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Avalanches and avalanche defence: translations of seventeen Russian articles

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PREFACE

The development of resources in mountainous regions in Canada, and the associated construction of roads and railways, have increased the need for information on avalanches and avalanche defence which has become an important part of the snow and ice research activities of the Division of Building Research of the National Research Council. The Division has been privileged to cooperate with the Department of Public Works and with the National Park Service of the Department of Indian Affairs and Northern Development in a long-term study of avalanches in the Rogers pass section of the Trans-Canada Highway. The Snow and Ice Section of the Division of Building Research is accumulating information on techniques of estimating the danger from avalanches at sites typical of Canadian conditions, and on methods of avalanche defence. These studies are extending into other areas in British Columbia and interest in the subject is developing in Canada.

Publications reporting experience obtained by scientists and engineers in other countries are a rich source of information. An "All-Union" conference on avalanches was held in Russia in 1965; the proceedings of that conference have been published. The Division of Building Research is pleased to make information presented to that conference available to Canadian engineers through the translation of some of the papers that were presented.

The Division wishes to record its thanks to Mr. H.R. Hayes and Mr. V. Poppe, Translations Section, National Research Council, for translating these papers and to Mr. P. Schaerer of this Division who checked the translations.

Ottawa
October 1969

N.B. Hutcheon
Director

NATIONAL RESEARCH COUNCIL OF CANADA

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Translators: H.R. Hayes and V. Poppe, Translations Section, National Science Library

TABLE OF CONTENTS

Page

TRANSACTIONS OF THE FIRST ALL-UNION CONFERENCE ON AVALANCHES. LENINGRAD, 1965

HANDBOOK ON AVALANCHE DEFENCE WORKS (PROVISIONAL). LENINGRAD, 1965

VARIATION IN THE HARDNESS OF AVALANCHE SNOW WITH TIME AND EXPERIENCE IN CLEARING SNOW SLIDES WITH BULLDOZERS

by

B.P. Bozhevol'nov and L.M. Rudakov

The paper describes a method of determining snow strength by way of hardness. A table is given illustrating the efficiency of snow removal by a bulldozer taking into account the density and hardness of snow.

The danger from snow avalanches can be controlled by triggering the avalanches by mortar fire. The basic principle of this method is as follows. On notice being given by the avalanche service, that avalanche hazard is imminent, all work and traffic are stopped, and men and equipment are evacuated. The avalanche is released and the snow mass is then cleared away. It is often difficult to clear away the conical piles of avalanche snow. The strength of such snow can be so great that it is impossible to cut with the blade of a bulldozer. In such cases it becomes necessary to loosen the snow by blasting.

Snow that has been disturbed tends to become stronger with time. This tendency is especially pronounced in well-compacted snow.

In such cases the strength of snow is best determined by its hardness. The hardness of snow is found by means of a conical hardness tester with a 60° angle at the apex. It is determined as a ratio of the load on the cone to the area of the projection of the imprint by the following formula:

$$\sigma_{т} = 1.046 \frac{P}{h^2} \text{ kg/cm}^2;*$$

where P is the load on the cone in kilograms and h is the depth of penetration of the cone in centimetres.

Characteristic deposits from avalanches set off by mortar fire were examined. One of the avalanches (No. 19) was wet: it was triggered when the air temperature was above zero. The other (No. 28) was dry, since it was set off when the air temperature was below zero.

The results of measurements of hardness of the snow and changes in its density with time are shown in Table I and Figure 1.

Each hardness value represents an average of 15 to 20 measurements, and each density value is an average of 3 to 5 measurements. The curves in Figure 1 also show the daily variation of the air temperature at six-hour intervals for the entire observation period.

As may be seen from the curves, the hardness of snow continuously increased from the moment of the occurrence of the avalanche. The most

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* Editorial note: The correct formula is: $\sigma_T = \frac{1}{1.046} \frac{P}{h^2}$, or $\sigma_T = 0.955 \frac{P}{h^2}$ kg/cm².

rapid increase occurred in the initial period; the curves become less steep later on.

The density of snow varies little (within the margin of error of the measurements). Therefore it may be regarded as remaining practically constant during the observation period. This indicates that the density of snow is not a prime indicator of strength. For example, it may be seen from the curves that at a relatively constant density, the hardness of snow changed from 1.5 to 16 kg/cm^2, i.e. it became more than 10 times as high (Table I, avalanche No. 19). Nevertheless, the density of snow may be regarded as a certain indirect indicator of strength, but only in the sense that after a long period of time for each density there will be a corresponding stabilized (ultimate) hardness.

The increase in the hardness of deposited snow with time occurs because of the following factors:

1) formation of thin ice coatings surrounding the snow grains in wet avalanches, i.e. due to freezing of the liquid phase;

2) as a result of internal process of sublimation; owing to differences in vapour pressure on convex and flat surfaces of crystals and especially on concave surfaces bends between grains are developed;

3) condensation of vapour from the air at certain temperatures and moisture contents;

4) regelation is of much less importance in this case.

One or the other of these factors may predominate, depending on the prevailing conditions.

This phenomenon is of great practical importance for clearing snow slides resulting from avalanches. The observations of a bulldozer clearing snow slides on the Osetin Military Road* have shown that the efficiency of these machines is strongly dependent on the strength (hardness) of snow and the depth of the snow slide.

The results of these observations are shown in Table II. It may be seen that the efficiency of a bulldozer is sharply reduced with the increase in the hardness of snow. With hardness exceeding 10 kg/cm^2, the clearing operation is so difficult that it becomes necessary to loosen the snow by blasting.

On comparing Figure 1 with Table II (dotted line on Fig. 1), it becomes obvious that bulldozers can work not only on dry avalanches but also in wet snow, providing they commence the clearing operation immediately after the descent of the avalanche. For example, it would have been simple to clear the cone from the wet avalanche No. 19 on the first day after its descent. This becomes much more difficult later.

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* Translator's note: In the Caucasus.

Hence these observations lead to a conclusion that in order to make best use of a bulldozer, the clearing operations should be started as soon as possible after the descent of an avalanche.

Table I

Experimental data on the condition of snow in avalanche cones

Avalanche No. 19				Avalanche No. 28			
Date	Time of day	Hardness, kg/cm^2	Density T/m^3	Date	Time of day	Hardness, kg/cm^2	Density T/m^3
1963 15/III	17:00	1.48	0.645	1963 17/III	12:45	0.10	-
15/III	18:20	2.66	-	17/III	14:00	0.17	0.332
16/III	12:15	8.33	0.665	17/III	17:30	0.69	0.333
17/III	15:40	12.50	0.700	18/III	11:00	1.38	0.305
19/III	12:30	16:10	0.655	19/III	10:30	2.68	0.345

Table II

Clearing of avalanche snow by bulldozer S-100

Section	Snow characteristics	Density, T/m^3	Hardness, kg/cm^2	Type of bulldozer operation
1	Snow in a cone from a dry avalanche, up to 1 m deep	0.25-0.35	0.5-1.0	Snow removal by foreward motion is possible; snow is dumped on both sides of the road without turning the bulldozer. Efficiency: up to 1.5-2.0 thousand m^3/hr.
2	Same as above, over 1 m deep	0.25-0.35	0.5-1.0	Removal by stages and to one side only. Efficiency is reduced to 300-500 m^3/hr.
3	Snow in a cone from a wet avalanche, over 1 m deep	0.45-0.50	up to 5.0	Removal to one side only. Efficiency is reduced to 100 m^3/hr and less
4	As above	0.6-0.7	over 5.0-10.0	Removal is very difficult; to increase the efficiency, snow is loosened by blasting.

