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Mechanism of Avalanche Release

Le mécanisme du déclenchement des avalanches

by André Roch

Best Available Copy

SNOW, ICE AND PERMAFRO
RESEARCH ESTABLISHME
Corps of Engineers, U. S.

THE MECHANISM OF AVALANCHE RELEASE

by
André Roch

The study of avalanches dates from the early inhabitants of the Alps. They classed avalanches as ground avalanches and powder avalanches. The tourists (Lunn, Kurz, Zdarsky) and the foresters (Coaz, Fankhauser, and more recently Mougin and Hess) defined avalanches according to the type of snow set in movement. Later the geologists (Paulcke), the geographers (Allix), and the naturalists (Seligman) examined the causes of avalanche release. Finally the engineers (Haefeli, Bucher, Fuchs, Croce, Bowden) have studied the mechanical basis of rupture, friction, the play of stress and resistance. In 1949, I was invited to the United States of America as an expert on avalanches (see Les Alpes 1950, p. 41-47). In regions of the west where the danger is acute, I advised the interested parties on precautions to be taken. I was asked what steps we take in the Alps to evaluate the danger and if it is possible to measure the stresses and resistances and calculate the time of release. On my return, I immediately began work on the task and set forth a theory which, if not false, was at least incomplete. Little by little the various types of release have been distinguished and the causes have become explicable. A part of the conclusions from these studies are presented here. There is nothing new, but I believe that I have been able to introduce a little order into the possibilities of failure of snow.

I. MECHANICS

To understand the mechanics of avalanche release, it is necessary to become acquainted with certain concepts of mechanics and with certain transformations of the snow. Therefore we will define some of these concepts and explain how the snow behaves according to its characteristics.

1. Internal friction of movement or kinetic friction

Coulomb (1736-1806), a French engineer, determined that the angle of internal friction of movement of a powdery material without cohesion is the same as the inclination of the natural slope of this material. Dry sand, for example, remains in equilibrium at a certain slope; the angle of this slope with the horizontal gives the coefficient of the friction of internal movement. If ϕ is the angle of inclination of the natural slope, $\mu = \tan \phi$ is the coefficient of kinetic friction. The same thing is true of snow without cohesion. The natural slope depends chiefly on the shape of the snowflakes and their mixture. Dry snow without cohesion remains in equilibrium at a slope related to the shape of the crystals. Isometric grains (spherical) have a natural slope of 22° to 23°. This angle is given by Professor Paulcke as the smallest slope on which one may still fear an avalanche. Depth hoar, in cuplike crystals, has a natural slope of 32° to 37°. New snow is an exception to this rule because the star-shaped flakes with fine branches become interlaced as they are deposited, making a network that allows it to maintain itself up to the vertical. However, as soon as the cohesion due to matting is broken, this new snow is the most slippery, as its angle of internal friction is only 17°, the smallest known for dry snow. As soon as new snow begins to move, the minute branches of the stars bend and break, producing an extremely fine powder. This is the reason that avalanches sliding over fresh snow slide the fastest.

The angles of kinetic friction of the different types of snow being known, one may lay down a first rule for the release of avalanches: they cannot be released on a slope smaller than their angle of internal friction. Practically, the slope must be measurably greater than this angle.

2. Cohesion

If the snow crystals are attached to each other, the snow acquires a certain cohesion, which depends on the number and surface of the contacts. Temperature has an important influence on cohesion. For equal contact surfaces, the cohesion is stronger at lower temperatures. As we have seen, the matting of fresh snow is one form of cohesion; also a degree of humidity holds the flakes together by capillarity.

3. Resistance to shear

This consists of cohesion and of a starting friction (static friction or adhesion) greater than the internal friction of movement. If the thickness of a snow cover is increased, its weight also increases, increasing proportionally the static friction and the kinetic friction. These frictions are thus proportional to the normal pressure to the shear plane. The resistance to shear is thus the sum of static friction and of cohesion, which is practically independent of the normal pressure to the shear plane.

