. There is known case of an avalanche in the Caucasus which had deposited in a river canyon and created a dam of 100 *m* thick. The snow there took several years to melt.

Despite an abundance of trigger mechanisms that give rise to an avalanche, the point of origin, i.e. where the movement is initiated, is rather uniform. With the exception of avalanches caused by the downfall of snow-drift accumulations, all others start either 'from a point', i.e. under violation of stability of a very small snow volume, or 'from a line', i.e. under violation of the stability of a significant snow layer (Figure 1). As a rule, those avalanches classed in the first group are composed of loose snow (***the loose-snow avalanches***) while the second type of avalanche is created from snow slabs (***the slab avalanches***).

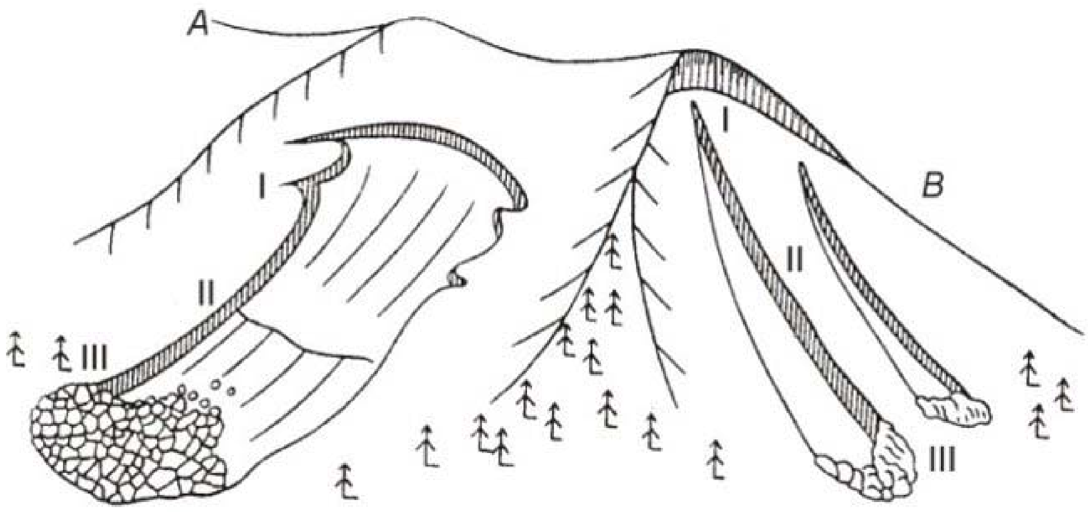

Figure 1. Avalanches: *A* – 'from a line', *B* – 'from a point'.
I - the zone of origin, *II* - the transit zone, *III* - the zone of deposition

The more loose the snow, the less its crystals are connected, and the smaller the volume of snow required for avalanche onset. Movement of the loosest, or 'wild' snow starts only with several particles. The onset of the avalanche process happens so fast that still nobody understands how such avalanches arise under natural conditions.

Avalanching from a snow slab begins with a cracking of the snow cover. The snow stratum suddenly breaks, a narrow crevice quickly grows, and soon, large blocks of snow begin to fall. In the upper part of the slope a broken line remains which circumscribes still motionless parts of the snow plate. The avalanche originating "from a line" was frequently observed by people, and sometimes it was caused by people. For instance, a casual skier on a slope; one moment they may appear safe, but the next an insidious crevice starts to spread, and the snow plates split to start their downward motion with a tremendous noise.

The great variety of avalanches makes it difficult to classify them. As early as the 1930s, many morphologic and generic classifications were proposed, but none of them could demonstrate a clear and easily understood comparison of avalanches. At the same time as when making operational observations of avalanches one must also strive to quickly and clearly inform the general public, about the main attributes (signs or characteristics) of an avalanche hazard, and in a way that could be clear for everybody to identify and characterize them. In other words, a distinctive code is needed which could allow transmission of information about avalanches via telegraph, teletype, or radio.