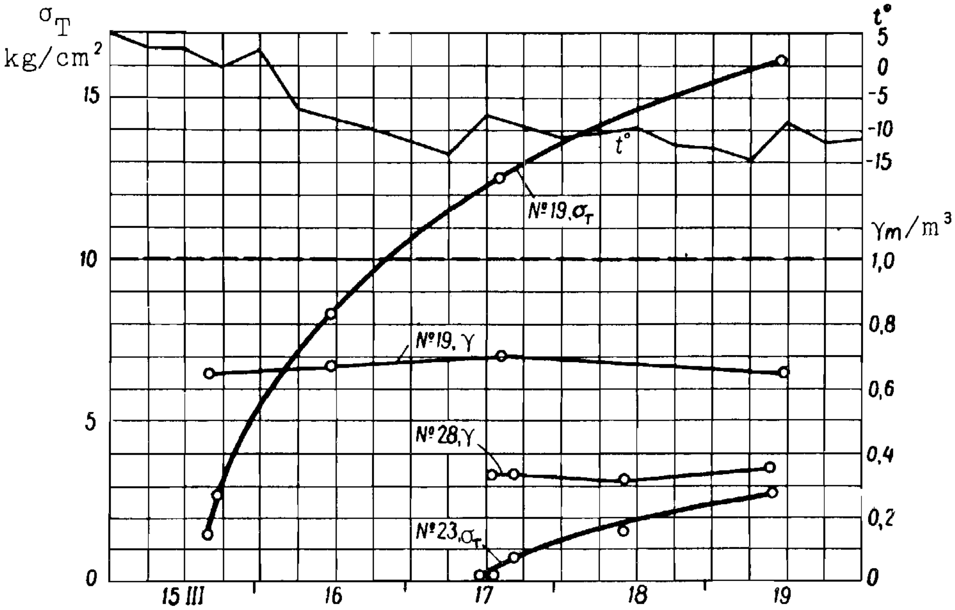

Fig. 1

Variations in hardness and density of avalanche snow in time

DETERMINATION OF THE LOCATION OF UNSTABLE SNOW AND THE MECHANISM OF WET AVALANCHE FORMATION

by

Yu. D. Moskalev

In this article the author gives the derivation of an equation of equilibrium for a snow layer on a fairly extensive slope and describes a nomogram for calculating the mechanical stability of snow cover where the water equivalent, cohesion and internal friction coefficient are known. The equation of equilibrium is extended to cases of viscous-plastic snow flow and the seepage of melt or rain water in a snow mass.

Most of the existing methods of evaluating the mechanical stability of a snow cover on fairly extensive slopes are based on a comparison of the component of its weight directed parallel to the slope and the shear resistance. The condition of equilibrium of a snow mass on a slope with a constant angle α is written in the form of an inequality(3)

$$\mathrm{tg}\,\alpha \leqslant \mathrm{tg}\,\psi, \text{ or } \alpha \leqslant \psi, \qquad (1)$$

where $\psi = \text{arc tan}\,\frac{\tau_c}{\sigma}$ is the angle of shear resistance, τ_c is the ultimate shear resistance, σ is the stress normal to the plane of shear.

This condition of equilibrium may be used directly in practice in those comparatively rare cases where the measurements are made for the same normal load as that occurring on the slope. If there is a requirement to determine the stability of a snow mass on a slope with a different normal load, it will be necessary either to repeat the test under the new conditions or to calculate the corresponding value of tan ψ, since for snow the ultimate shear resistance τ_c depends on the pressure σ normal to the surface of the shear. This dependence is fairly complex, and as yet comparatively little work has been done on it. Probably it can best be described as approximately parabolic which becomes linear at sufficiently high pressures. For rough practical calculations the ultimate shear resistance may be found from the simple relation

$$\tau_c = c + \sigma\,\mathrm{tg}\,\varphi, \qquad (2)$$

where c is a certain constant value called cohesion; φ is the angle of internal friction of the snow or the friction of the snow against the substratum.

Since the normal weight of a snow mass is small in absolute value, the straight-line relationship may be taken only as a first approximation, and the magnitudes of the angle of internal friction and the cohesion acquire a conditional meaning. However, for approximate calculations when only the cohesion value is known more or less precisely, and the friction coefficient is obtained from tables, linear extrapolation of τ_c values is obtained more conveniently by determining the forces holding the snow on the slope.

Substituting the expression $\tau_c = \sigma \operatorname{tg} \psi$ in (2), we find

$$\operatorname{tg} \psi = \frac{c}{\sigma} + \operatorname{tg} \varphi . \qquad (3)$$

The pressure σ normal to a horizontal plane is proportional to the water equivalent of the overlying snow mass; if the cohesion is expressed in tons per square metre, kilograms per square decimetre, grams per square centimetre, respectively, the proportionality factor is equal to unity. For a slope with angle α the normal pressure

$$\sigma = w \cos^2 \alpha ,$$

since the normal weight component of the snow, numerically equal to its water equivalent w, is distributed over an area $\frac{1}{\cos \alpha}$ in size.

On comparing (3) with (1), we obtain an equation of equilibrium for a snow mass on a slope when retaining forces at the boundary of the layer are absent (or when they are negligible):

$$\operatorname{tg} \alpha \leqslant \frac{c}{w \cos^2 \alpha} + \operatorname{tg} \varphi ,$$

$$\sin \alpha \leqslant \frac{c}{w \cos \alpha} + \operatorname{tg} \varphi \cos \alpha ,$$

$$\cos \alpha (\sin \alpha - \operatorname{tg} \varphi \cos \alpha) \leqslant \frac{c}{w} . \qquad (4)$$

Having denoted $w = \gamma h$, where γ is the unit weight of the snow and h is its vertical depth above the critical horizon, and $\operatorname{tg} \varphi = f$ is the coefficient of friction, we obtain a common expression for the condition of equilibrium.

$$\gamma h_{н} (\sin \alpha - f \cos \alpha) - c = 0 ,$$

where h_H is the depth of the layer measured perpendicularly to the slope.

If the forces at the boundaries of the layer are taken into account, the right side of the equation will not be zero, but the sum of these forces per unit area of the layer. In particular, if of these we take into account only the resistance to fracture n, we can obtain Saatchyan's formula for a layer of unit width and length l (2):

$$l \gamma h_{н} (\sin \alpha - f \cos \alpha) - cl - n h_{н} = 0 .$$

Analyzing the condition of equilibrium of an elementary volume on different slopes or on various sectors of a slope of varying steepness, it is possible to trace the areas where the snow stratification is potentially unstable, i.e. the work of virtual displacement of each sector of snow within these areas is positive. It is precisely these zones which must be considered as locations where avalanches may initiate; if, however, at each point on the slope, conditions of equilibrium are observed and the work on virtual displacements is negative, the snow can descend the slope only as a result of some outside force, in which case the displacement of snow masses originating in these sectors will die out.

The boundaries of the area in which a snow layer may break away are extended to more gentle slopes as a result of the deformation of unstable snow lying higher up the slope.

If relationship (4) is split into two parts it is more convenient for calculations

$$N = \cos\alpha(\sin\alpha - f\cos\alpha)$$

and

$$f' = \frac{c}{w}.$$

Equation (4) is easily represented in the form of a nomogram (see Fig. 1). The left and right scales of the nomogram are evenly divided and the friction coefficients and relations $f' = \frac{c}{w}$ plotted on them; the angles of slopes covered with unstable snow are marked on the curve in the centre. The condition of equilibrium of the snow on the slope is:

$$N \leqslant \frac{c}{w}. \qquad (5)$$

From the nomogram it is easy to see that for given physical-mechanical properties and water equivalent of the snow mass, the angles of the slopes with an unstable snow cover have a lower and an upper limit if the relationship $\frac{c}{w}$ is less than 0.5. Shallower and steeper slopes will be characterized by a stable snow layer: in the first case, in consequence of the small value of the shearing component due to weight, and in the second case, because the snow load is distributed over a larger area of the slope (i.e. the thickness of snow cover will decrease for the same depth of snow or the same layer of precipation).