II. POSSIBILITIES OF RUPTURE OF THE AVALANCHE

These characteristics being known, we may begin to analyze the release of an avalanche. The snow cover on a slope is drawn downwards by its weight, in a component parallel to the slope, known as the shear stress or the tendency to shear. It is held back by the shear strength of the weakest layer or by the adhesion of the series of strata to the ground. But, as the slopes are not infinitely long and wide, the snow may be anchored at the top, attached laterally, or supported at the bottom. For an avalanche to be released, five breaks must occur: one in tension at the top, two lateral shear breaks, one failure in compression at the bottom of the slope, and one shear failure on the supporting stratum. It seems impossible that the snow can break all these anchorages; but failures usually occur one after the other so that a single break, known as the primary rupture, can often bring on the other breaks, called secondary, and so detach a mass of snow. If the resistances are strong enough to withstand the primary rupture, no avalanche results. It is thus necessary for the movement to propagate. For this the mass first set in motion must be large enough to break the anchorage of successive masses. The release of the avalanche may occur in various ways. It may be the result of an exterior accident that produces one of the ruptures listed, of which the first is the primary rupture, or the result of one spontaneous break which causes the other, secondary breaks.

To classify the possibilities of a rupture, we divide releases into two classes according to the cohesion of the snow masses set in motion. These are the simple equilibrium rupture of poorly coherent snow, and the release of avalanches of coherent snow.

A. Simple Equilibrium Rupture of Snows with Low Cohesion

If the snow had no cohesion, like dry sand for instance, it would slide to the bottom of slopes steeper than its natural angle of repose, and collect at the foot of the mountains, in proportion to the amount of its accumulation in the Alps. But the cohesion of snow, small as it may be, allows it to stay on slopes steeper than its natural angle of repose without cohesion. Due to its matting, fresh snow may cling even to vertical surfaces. But once this slight cohesion is broken, if the slope is steep enough for an initial mass to be set in motion, it will break the cohesion of successive masses and a slide will result.

Let us consider the case where the snow layers likely to slide have relatively low cohesion. If the slope is long and wide in relation to the thickness of the snow layers, which is ordinarily the case in nature, the upper, lateral, and lower anchorages have little ability to hold the snow and are negligible. A first break occurs when the shearing stress equals the resistance. This original break is called a simple equilibrium rupture.

In such a case there is no secondary rupture. There are three chief causes of such a failure: 1) an increase in shearing stress resulting from additional load (a fall of snow, the passage of a skier, etc.); 2) a decrease of cohesion and also of internal friction caused by destructive metamorphism; and 3) a reduction of cohesion due to a rise in temperature.

1. Simple equilibrium rupture caused by additional load

The most ordinary case is overload caused by a new snowfall. During the snowfall, the stress increases faster than the cohesion, which, at low temperatures, takes 2 or 3 days to increase its strength. If the slope is steeper than the angle of kinetic friction, the slide occurs as soon as the force is sufficient to overcome the resistance due to cohesion and static friction. Avalanches of this type occur in short sequence. They slide first on the steepest slopes and later on slopes less and less steep, as the deposited snow increases. Once the mass starts to move, the slight cohesion is broken and the starting (static) friction is replaced by the friction of movement (kinetic) which is less, thus facilitating the sliding. Catastrophic avalanches which are caused by huge snowfalls of more than a meter in thickness are of this type. Under these conditions, the steep slopes are usually less dangerous than the gentler slopes. Steep slopes of 40 to 54° clear themselves in proportion to the amount of snowfall, while it requires a very thick snow cover for motion on a slope of say 30°. The shear break spreads like a flash, as the entire slope is unstable. Moreover the mass disintegrates like collapsing scaffolding; the moving snow crystals mix with air and form a mass similar to a heavy gas which takes on devastating speed. The great speeds attained by avalanches of this type result from the very feeble resistance encountered by a gas and from the fact that a large portion of the slope starts to slide simultaneously. The upper masses slide in the track left by the masses ahead, which are also in motion and not only provide no resistance but tend to pull the heavy gas which follows them and catches up with them. The speeds attained are about 300 to 350 km/hr.