The avalanche classification problem was solved in the beginning of 1970s, when an international group of scientists, headed by Swiss specialist M. De Quervain, had created a classification where all essential attributes of avalanches were written in the matrix form, and combinations of them could identify and determine each avalanche (Table 1). An avalanche is described by letter and digital indices which is easily decoded. If, for example, you get a message about the avalanche coming down like *A2 B4 C1 D2 E1 F4 G1 H1*, it means: the avalanche had moved from a line on the ground, consisting of dry firn snow slabs, has traveled down a groove in the form of a dust cloud, its deposits were fine-cloddy, it was a dry avalanche, and without clear pollution.

Zone	**Criterion**	**Alternative characteristics and name of avalanche**	
Genesis	A. Movement Start type	A1. Movement from a point (a loose-snow avalanche)	A2. Off-the-line movement (a snow-slab avalanche) A3. Soft slab A4. Hard slab
	B. Position of sliding surface	B1. Inside snow cover (a surface layer avalanche) B2. Break-off in a new snow cover B3. Break-off in an old snow cover	B4. Over the subsoil (a full-depth avalanche)
	C. Liquid water In snow	C1. Not available (a dry-snow avalanche)	C2. Available (a wet avalanche)
Transit	D. Path form	D1. Even slope movement (an unconfined avalanche)	D2. Trough movement (a confined avalanche)
	E. Type of movement	E1. Snow dust cloud (a powder avalanche)	E2. Flow along the subdoil surface (a flowing avalanche)
Deposition	F. Surface roughness of deposits	F1. Buckshot (buckshot deposits) F2. Angular blocks F3. Rounded chunks	F4. Fineshot (fineshot deposits)
	G. Liquid water in Snow deposits	G1. Not available (dry avalanche deposits)	G2. Available (wet avalanche deposits)
	H. Polluted deposits	H1. No definite pollution (a clear avalannche)	H2. Registered pollution (a polluted avalanche) H3. Fragments of rock, soil residues H4. Branches, trees

Table1. International morphological classification of avalanches

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Biographical Sketch

Vladimir Mikhailovich Kotlyakov (born in 1931) is a member of the Russian Academy of Sciences (elected in 1991). He is Director of the Institute of Geography, Russian Academy of Sciences. With particular interest in glaciology and physical geography in polar and mountain regions, he directed the twenty-year project resulted in the World Atlas of Snow and Ice Resources (published in 1997).

V.M. Kotlyakov participated in many expeditions. He worked and wintered in the Arctic, the Antarctica, at the slope of the highest summit of Europe, the Elbrus, headed the high mountain glaciological expeditions to the Pamirs.

The main theoretical results of V.M. Kotlyakov`s works consist in elucidation of laws of snow and ice accumulation of the Antarctic ice sheet as well as ice sheets in general (1961), the snowiness of the Earth and its fluctuations within time and space (1968), the tasks and abilities of the space glaciology (1973), the application of isotope and geochemical methods to the study of the environment and its evolution (1982), the study of the past for four glacial-interglacial cycles (1985 and further on). During the last years, V.M. Kotlyakov dealt with the global changes of the environment, geographical aspects of global and regional ecological problems, the problems of interaction between the Nature and society.

V.M. Kotlyakov is the honorary -president of the Russian Geographical Society and the President of the Glaciological Association. In 1987–91, V.M. Kotlyakov was elected the President of the International Commission of Snow and Ice, in 1987–93, he was the member of the Special, and later Scientific, ICSU Committee of the International Geosphere-Biosphere Programme, in 1988–96, the vice-president of the International Geographical Union. Now he is a member of the Earth Council.

V.M. Kotlyakov is elected a member of the Academia Europaea and the Academies of Sciences of France and Georgia, a foreign member of the American, Mexican, Italian, Georgian, and Estonian Geographical Societies.