When $\frac{c}{w} \approx 0.5$, slopes of only a certain specific steepness will present an avalanche hazard; if, however, $\frac{c}{w}$ is more than 0.5, the snow on all the slopes is stable.

When $\frac{c}{w} \to 0$, the condition of equilibrium $\mathrm{tg}\,\alpha \leqslant f$, or $\alpha \leqslant \varphi$ is true.

It is also possible to arrive at these conclusions by analyzing equation (4).

The proposed nomogram provides a means of rapidly estimating the stability of the snow cover on slopes and reduces the number of calculations. The contours of sectors with unstable snow plotted on a topographic chart of avalanche prone areas provide a picture of the locations where avalanches may start in a specific snow environment.

The formulae of equation (4) describe the conditions under which a snow layer forming an avalanche separates in the event of rupture of a critical horizon, or a viscous-plastic flow, if the snow can undergo appreciable deformation without collapsing. In the first case the bonds between the ice particles are destroyed together with the cohesive force, which results in a sharp reduction of stability: the friction force is no longer sufficient to hold the snow sheet on the slope after tension fractures have formed and compressive stresses are created in it. In the second case a steady flow of snow occurs.

The viscous-plastic properties of snow favours the equalization of shearing stresses along the entire base of a slowly creeping snow layer. Moreover, if the shearing force exceeds the retaining force in one sector or another, this does not necessarily result in the triggering of an avalanche, provided the force does not cause the snow layer to shear in the area of compression; transverse cracks may appear in the area of tensile stress without causing an avalanche.

The rate of viscous-plastic deformation of a uniform layer of snow may be calculated by N.N. Maslov's formula for plastic clay (1):

$$v = \frac{\gamma}{\eta}\left(dy - \frac{y^2}{2}\right)(\sin\alpha - \operatorname{tg}\varphi\cos\alpha) - \frac{c}{\eta}y,$$

where η is the plastic viscosity factor of the snow cover; d the thickness of the snow layer; y the distance reckoned from the bottom of the layer normal to the slope. Maximum flow rate is observed at the surface (y = d):

$$v_{max} = \frac{\gamma}{2\eta}d^2(\sin\alpha - \operatorname{tg}\varphi\cos\alpha) - \frac{c}{\eta}d.$$

Freshly fallen snow undergoes irreversible deformations under the slightest stresses, in consequence of which cohesion and internal friction for prolonged loads may be disregarded, and then the maximum rate is found by the formula

$$v_{max} = \frac{\gamma}{2\eta}d^2\sin\alpha.$$

Where the quantities in the formula are constant, the rate of deformation is also constant. The flow process begins at that point where there is a local concentration of stresses and takes in the whole of the area along the weakest horizon. If the maximum resistance to fracture and cleavage is exceeded, the layer will slide, i.e. an avalanche will occur.

Maximum rate of deformation may be expressed in terms of time t and the limiting value of surface deformation $s_{\text{пр}}$, at which, according to observations, avalanches are initiated. Using these data it is easy to calculate the time from the start of a viscous-plastic deformation to the descent of an avalanche (under stable conditions):

$$t = \frac{2\eta s_{\text{пр}}}{\gamma d^2\sin\alpha}, \text{ if } c = 0 \text{ and } \varphi = 0,$$

$$t = \frac{2\eta s_{\text{пр}}}{\gamma d^2(\sin\alpha - \operatorname{tg}\varphi\cos\alpha)}, \text{ if } c = 0$$

$$t = \frac{2\eta s_{\text{пр}}}{\gamma d^2(\sin\alpha - \operatorname{tg}\varphi\cos\alpha) - 2cd} \text{ where } c \neq 0$$

or, having introduced the limiting angular deformation $\varepsilon_{\Pi p} = \frac{s_{\Pi p}}{d}$, with the same assumptions we obtain:

$$t = \frac{2\eta\varepsilon_{np}}{\gamma d \sin\alpha}, \quad t = \frac{2\eta\varepsilon_{np}}{\gamma d(\sin\alpha - \operatorname{tg}\varphi\cos\alpha)}$$

and

$$t = \frac{2\eta\varepsilon_{np}}{\gamma d(\sin\alpha - \operatorname{tg}\varphi\cos\alpha) - 2c}.$$

This formula may be transposed as follows:

$$\cos\alpha(\sin\alpha - f\cos\alpha) \leqslant 2\frac{c + \eta\frac{\Delta\varepsilon}{\Delta t}}{w} = \frac{c_э}{w},$$

where the expression $2\left(c + \eta\frac{\Delta\varepsilon}{\Delta t}\right) = c_э$ is a factor equivalent to the cohesion, $\frac{\Delta\varepsilon}{\Delta t}$ is the rate of angular deformation of the snow cover. Calculations for this condition of stability are easily made for a group of slopes by means of the nomogram shown in Figure 1.

The condition of stability (1) is extended to a snow cover containing free (gravity) water, but in this case, besides the change in the tensile properties of the snow, it is necessary to take into account the apparent decrease of the angle of shear resistance due to the effect of seepage forces

$$P = \gamma_в V I,$$

where P is the seepage force, $\gamma_B = 1$ the specific gravity of water, V the volume of the layer with seeping water, I is the hydraulic gradient of the flow below or within the snow. This seepage force is directed along flow lines from large pressures to lesser ones. If the water seeps down the slope, the hydraulic gradient per unit width is equal to the sine of the angle of incline of the slope and

$$P = 1 \cdot h_в x \sin\alpha = h_в x \sin\alpha,$$

where h_B is the depth of the layer saturated with water; x is the horizontal projection of the snow layer in question.

On the other hand, the effective pressure between the particles of water-saturated snow decreases as a result of buoyancy. The vertical uplifting force acting on the volume element of a snow layer with vertical faces and a cross-sectional area equal to unity is found from the relationship

$$P_в = \gamma_в(1 - n)h_в = (1 - n)h_в,$$

where n is the porosity of the layer of snow in which seepage occurs per unit volume. The porosity may be calculated from the unit weight (density) of snow with moisture content e using $n = 1 - (1.09 - 0.09e)\gamma$. The effective normal pressure is

$$\sigma_э = |w - (1 - n)h_в|\cos^2\alpha.$$

Since the ultimate shear strength depends on the effective normal pressure

$$\tau_c = \sigma_{\text{э}} \operatorname{tg} \psi,$$

we find that the snow layer in question with a length $\frac{x}{\cos \alpha}$ is held on the slope by a force $\frac{\tau_c x}{\cos \alpha} = \frac{\sigma_{\text{э}} x}{\cos \alpha} \operatorname{tg} \psi$.

The total shearing force is equal to the sum of the contribution to the shear stress due to the weight and the seepage force:

$$wx \sin \alpha + h_{\text{в}} x \sin \alpha .$$

Writing the equation of equilibrium, we obtain

$$wx \sin \alpha + h_{\text{в}} x \sin \alpha - \frac{\sigma_{\text{э}} x}{\cos \alpha} \operatorname{tg} \psi \leqslant 0$$

or

$$(w + h_{\text{в}}) \sin \alpha - \frac{\sigma_{\text{э}}}{\cos \alpha} \operatorname{tg} \psi \leqslant 0,$$

$$(w + h_{\text{в}}) \sin \alpha - [w - (1 - n) h_{\text{в}}] \cos \alpha \operatorname{tg} \psi \leqslant 0,$$

whence

$$\operatorname{tg} \alpha \leqslant \frac{w - (1 - n) h_{\text{в}}}{w + h_{\text{в}}} \operatorname{tg} \psi .$$

Comparison with (1), shows that this condition of equilibrium is equivalent to a reduction of tg ψ, since the relationship $\frac{w - (1 - n)h_B}{w + h_B}$ is less than unity, and only in the absence of seepage water ($h_B = 0$) becomes equal to unity.