When the snowfall accumulates in quantity on a relatively gentle slope, often the matting or the cohesion due to packing prevents equilibrium rupture, but a minor occurrence such as the fall of a snow clump or a cornice or an equilibrium break on a steeper slope nearby may set the entire slope in motion. This explains why, during catastrophic situations, avalanches occur in places where they have never been seen before and nothing happens in tracks known for frequent slides. Another fact, appearing paradoxical, is that a heavy accumulation of snow on a solid foundation may be more dangerous than on an unstable one. On a solid base the new snow builds up until it slides by itself, while the weak underlayer would probably have broken earlier and the avalanche would not have been so great (case of d'Airolo, February 1951).

2. <u>Simple equilibrium break caused by destructive metamorphism</u>

Snow crystals form in the atmosphere in the shape of stars, needles and plates, columns, or combinations of these forms. Snow on the ground has therefore physical and mechanical characteristics due chiefly to the nature of the crystals. For instance the stars and the needles become interlaced. At the start of their transformation, the stars tend to lose their dendritic form, which more or less nullifies the matting of fresh snow. This is what is known as destructive metamorphism. The flakes become progressively rounded and during great cold tend to stick together. We have seen that the natural slope of cohesionless snow depends chiefly on the form of the crystals. So, as the flakes become more and more spherical, the inclination of the slope on which the snow mass will remain in equilibrium diminishes. As the cohesion is very weak, one will see slides wherever exterior accidents set them in motion; dropping of clumps of snow from trees or rocks, a slide of stones, the passage of a skier, etc. The initial quantity of snow set in motion is important. One observes that pushing a little snow down a steep slope with skis releases nothing, the slide does not spread. Pushing a larger mass causes a slide which collects more and more snow in its passage and slides faster and faster if the slope is uniform. Sunshine activates the destructive metamorphism. After its appearance, a number of small slides occur on the steepest slopes. They may slide spontaneously because a snow grain has fallen on its neighbor and so on, starting a break which continues toward the bottom by chain reaction, resulting in pear-shaped slides.

During severe cold, metamorphism is greatly retarded on slopes that get no sun. Fifteen days may go by before the snow, remaining powdery, sets itself in motion. Slides form first on the steep slopes, then on the planes less and less inclined, in proportion to the disappearance of the matting and to the rounding of the snow grains.

Once set in motion, new snow has a very small angle of dynamic friction (17°). But it is more or less matted, so that a small slide is checked by having to break down

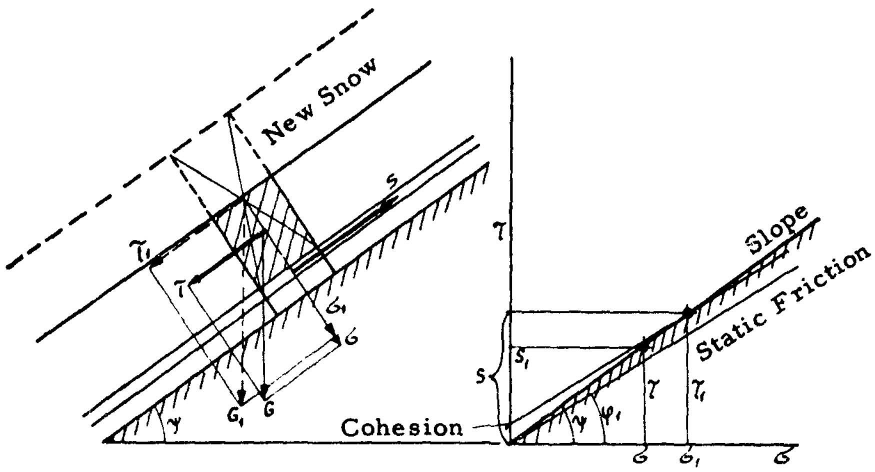

Figure 1. Analysis of a simple equilibrium break in snow of low cohesion.