Given the linear dependence $\tau_c = c + \sigma_{\text{э}} \operatorname{tg} \varphi$, we obtain:

$$\operatorname{tg} \alpha \leqslant \frac{w - (1 - n) h_{\text{в}}}{w + h_{\text{в}}} \left(\frac{c}{\sigma_{\text{э}}} + \operatorname{tg} \varphi \right)$$

or

$$\operatorname{tg} \alpha \leqslant \frac{w - (1 - n) h_{\text{в}}}{w + h_{\text{в}}} \left[\frac{c}{w - (1 - n) h_{\text{в}}} \frac{1}{\cos^2 \alpha} + \operatorname{tg} \varphi \right],$$

whence

$$\operatorname{tg} \alpha \leqslant \frac{c}{(w + h_{\text{в}}) \cos^2 \alpha} + \frac{w - (1 - n) h_{\text{в}}}{w + h_{\text{в}}} \operatorname{tg} \varphi$$

and, further,

$$\cos \alpha \left[\sin \alpha - f \frac{w - (1 - n) h_{\text{в}}}{w + h_{\text{в}}} \cos \alpha \right] \leqslant \frac{c}{w + h_{\text{в}}} .$$

Comparing with (4), it is readily seen that the effect of seepage water is equivalent to a reduction of the coefficient of internal friction of the snow and an increase of the water equivalent (water content) of the snow layer in question. If the equivalent of the coefficient of internal friction $f_{\text{э}} = f \frac{w - (1 - n) h_{\text{в}}}{w + h_{\text{в}}}$ and the equivalent water content $w_{\text{э}} = w + h_{\text{в}}$, are included in the condition of equilibrium, stability estimates may be obtained with the nomogram shown at Figure 1.

For other filtration conditions it is necessary to introduce other equivalent internal friction and water content values. Thus, if water seeps vertically from top to bottom, completely saturating the snow layer in question (as, for example, in heavy rain), the hydraulic gradient is approximately equal to unity and the seepage force is added to the force of gravity, which is equivalent to an increase in the unit weight of snow to unity; in this case

$$w_{\text{в}} = w + h \text{ and } f_{\text{в}} = f\,\frac{w + nh}{w + h} = f\,\frac{\gamma_{cp} + n}{\gamma_{cp} + 1},$$

where γ_{cp} is the average density of the snow cover.

In all these formulae the water equivalent w is the total moisture reserve in the portion of the snow cover in question, determined by means of a snow sampler after the free water has drained out of it. The latter occurs in the snow cover if its moisture content e exceeds the maximum water-retaining capacity e_0.

If the water content of the snow cover is less, its stability should increase in consequence of the capillary forces on the bonds of the ice granules: the snow becomes adhesive and is retained firmly on the slopes. The condition $e > e_0$ serves as an indication of the possibility of avalanche danger. If, in addition to this, rain falls on the snow cover, it increases the total water content and the static load on the slope.

In the above discussions it has been provisionally assumed that the depth of the water-saturated layer is constant in the portion of snow layer being investigated. This may be the case if the snow layer is fed by melt water from a larger area lying above it (for example, an inclined plateau), and the increase in the flow rate within the given area may be disregarded. If rain or melt water flows over the entire surface of the snow cover, the flow rate will increase towards the foot of the slope; and here the snow becomes saturated, which results in a loss of stability for the entire snow layer.

For a unit width of flat slope on which rain or melt water flows with a uniform rate ω per unit of area of horizontal projection, we can write

$$q = \omega l \cos\alpha,$$

where l is the length of the slope (along the incline) of steepness α; on the other hand, the very same quantity of water must filter through the snow in the lower part of the slope

$$q = kh_{\text{в}} \sin\alpha \cos\alpha,$$

where k is the permeability of the water-containing snow.

Hence, we can find the depth of the water-saturated layer (when a water-resisting layer or impervious soil is present):

$$h_{\text{в}} = \frac{\omega l}{k \sin\alpha}.$$

Depressions in the slopes facilitate concentration of flow in channels of sub-snow and inter-snow streams, which are fed over comparatively large areas, thus increasing the probability of wet avalanches in such sectors (other conditions being equal).

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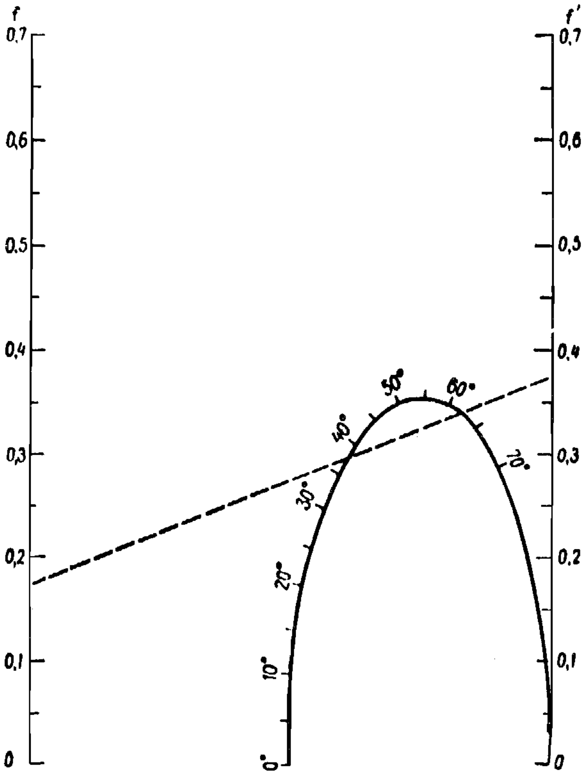

Fig. 1

EQUILIBRIUM EQUATIONS FOR SNOW MASS ON SLOPES

by

Yu. D. Moskalev

The paper contains a solution of the two-dimensional problem on the initiation of a viscous-plastic flow in a snow mass on a cylindrical slope. Three states of equilibrium are discussed. It is suggested that the effect of melt or rain water seeping through the snow should be accounted for by way of equivalent values for water content and the coefficient of internal friction of snow.

Under certain conditions, the snow cover on slopes acquires a state of slow viscous-plastic flow, which is accompanied by the appearance of tension cracks in the upper part of the slope and warping of the snow mass in the lower part. If the strength in the warped area is exceeded, slow sliding will be transformed into an avalanche.

The initiation of the plastic flow occurs when:

$$\tau \geqslant \tau_c,$$

where τ is tangential stress in the critical layer of the snow mass; $\tau_c = c + f\sigma$ is the shear strength which depends on the stress σ normal to the plane of shear; c is cohesion or shear strength when normal stress is zero; f is coefficient of internal friction; $f = \operatorname{tg} \varphi$, where φ is the angle of internal friction.

It is sometimes essential to calculate the forces in the snow cover at any point of the slope, determine the possible dimensions of the snow mass which will cause an avalanche, or estimate its stability on the slopes. If the slope has a more or less cylindrical form, it is sufficient to solve a two-dimensional problem. An approximate solution of this problem is as follows.

An elementary vertical prism in the snow mass is subjected to:

1) the gravitational force $dQ = \gamma h ds \cos \alpha$, where h is the depth of the snow cover above the assumed sliding surface, γ is the average unit weight of snow, and $\gamma h = w$ is the water equivalent (water content) of the given snow mass, ds is the area of the base;

2) the bearing reaction R, which deviates from the normal to the bearing surface by an angle φ;

3) the forces of cohesion;

4) the normal forces P and tangential forces T on the lateral planes (Fig. 1).

The calculations are made for a snow mass with a width equal to unity.

Summing the horizontal and vertical components of the forces:

$$x = R \sin(\alpha - \varphi) - c dx + P_1 - P_2 = 0;$$
$$Z = dQ - R \cos(\alpha - \varphi) - c dz + T_1 - T_2 = 0,$$

where α is the angle of slope; dx is the horizontal and dz is the vertical projection of the base area ds of the elementary prism.

The bearing reaction may be expressed in terms of the weight of the elementary prism:

$$\overline{R}=\overline{N}+\overline{F},$$

where the normal component of weight is N = γhds cos α and the friction force is F = fN. From this we determine:

$$R=N\sqrt{1+f^2}=\gamma h\cos\alpha\sqrt{1+f^2}\,dx=\gamma h\frac{\cos\alpha}{\cos\varphi}\,dx.$$

On adding up the equations of equilibrium within the given section of the slope with a length ι, we obtain

$$\Sigma X=\int_l\gamma h\frac{\cos\alpha}{\cos\varphi}\sin(\alpha-\varphi)\,dx-\int_l c\,dx-P_{0x}-P_x=0,$$

$$\Sigma Z=\int_l\gamma h\,dx-\int_l\gamma h\frac{\cos\alpha}{\cos\varphi}\cos(\alpha-\varphi)\,dx-\int_l c\,dz-P_{0z}-P_z=0,$$

where P_{ox} and P_{oz} are the projections of the force in the upper cross-section of the snow mass. From this we determine the projections of the force in the given cross-section:

$$P_x=\sigma_p d_0\cos\alpha_0+cX-\int_l\gamma h\cos\alpha(\sin\alpha-f\cos\alpha)\,dx, \qquad (1)$$

$$P_z=\sigma_p d_0\sin\alpha_0+cZ-Q+\int_l\gamma h\cos\alpha(\cos\alpha+f\sin\alpha)\,dx, \qquad (2)$$

where σ_p is the weighted average tensile strength of the given snow mass, d_o is its thickness at the point of the expected fracture (the upper discontinuity of the slope), α_o is the angle of slope in the fracture zone, X and Z are the lengths of horizontal and vertical projections of the slope section, respectively.

After modifications, the second of the aforementioned equations is transformed into a more convenient form, since:

$$\cos\alpha(\cos\alpha+f\sin\alpha)\equiv 1-\cos\alpha\,\mathrm{tg}\,\alpha(\sin\alpha-f\cos\alpha),$$

$\int$ γhdx = Q is the weight of the snow mass and tg α dx = dz, therefore

$$P_z=\sigma_p d_0\sin\alpha_0+cZ-\int_l\gamma h\cos\alpha(\sin\alpha-f\cos\alpha)\,dz. \qquad (2a)$$

The product γh may be replaced by the water equivalent of the snow mass multiplied by the specific weight of water $\gamma_B = 1$.

In the presence of free (gravitational) water in the snow, it is essential to consider the unit seepage forces and the reduction in friction forces resulting from the suspending effect of water. The equation under the integral sign is as follows:

$$w_э\cos\alpha(\sin\alpha-f_э\cos\alpha),$$

where $w_{\text{э}}=\gamma h+\gamma_{\text{в}}h_{\text{в}}$ is the equivalent water content of the snow mass, $f_{\text{э}}=f\frac{\gamma h-(1-n)\gamma_{\text{в}}h_{\text{в}}}{\gamma h+\gamma_{\text{в}}h_{\text{в}}}$ is the equivalent coefficient of internal friction of water-saturated snow during downward seepage of water along the slope; n is the porosity of snow containing water; $h_{\text{в}}$ is the depth of water-saturated snow layer.

In the case of vertical filtration throughout the entire depth of the snow cover:

$$w_{\text{э}}=\gamma h+\gamma_{\text{п}}h=(\gamma+1)h \text{ and } f_{\text{э}}=f\frac{\gamma h-nh\gamma_{\text{п}}}{\gamma h+\gamma_{\text{п}}h}=f\frac{\gamma-n}{\gamma+1}.$$

It is obvious that seeping water increases the water equivalent of the snow mass and reduces the effective internal friction of snow, i.e. it has a very detrimental effect on the stability.

On taking the probable position of the fracture line (if the tensile strength of the snow mass is considerably less than its shear strength, the upper boundary of unstable snow mass may be assumed with sufficient accuracy), it is simple to construct a diagram of the function cos α (sin α - f cos α) and to integrate it by the graphic method with respect to dx and dz down to the given cross-section. If internal forces in this cross-section do not exceed the average (for this cross-section) ultimate shear or tensile strengths of snow (depending on the size of the force), we may proceed with the calculation until the strength characteristics in one of the cross-sections are exceeded. When this happens, the positions of the lines of shear or rupture of the snow mass are determined by interpolation.

Equations (1) and (2) permit us to determine only the value and the angle of slope of the resultant. They do not reveal its position. To determine the latter, it is necessary to find the sum of moments due to the various forces.

Horizontal and vertical coordinates are drawn from any point in the plane of the slope profile (Fig. 1).

The resultant gravity moment is determined as a sum of the moments due to the weight of unit volumes of the snow mass, which is equal to:

$$m_0(Q)=\int_l \gamma h x\,dx,$$

where x is the abscissa of the unit volume

If the water equivalent of the snow cover on a slope is constant, the resultant of the forces of gravity proceeds vertically through the middle of the given section and is equal to the weight of the snow mass.

The moment of the elementary force of cohesion is:

$$dm_0(c)=c\,(z+x\operatorname{tg}\alpha)\cos\alpha\,dl=cr\sin(\alpha+\delta)\,dl,$$

where

$$r=\sqrt{x^2+z^2} \text{ and } \delta=\operatorname{arctg}\frac{z}{x}.$$

The sum of the moments is:

$$m_0(c) = c\int_l r\sin(\alpha+\delta)\,dl.$$

The moment of the elementary bearing reaction R is:

$$dm_0(R) = r\gamma h\cos\alpha\,\frac{\cos(\alpha+\delta-\varphi)}{\cos\varphi}\,dx$$

and the sum of the moments is:

$$m_0(R) = \int_l r\gamma h\cos\alpha\,\frac{\cos(\alpha+\delta-\varphi)}{\cos\varphi}\,dx.$$

The force resisting rupture in the upper cross-section of the snow mass has the following moment:

$$M_0 \approx \sigma_p d_0 r_0 \sin(\alpha_0+\delta_0),$$

while the moment M in the given cross-section is equal to the product of the resultant and the arm of its action.

The required moment M may be determined from the equation of the sum of moments:

$$M + M_0 + c\int r\sin(\alpha+\delta)\,dl + \int_l r\gamma h\cos\alpha\,\frac{\cos(\alpha+\delta-\varphi)}{\cos\varphi}\,dx - \int_l \gamma h x\,dx = 0. \tag{3}$$

If the snow cover contains gravity water, the calculations are carried out using the equivalent value of water content instead of γh, and the equivalent angle of friction $\varphi_э$ = arc tg $f_э$ instead of φ.