G = weight of a parallelepipedon of snow of unit base, located above the weakest layer.
σ = Component of weight G normal to the slope.
τ = Component of weight G parallel to the slope.
S = resistance to shear, consisting of cohesion and static friction proportional to σ.

On the diagram to the right, σ is shown on the abscissa and τ on the ordinate. For each σ there is a corresponding τ determined by the slope of the terrain. An equilibrium break occurs when $\tau = S$. S can decrease to $S_1 (\tau = S_1)$ due to metamorphism or warming, or τ can increase to $\tau_1 (\tau_1 = S)$ due to additional load from a new snowfall.

the cohesion of the snow in its path, which it must set in motion. This is the reason that a thin snow does not break loose. However this resistance is very small for a heavy mass, and the avalanche may reach great speed.

The first stage of metamorphism destroys the fine branches of the starshaped crystals. The resulting grains are more or less elongated. The angle of dynamic friction increases from 17° to 40°. But the crystals continue to become more rounded, and the angle decreases progressively to 23° for spherical grains.

On mountain heights in winter, falling crystals are chiefly small plates which are blown to the bottom of the slopes, where they collect into extremely compact drifts. Above 3200 m in the Alps there are, therefore, few avalanches in winter. They do not start except in places where the wind has drifted the snow to great depths. They are more frequent at the beginning of summer, when moist snow accumulates on the steep slope.

In conclusion, the most stable snow is new snow, not drifted, in a relatively thin blanket (up to 20 cm). The natural angle of slope of such snow is vertical, and, if a break occurs, it cannot spread. Being very compressible, this type of snow absorbs shocks. However, a large mass set in motion may change this high angle of natural slope into low internal friction of movement, so that a slightly metamorphosed snow cover with low cohesion is even more stable, because the angle of friction of movement is greater.

3. Simple equilibrum break due to warming-up

A rise in temperature decreases cohesion and activates metamorphism, two factors favorable to the release of slides. Heat penetrates the snow cover slowly so that its action must be judged with care. When the temperature of the air rises above 0° C, the whole cover warms up until moisture infiltrates the snow, which completely loses the cohesion of contact but acquires a sort of cohesion due to capillarity — stronger if the grains are small than if the snow is fresh or the grains are large.

When the temperature rises immediately after a snowfall, there are three zones in which the danger varies according to the altitude. At low elevations the snow slides at once or packs and is not dangerous. At a certain altitude, it becomes slightly moist and preserves a certain cohesion which allows it to maintain a precarious equilibrium. It is very slippery and dangerous. At an altitude where the temperature remains below 0° C, the danger is less because the snow remains light.

A sudden and considerable rise of temperature after a heavy snowfall leaves no time for the snow to consolidate. One observes snowballs forming spontaneously and rolling down the slopes, and slides start everywhere.

B. Avalanche Release of Coherent Snow

As soon as the snow acquires a certain cohesion and forms a snow slab, the mechanism of avalanche release becomes more complicated because the anchorages on the sides, above, and below enter into the problem. The compact stratum of snow (snow slab) need not be on the surface. It suffices if under a layer of some cohesion there is a weaker layer, or even if the adhesion of the series of strata with the ground is weaker than the cohesion of the snow cover. The interest in the mechanism of release of a snow slab is due to the fact that the slab may remain attached to the mountain by its anchorages above, below, or on the sides, even when the shear stress at the ground surface is greater than the shear strength, but that it may also break away when the shearing strength of the weakest layer is as much as two or three times greater than the stress. We have seen that five breaks are required before a snow slab can move away. Depending on the sequence of breaks, we can distinguish two principal cases: 1) a primary shear failure along the bottom, which eventually causes the anchorages to break, or 2) a primary rupture at the longitudinal or lateral limits of the slab, which results in slippage of the weakest of the lower layers, or of the slab on its foundation.