In the special case of a circular cylindrical surface (r = const), the angle $90^\circ - \delta = \alpha$, so that $\alpha + \delta = 90^\circ$. In this case, equation (3) assumes a much more simple form:

$$M + M_0 + cr\int_l dl + r\,\mathrm{tg}\,\varphi\int_l \gamma h\cos\alpha\,dx - \int_l \gamma h x\,dx = 0.$$

Since $\cos\alpha = \frac{z}{r}$ and the arc ı is enclosed between α_0 and α, we obtain:

$$M = \int \gamma h x\,dx - f\int \gamma h z\,dx - crl - \sigma_p d_0 r.$$

If the water equivalent is constant, the integrals in the equation are easily found analytically:

$$\int_l \gamma h x\,dx = \gamma h\int_x^{x_0} x\,dx = \gamma h\,\frac{x_0^2 - x^2}{2} = \gamma h(x_0 - x)\,\frac{x_0 + x}{2}$$

and

$$\int_l \gamma h z\,dx = \gamma h\int_x^{x_0} \sqrt{r^2 - x^2}\,dx = \frac{\gamma h}{2}\,|x_0 z_0 - xz + r^2(\alpha_0 - \alpha)|,$$

where α_0 and α are angles of slope at the beginning and end of the given section.

If it is only the average density of the snow cover that may be regarded as constant, the calculation is reduced to the determination of static moments of areas by approximate methods. The integral $\int$ zhdx is only approximately equal to the static moment of the area of longitudinal cross-section of the snow cover (depth h must remain considerably smaller than the minimum value of the z coordinate).

In the case of a circular cylindrical surface, equations (1) and (2) assume a more simple form also. Since $\gamma hdx = gdm$, where dm is unit mass and g is acceleration due to gravity, we can introduce the centrifugal moment of inertia $\int xzdm$ and the axial moment of inertia $\int z^2dm$ into the equation:

$$P_x = \sigma_p d_0 \cos\alpha_0 + cX - \frac{1}{gr^2}\left(\int xzdm - f\int z^2dm\right),$$

$$P_z = \sigma_p d_0 \sin\alpha_0 + cZ - Q + \frac{1}{gr^2}\left(\int z^2dm + f\int xzdm\right).$$

Weight ascribed to the sliding arc is proportional to the depth of snow and inversely proportional to $\cos\alpha$. (The product $\gamma h \cos\alpha$ may be called the specific snow load on the slope.) In practice the depth of the snow cover is considerably less than the minimum value of the z coordinate, and the calculation of moments of inertia of the sliding arc may be substituted by the calculation of moments of inertia of the area of the longitudinal cross-section of the snow mass:

$$P_x = \sigma_p d_0 \cos\alpha_0 + cX - \frac{\gamma}{r^2}\left(\int xzds - f\int z^2ds\right),$$

$$P_z = \sigma_p d_0 \sin\alpha_0 + cZ - Q + \frac{\gamma}{r^2}\left(\int z^2ds + f\int xzds\right),$$

where ds is unit area.

If the water equivalent is constant, the equations will assume the following forms:

$$P_x = \sigma_p d_0 \cos\alpha_0 + cX - \frac{w}{r^2}\left(\int xzdx - f\int z^2dx\right),$$

$$P_z = \sigma_p d_0 \sin\alpha_0 + cZ - Q + \frac{w}{r^2}\left(\int z^2dx + f\int xzdx\right),$$

i.e. determinations are made of moments of inertia of the arc with variable weight $d\iota = \frac{dx}{\cos\alpha}$. If the arc is ascribed a constant weight numerically equal to its length, it becomes necessary to determine the moments of inertia of the highest order:

$$P_x = \sigma_p d_0 \cos\alpha_0 + cX - \frac{w}{r^3}\left(\int xz^2dl - f\int z^3dl\right),$$

$$P_z = \sigma_p d_0 \sin\alpha_0 + cZ - Q + \frac{w}{r^3}\left(\int z^3dl + f\int xz^2dl\right).$$

For constant water equivalents, the moments of inertia may be determined analytically:

$$\int xzdx = \int_{x_1}^{x_2} \sqrt{r^2 - x^2}\, xdx = \frac{1}{3}\left[(r^2 - x_1^2)\sqrt{r^2 - x_1^2} - (r^2 - x_2^2)\sqrt{r^2 - x_2^2}\right] =$$

$$= \frac{1}{3}(z_1^3 - z_2^3) = \frac{Z}{3}(z_1^2 + z_1 z_2 + z_2^2);$$

$$\int z^2 dx = \int_{x_1}^{x_2} (r^2 - x^2)\, dx = r^2 X - \frac{1}{3}(x_2^3 - x_1^3) =$$

$$= r^2 X - \frac{X}{3}(x_1^2 + x_1 x_2 + x_2^2).$$

(Factor 1/3 $(x_2^3 - x_1^3)$ is the moment of inertia $\int x^2 dx$ relative the Z axis.)

The moments of inertia may be expressed in terms of the area and the radii of gyration:

relative the X axis $\int z^2 ds = i_x^2 s;$

relative the Z axis $\int x^2 ds = i_z^2 s;$

relative the X and Z axes $\int xzds = i_{xz}^2 s.$

When h is constant, the determination of the radii of gyration is quite simple:

$$i_x^2 = r^2 - \frac{x_1^2 + x_1 x_2 + x_2^2}{3} = r^2 - i_z^2,$$

$$i_z^2 = \frac{x_1^2 + x_1 x_2 + x_2^2}{3} = r^2 - i_x^2,$$

$$i_{xz} = \frac{Z}{X}\,\frac{z_1^2 + z_1 z_2 + z_2^2}{3}.$$

It is evident that $i_x^2 + i_z^2 = r^2$, i.e. these two radii of gyration are projections of the radius of the sliding arc and determine a certain point on the latter.

Returning now to equations (1) and (2), we may write:

$$P_x = \sigma_p d_0 \cos\alpha_0 + cX - \gamma s \frac{i_{xz}^2 - f i_x^2}{i_x^2 + i_z^2},$$

$$P_z = \sigma_p d_0 \sin\alpha_0 + cZ - Q + \gamma s \frac{i_x^2 + f i_{xz}^2}{i_x^2 + i_z^2}.$$

Having determined the projections of force P in the given cross-section, we can find this force $P = \sqrt{P_x^2 + P_z^2}$ and the angle formed by vector $\overline{P}$ with the horizontal or vertical axis, e.g.: $\operatorname{tg}(\widehat{\overline{P}, x}) = \frac{P_z}{P_x}$. . The line of action of force P can be determined completely if the moment M: $p = \frac{M}{P}$ is known and where p is the arm of vector $\overline{P}$ relative to point O.

In equations (1) and (2) and in all equations that follow, the integrals $I_1 = \int_l \gamma h' \cos\alpha\,(\sin\alpha - f\cos\alpha)\,dx$ and $I_2 = \int_{l'} \gamma h \cos\alpha(\cos\alpha + f\sin\alpha)dx$ are analytical expressions of the resultant of bearing reactions with allowances for friction forces.