1. Primary shear failure along the bottom

As in the case of poorly coherent snow, a simple equilibrium break may occur when the stress equals the resistance of the weakest underlying layer. But if one stratum is firm, it is not certain that an avalanche will occur as soon as the stress equals the strength, as the slab may remain anchored laterally, supported from below, or suspended from above. This is the case if the slab is small enough or the cohesion strong enough.

A break at the ground that does not result in dislodging the slab is a special case. With a small slab, the lateral anchorages usually break before shear along the ground, (case no. 2).

As the snow is plastic and compressible, the effect of the anchorages is valid only to a distance of three or four times the thickness of the snow-blanket, as long as there is no creep on the ground. Thus if the slab is long and wide in proportion to its thickness, as is usually the case, these anchorages are negligible and we have a simple basal shear with resulting lateral breaks. This shear is caused perhaps by an additional load or perhaps by a loss of cohesion of the weakest of the internal strata.

If the snow cover creeps on the ground, the anchorages at the limits are more important, especially if the creeping velocity is large and the snow is compact and not very compressible. In such conditions, the primary rupture takes place at the lateral, upper, or lower limits.

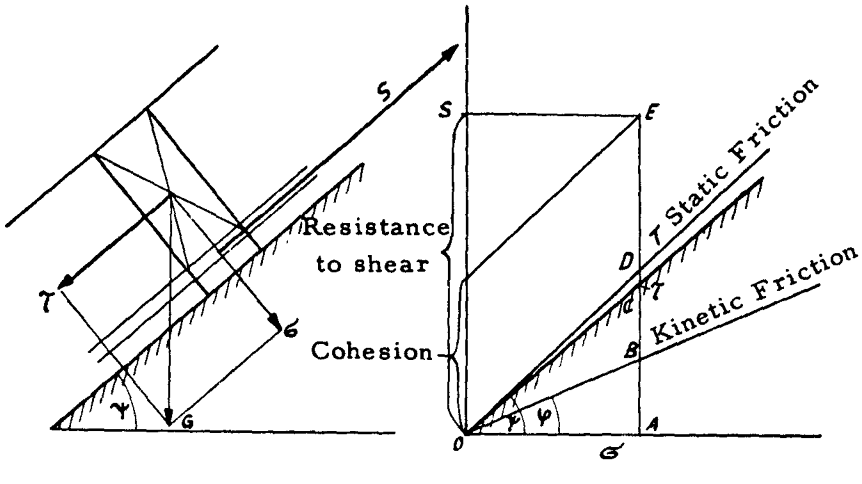

Figure 2. Analysis of avalanche release of coherent snow.

S = resistance to shear of the weakest layer.
τ = Component parallel to the slope of the weight of a parallelepipedon of snow of unit base.

In this example the resistance to shear S is 2.1 times greater than the shear stress τ and an avalanche seems impossible. The diagram shows σ on the abscissa and τ on the ordinate. Suppose that a slab of very coherent snow is set in motion by a shock. At that moment, the cohesion, ED, and the difference between the static friction and the kinetic friction, DB, are eliminated from the resistance to shear. Only the kinetic friction, AB, still holds the block. As soon as movement starts, the stress, τ = AC, is larger than the resistance, AB. But the first slab released must be large enough to overcome the resistance, AE, of the snow mass in its path. Otherwise the movement will not spread.

This break with the ground may also take the form of collapse when the component of the snow's weight normal to the slope is greater than the component parallel to the slope, that is, for slopes of less than 45°. This collapse is often accompanied by a resonant noise well known to skiers. At the moment when the slab sinks, the cohesion of the broken layer is eliminated. If the slope is sufficiently steeper than the angle of interior dynamic friction of this layer to allow the movement to spread, the slab will slide; otherwise it will remain as though glued to the foundation.

2. Primary ruptures at the upper, lower, or lateral boundaries of the slab

Primary ruptures on the edges of a snow slab have no effect unless the shock succeeds in overcoming the resistance to shear at the ground and unless the movement of the initial slab spreads. The less the shear strength exceeds the static shear stress, the greater the probability of failure. Measurements in nature show that avalanches may occur when the resistance is up to three times the stress. This resistance is made up of cohesion plus static friction. If something produces a shock, adding a momentary force sufficient to give a combined force equal to the strength, the resistance is overcome and cohesion is eliminated. As soon as the slab begins to move, the static (starting) friction changes to dynamic friction (of movement) which is smaller. Nothing then remains to hold the slab in place but the dynamic friction. If the slope is enough steeper than the angle of dynamic friction to permit the slab to break its attachments and the mass first set in motion dislodges the slabs in its path, an avalanche will occur. If not, there will be only a break without consequences. We have, therefore, a relation between the weight and the cohesion of the slab, on one

New snow screened through 4-mm mesh. Natural slope 60-61°.

Very fine-grained old snow, unscreened. Natural slope 40-41°.

Coarse-grained old snow, screened through 2-mm mesh. Natural slope 32-35°.

(photos Institut, neige et avalanches)

Slab avalanche released by explosion of a mortar shell. The initial slab releases the snow in its path as it moves along. (The resistance to shear of the weakest underlying layer is large in comparison to the stress.)
(photo Frohlich, Davos-Dorf)

Slab avalanche released by skiers, on Derbyschuss, Parsenn. The whole slope is released at once and broken into blocks. The situation is more unstable than in the preceding photograph. (The resistance to shear of the weakest underlying layer is slightly greater than the stress. (photo Caspar, Davos-Platz)

Slab avalanche on Dorftali, Davos. Wind-drifted, very compact and dense snow has slid on a relatively strong old snow surface. The avalanche broke up into large blocks but did not spread.

hand, and, on the other hand, a relation between the weight of the slab and the resistance to shear of the weakest layer which supports it.

Primary breaks along the edges are caused by stresses resulting from the plasticity of the snow. The snow creeps downslope at a rate depending on its plasticity, on the steepness of the slope, and on intervening obstacles. A high temperature makes the snow more plastic. Any differences in rate of creep produce stresses in the snow-field. A lengthwise acceleration stretches the snow, a retarding of creep compresses it, a lateral variation of velocity produces shear. Differences in thickness of the snow also create stresses. As soon as these forces equal the corresponding resistance, breaking occurs. To release the avalanche the shock of this first rupture must over-come the other resistances, most importantly, as we have noted, the shear strength along the ground.

The ruptures at the edges may be by compression at the bottom of the slope. These are rare. They may be the shear breaks known as "fermetures eclair"* by analogy because the snow cracks in a zig-zag line. The most frequent are tension breaks on convex parts of the slope. It often happens that the snow cracks more or less every-where without avalanches occurring. In this event the shock due to the tension break or other cause had not sufficient force to break the cohesion of the weakest lower layer or the adherence of the whole cover to the ground. If the slab is thick and very compact, an enormous force is required to break it. The shock of such failure in tension will be correspondingly strong and break the cohesion with the underlying stratum over a wide area. A large slab is more likely to propagate movement than a small one. Avalanche release caused by primary tension breaks or otherwise occurs at the precise moment when the stress equals the strength. At equal strength, the heavier masses slide sooner; at equal weights, the stronger masses slide later. The layers on the most convex slopes are the first to break. These facts explain why tourists sometimes cross a slope without anything happening, but later the entire snow cover on the slope breaks loose and would certainly have engulfed the skiers of a few hours before.