The modulus of this resultant $|\overline{R}| = \sqrt{J_1^2 + J_2^2};$ for a round cylindrical surface and constant unit weight is:

$$|\overline{R}| = \frac{\gamma s}{l_x^2 + l_z^2}\sqrt{(l_{xz}^2 - f l_x^2)^2 + (l_x^2 + f l_{xz}^2)} = \\ = \frac{\gamma s}{l_x^2 + l_z^2}\sqrt{(1+f^2)(l_x^4 + l_{xz}^4)}$$

or in a different way:

$$|\overline{R}| = \frac{\gamma s}{z^2 \cos\varphi}\sqrt{l_x^4 + l_{xz}^4}.$$

The resultant forms an angle with the vertical axis:

$$\operatorname{tg}\left(\overline{R}\,\widehat{,}\,z\right) = \frac{\int_l \gamma h \cos\alpha\,(\sin\alpha - f\cos\alpha)\,dx}{\int_l \gamma h \cos\alpha\,(\cos\alpha + f\sin\alpha)\,dx};$$

for a circular cylindrical surface:

$$\operatorname{tg}\left(\overline{R}\,\widehat{,}\,z\right) = \frac{l_{xz}^2 - f l_x^2}{l_x^2 + f l_{xz}^2}.$$

Since the moment of this resultant relative to a point O is also known from equation (3), it is possible to determine the arm of the resultant, i.e. to determine fully the line of its action.

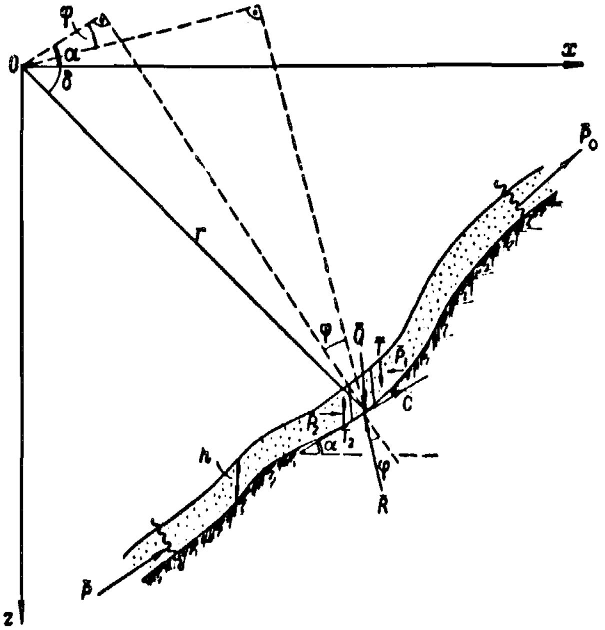

Fig. 1

EQUATIONS OF THE MOTION OF SNOW AVALANCHES

by

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Equations are deduced for the motion of an avalanche of arbitrary form and for the motion of an avalanche whose mass remains almost unchanged, and which moves along a plane path approximating the arc of a circle. Methods of calculating the motion of jumping avalanches are also considered.

The motion of snow avalanches is determined by a fairly large number of factors, the majority of which cannot be accounted for in calculations without certain assumptions. Therefore, theoretically precise but complex formulae of motion have no special advantages over simpler equations.

Summing the energies of the avalanche body and the snow cover forming the avalanche results in a very simple equation:

$$T - T_0 = A_Q + A_R - a, \tag{1}$$

where T is the kinetic energy of the avalanche at a given point on its path (at the beginning of the path $T_o = 0$); $A_Q = \int_S \bar{Q} d\bar{s}$ is the work due to gravity; $d\bar{s}$ is the unit length of path; $A_R = \int_S \bar{R} d\bar{s}$ is the work required to overcome the resistance forces along the path, which is at an angle φ to the normal; α is a correction to the work associated with the path resistances which depends on the velocity (mixing of snow, air resistance, centrifugal forces on curved portions of the path, etc.); the latter may be omitted in calculations concerning avalanches moving with moderate velocities.

Having expressed the kinetic energy of each unit volume of the avalanche in terms of mass and velocity, we obtain:

$$T = \frac{1}{2} \int_M v^2 dm,$$

and from this we can obtain the average velocity of the avalanche for a given direction:

$$v_{\text{cp}}^2 = \frac{2T}{M}.$$

Since

$$dm = k \frac{\gamma}{g} h dF,$$

$$T = \frac{1}{2} \int_F k v^2 \frac{\gamma}{g} h dF, \tag{2}$$

where k is a coefficient which indicates the proportion of the snow mass (in terms of depth) that came down as an avalanche; γ is unit weight of snow; h is the depth of snow; g is acceleration due to gravity; dF is the projection on a horizontal plane of the inclined area; F is the projection on a horizontal plane of the area of the snow mass which came down as an avalanche.

The mass of the avalanche is equal to the total mass of snow brought down from the section F and may be expressed as follows:

$$M=\int_F k\frac{\gamma}{g}h\,dF. \tag{3}$$

The boundaries of the unstable snow cover which forms an avalanche may be found by calculations based on statics as follows. The lower and the upper limits of the angle of the slope on which the snow will be in a state of unstable equilibrium are found from the equation of equilibrium of an elementary prism for the given depth and physico-mechanical properties of snow in the critical layers. The boundaries of the unstable snow are determined from these angle of slope and are traced on a topographical map. It is necessary to add to this the area of the snow cover which, presumably, also will be brought down by the moving avalanche. In calculations using the data on avalanches which have already occurred, this area is taken directly from maps or aerial photographs of avalanches.

Within the confines of a section with an unstable snow mass, the avalanche moves with positive acceleration, and outside this section with negative acceleration. The work of the force of gravity A_Q does not depend on the geometrical form of the path and may be expressed as the difference of potential energies of the avalanche between the initial and given stages.

$$A_Q=\int_F k\gamma hH\,dF, \tag{4}$$

where H is the height of fall (vertical) of each element of the snow cover (Fig. 1).

The work of the resistance forces is determined as an integral of the scalar product of the vectors of reaction force $\bar{R}$ and the unit length of path ds, which together form the angle $90^\circ + \varphi$ ($\varphi = \operatorname{arctg} f$, where f is the coefficient of resistance):

$$dA_R=\int_s R\cos(90^\circ+\varphi)\,ds=$$

$$=-\int_s R\sin\varphi\,ds=-\int_s R\frac{\operatorname{tg}\varphi}{\sqrt{1+\operatorname{tg}^2\varphi}}\,ds=-\int_s fR\cos\varphi\,ds.$$

Since R cos φ represents a reaction normal to slope related to weight Q by the equation N = Q cos α, the integral assumes the following form:

$$dA_R=-\int_s fQ\cos\alpha\,ds=-\int_s fQ\,dx,$$

where dx is the horizontal projection of the unit length of path, and α is the angle of the slope to the horizontal.

Each element of the snow cover which has descended as an avalanche follows its own path, not known to us beforehand and largely incidental. We may arbitrarily take the maximum possible displacements as being from the starting point to the avalanche deposit zone, the whole of which is assumed to be located at a certain level (in practice it will be located on an inclined surface with a fairly gentle slope).

Then the work of resistance forces will be equal to:

$$A_R = -\int_F dF \int_s kf\gamma h dx. \qquad (5)$$

By substituting this into (1) we obtain:

$$T = \frac{1}{2g}\int_F kv^2\gamma h dF = \int_F k\gamma h H dF - \int_F dF \int_s kf\gamma h dx - a.$$

If we assume that k, f and $\gamma h = w$ (w is water equivalent of the snow mass) are constant and ignore the correction factor α, this will considerably simplify the equation:

$$T = \frac{kw}{2g}\int_F v^2 dF = kw\int_F H dF - fkw\int_F dF \int_s dx$$

and after reduction:

$$T = \frac{1}{2g}\int_F v^2 dF = \int_F H dF - f\int_F dF \int_s dx.$$

Since:

$$v_{\text{cp}}^2 = \frac{2T}{M} = \frac{\frac{kw}{g}\int_F v^2 dF}{\frac{kw}{g}\int_F dF} = \frac{\int_F v^2 dF}{F},$$

$$T = \frac{1}{2g} v_{\text{cp}}^2 F = \int_F H dF - f\int_F dF \int_s dx, \qquad (6)$$

From this we can find the average velocity.