III. THE PROPAGATION OF MOVEMENT

This question has been referred to several times in this article. It is more or less important depending on the degree of stability of the snow layers. If the break is a simple equilibrium rupture, and the anchorages along the edges do not interfere, the propagation of movement follows naturally because the equilibrium is unstable. Here shear stress is almost equal to shear strength of the layer immediately underlying the layer of minimum tensile strength, so that the most minor event will put the mass in motion. The equilibrium might be so precarious that motion spreads without resistance. But as soon as cohesion becomes important and the basal shear strength becomes greater than the stress, the propagation of the initial movement takes on importance and even becomes a condition for sliding. As we have observed, the initial masses of snow of slight cohesion or the slab first set in motion must be large enough to break the cohesion of successive masses and set them in motion. The dynamic friction (static friction) must overcome a certain adhesion, which makes it greater than the friction of movement. It decreases with increasing speed, reaches a minimum quite rapidly, then begins to increase again, at least if the snow remains dry. If the snow becomes moist, the moisture acts as a lubricant or as a brake. One may sometimes observe an avalanche that has stopped after sliding a very short distance, while in the same neighborhood another slide which broke loose under what appear to be similar conditions has cleared the whole slope. In the first case, the speed remained too low and the friction was too great to allow propagation of movement. The nature of the impact of the initial mass set in motion upon the masses below also plays a part. A snow slab that is compact and not very compressible thrusts against slabs over a large area so that either the avalanche is blocked at once or the movement spreads. The movement of a snow slab that is relatively soft and compressible is less likely to spread because the impact is softened.

* Literal translation would be "zip fasteners."

In conclusion one may say that the propagation of movement is favored as: 1) The ratio of the resistance to the stress approaches unity; 2) The slab is compact, heavy and large, and poorly anchored laterally and longitudinally; 3) The inclination of the slope is greater than the angle of dynamic friction of the lubricating layer.

IV. EXTERIOR EVENTS THAT CAUSE AVALANCHE RELEASE

Clumps of snow dropping from trees, rocks, or from below cornices; a fall of stones; the passage of an animal or a skier, etc., may set off avalanches. Such events may add the extra stress required to cause rupture, or they may shake a layer under stress and cause its fracture. In the Alps, the break-off of cornices is rare in winter and does not occur until spring when the snow becomes moist. However, at Alta, Utah, U. S. A., for instance, where the snowfall is much heavier than here, cornices grow during a snowfall until they break and fall, possibly launching an avalanche, and then begin to grow again as the storm continues. This is certainly also the case in the Alps when huge snowfalls bring about catastrophies.

A skier crossing a slope produces two effects on the snow. His weight may cause a break, and the track of his skis cutting into a snow layer under stress may bring about a rupture.

Shooting is most effective against the convex parts of slopes. Sometimes the avalanche does not start at the point of explosion of the shell, but the shock of the explosion releases an avalanche on a neighboring slope that is under stress. It has also happened that charges exploded on a slope had no effect, while a skier jumping at a convex part set the entire mass in movement. At the place of explosion, the shear resistance of the slab is broken within a certain perimeter, insufficient for propagating the disturbance, while the slab under stress is large enough to continue the movement when released. Layers that absorb shocks are consequently more difficult to set in motion than compact layers which are sensitive to shock.

V. CONCLUSIONS FOR TOURISTS

In view of the complexity of the mechanism of avalanche release, it is obvious that the tourist sometimes unknowingly exposes himself to danger. Experience combined with observation of nature can inform him fairly well on the situation. Nature as a matter of fact reveals almost everything, but to observe wisely requires discernment and some knowledge and experience.

The late Maurice Crettex, the famous guide of Champex, who did not lack imagination, used to explain to his travellers how he could judge the avalanche danger. He thrust the handle of his ice ax full length into the snow pack, put his ear to the upper end and said he could hear whether or not there was danger. For myself, I do not believe that danger made much noise. But the act of planting his ax revealed to him the cohesion of the different layers.

The characteristics that make it possible to predict danger are: 1) The stratification of the snow cover and the cohesion of the different layers. 2) The relation between the shear strength of the weakest layer and the shear stress caused by the snow layers above it. This relationship gives the degree of stability. From this and the stratification and cohesion, one may determine what type of break to expect. If the snow has little cohesion, ruptures of the lateral, top, and bottom anchorages cannot bring about release when the ratio of stability is greater than unity, i.e., when shear strength is greater than shear stress. In more compact layers, avalanches may start when the stability ratio is larger, probably up to 3, i.e., a strength three times greater than the stress. 3) Observation of recent avalanches gives an idea of the immediate danger. 4) Meteorological observations and their development largely determine the danger — snowfall, wind, rise of temperature. 5) The tourist should also note the possibilities of any occurrences that might bring about slides. Slopes exposed to the fall of snow clumps or stones may be dangerous. A broken terrain results in tensile and shearing stresses in the snow cover.

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VI. AVALANCHE SITUATIONS

Analysis of different avalanche situations helps in shaping experience. Certain causes are usually predominant in starting a series of avalanches. These causes are combined more or less and it is often difficult to judge which are the more important. This combination is often subjective. The four chief causes are: 1) snowfall; 2) wind; 3) existence of lubricating internal layers; and 4) a rise of temperature.

1. Snowfall

This is one of the chief causes of avalanches. A snowfall up to 30 cm thick is dangerous only to the tourist; above 50 cm it threatens the avenues of communication (highways, railroads, etc.); and above 1 m it becomes catastrophic and threatens the villages. This danger is easy to detect; at worst one may err in judging its magnitude. There is danger during and immediately after snowfalls of a certain amount. During severe cold, it continues for a certain time. The heavier the snowfall, the greater the danger, but also the quicker it passes, because either the avalanches start or the snow settles.

2. Wind

Wind influences the deposition of the snow. It accumulates it or clears it. It forms slabs, drifts, and cornices. It localizes the danger on certain slopes. It can also create danger by moving snow already on the ground. When blowing very strongly, the wind may completely eliminate the danger on the heights by clearing the snow, which collects lower down. The danger produced by a violent wind is strictly localized. It should be easily recognized by the tourist, especially at the beginning of winter and in the spring. But the danger caused by a moderate wind is far more difficult to estimate.

3. Internal lubricating layers

After heavy snow-falls, avalanches usually slide on a layer of fresh snow, the most friable, deposited during a calm. However, the new deposit of snow may slide on an old internal layer that has remained weak. These internal layers are a latent danger that may persist for a long time, until the avalanches come down or until it is eliminated by a temperature rise or by consolidation. These lubricating internal layers are sometimes formed by a deposit of hoar frost on the surface, or by a thin fall of snow that remains for some time exposed to the air. This becomes metamorphosed without packing and loses its plasticity. When covered over, it resists the pressure of succeeding layers. Having lost its plasticity, it does not pack and remains weak and dangerous. This danger, which menaces tourists chiefly, is one of the most difficult to detect, even for specialists, because it makes avalanches unpredictable. It exists as long as these layers remain weak. They are usually dislodged by failure in tension due to an additional load of deposited or wind-drifted snow. It is also very difficult to determine when these loose internal layers cease to be dangerous. The danger may be eliminated by a heavy fall of snow that starts avalanches or finally packs these dangerous layers, or by a considerable rise of temperature.

4. Rise of temperature

Warming-up lessens the cohesion of the snow and makes it more plastic, so that it creeps more quickly, increasing the tensile and lateral shearing stresses. A rise in temperature increases danger, but it also eliminates it rapidly, either by starting avalanches on all sides, or by packing the snow layers, which thus develop strength.

It follows from this study that, under certain conditions, it is easy to predict avalanches but that, under certain other conditions, the danger is difficult to detect. Consequently accidents to tourists cannot be entirely eliminated.

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