The geometrical meaning of the integral $\int_F HdF$ is the volume of a body bounded above by the section of the slope from which the avalanche has descended, from below by a plane at the level of the given point on the trajectory, and from the sides by a cylindrical (in a general sense) surface. If we assume that the lengths of the paths of all points of the avalanche differ little from the lengths X of perpendiculars from initial positions of elementary volumes to the axis which cuts across one path of the avalanche at the lower given point perpendicular to the general direction of the path, we find that the geometrical meaning of the double integral is:

$$\int_F dF \int_s dx = \int_F X dF,$$

i.e. it is the static moment of the area F relative to the lower given boundary, determined from the topographical map. This moment can also be expressed in terms of the coordinate of the centre of gravity of the given area x_c:

$$\int_F X dF = x_c F.$$

Similarly, the volume of the body is:

$$\int_F H dF = H_{cp} F,$$

where H_{cp} is the average height of the section, or the height of the centre of gravity of the snow cover above the given level. Equation (6) now assumes an even simpler form:

$$\frac{v_{cp}^2}{2g} = H_{cp} - f x_c,$$

hence

$$v_{cp}^2 = 2g(H_{cp} - f x_c).$$

In the case of a winding avalanche path, the coefficient of resistance should be multiplied by a coefficient that takes this winding into account. It is assumed to be equal to the ratio of the average actual length of the avalanche path to the shortest distance between the fracture area and deposit zone.

If we examine only the initial and final states of the avalanche, then

$$v = 0 \text{ and } H_{cp} - f x_c = 0.$$

From this we can determine the coefficient of resistance:

$$f = \frac{H_{cp}}{x_c} \text{ or } f = \frac{\int_F H dF}{\int_F X dF}.$$

The latter expression is more convenient, since the volume and the static moment can be easily determined by approximate methods.

In a general case, where the deposit of the avalanche is not all at the same level, it is possible to find the centre of gravity of the deposit and of the snow cover in its original position. The tangent of the angle of incline of the straight line connecting these points may be regarded as the coefficient of resistance. The same should be done when the water equivalent of the descended snow mass is not constant throughout its area.

On the other hand, in some cases the calculations are considerably simplified.

In the case of an avalanche with a constant width, the coefficient f may be determined as a ratio of the area of a two-dimensional figure formed by the profile of the path (i.e. the vertical from the initial point and the horizontal from the terminal point of the path) to half the horizontal projection of the distance between the fracture area and the deposit zone.

In the case of a trough-like avalanche with a large initial mass and a long run, where the increase in the mass and the fracture area can be ignored, we obtain:

$$f = \frac{H}{X},$$

where H is the height of the fracture point above the deposit of the avalanche, and X is the projection on a horizontal plane of the avalanche path.

This ratio is given in the paper by M.B. Barban(1). The agreement between experimental results concerning the movement of an avalanche obtained by different methods indicates that a trough-like avalanche with a large initial mass may be regarded as a material point (that is, we may describe the movement using the centre of the masses for calculations). The same follows also directly from the aforementioned arguments.

If we consider the resistance of the medium, the movement of the centre of the mass of an avalanche is described by differential equations, which can be solved analytically only in particular cases(2). The differential equation for an avalanche moving along a flat path with a constant radius of curvature ρ (Fig. 2) is as follows:

$$-I\frac{d\omega}{dt}=\rho\,|mg\sin\alpha-fm(g\cos\alpha+\omega^2\rho)-k_1\omega^2\rho^2|, \tag{8}$$

where I is the moment of inertia of the avalanche relative to the centre of curvature, which is equal to $m\rho^2$ when the dimensions of the avalanche are relatively small compared with ρ; ω is the angular velocity of the avalanche (there is no translational motion in this case); α is the angular coordinate of the centre of mass of the avalanche; f and k_1 are coefficients of resistance to the movement (f is analogous to the coefficient mentioned earlier); other factors are as before, The ratio $\frac{k_1}{m}$ is assumed to be constant.

This is a second order equation relative to α. We now reduce the order, having multiplied and divided the left part by $d\alpha$:

$$-m\rho^2\frac{d\omega}{d\alpha}\frac{d\alpha}{dt}=\rho mg\sin\alpha-\rho fm(g\cos\alpha+\omega^2\rho)-\rho k_1\omega^2\rho^2;$$

after reduction and modifications, we obtain a heterogeneous, linear, first order equation relative to ω^2:

$$-\frac{d\omega^2}{d\alpha}+2\left(f+\rho\frac{k_1}{m}\right)\omega^2=2\frac{g}{\rho}(\sin\alpha-f\cos\alpha)\,. \tag{8a}$$

We then solve the corresponding homogeneous equation:

$$-\ln\omega^2+2\left(f+\rho\frac{k_1}{m}\right)\alpha+\ln\tilde{C}=0.$$

By taking for the sake of simplicity

$$2\left(f+\rho\frac{k_1}{m}\right)=k_0,$$

we vary the arbitrary constant $\tilde{C}$ and obtain:

$$\omega^2=\frac{2g}{(k_0^2+1)\rho}|(k_0+f)\sin\alpha-(fk_0-1)\cos\alpha|+\tilde{C}e^{k_0\alpha}.$$

The constant of integration is determined from initial conditions: $\omega = \omega_0$ at $\alpha = \alpha_0$.

$$\tilde{C}=\omega_0^2e^{-k_0\alpha_0}-\frac{2g}{k_0^2+1}\frac{e^{-k_0\alpha_0}}{\rho}[(k_0+f)\sin\alpha_0-(fk_0-1)\cos\alpha_0].$$

On converting to linear velocity, we obtain

$$v^2 = \frac{g}{b}(\sin\alpha - f_{\text{пр}}\cos\alpha) + \\ + \left[v_0^2 - \frac{g}{b}(\sin\alpha_0 - f_{\text{пр}}\cos\alpha_0)\right]e^{-k_0(\alpha_0-\alpha)}, \tag{9}$$

where

$$b = \frac{1}{2\rho}\,\frac{1+k_0^2}{k_0+f}, \quad f_{\text{пр}} = \frac{k_0 f - 1}{k_0 + f},$$

the angles α_0 and α are measured in radians from the vertical.

If we solve the equation relative to the angular coordinate α, we arrive at the following equation

$$\alpha_0 - \alpha = \frac{1}{k_0}\ln\frac{a_0 - bv_0^2}{a - bv^2}, \tag{9a}$$

where

$$a_0 = g(\sin\alpha_0 - f_{\text{пр}}\cos\alpha_0),$$
$$a = g(\sin\alpha - f_{\text{пр}}\cos\alpha),$$

or for the distance travelled by avalanche snow expressed in linear units:

$$s = \frac{\rho}{k_0}\ln\frac{a_0 - bv_0^2}{a - bv^2}. \tag{9b}$$

For a straight path, when $\rho \to \infty$, $\alpha_0 = \alpha$, $b \to \frac{k_1}{m}$, $\frac{k_0}{\rho} \to 2\frac{k_1}{m} = 2b$, $f_{\text{пр}} \to f$, and equations (9) and (9b) assume the following form:

$$v^2 = \frac{a}{b} + \left(v_0^2 - \frac{a}{b}\right)e^{-2bs}, \tag{10}$$

$$s = \frac{1}{2b}\ln\frac{a - bv_0^2}{a - bv^2}. \tag{10a}$$

The equations (10) and (10a) are similar to the equations for the movement of the avalanche given in the paper by S.M. Kozik(2) and in papers by foreign investigators(4), where they are given in parametric form.

$$v = v_{\max}\,Th\left(\frac{v_{\max}t}{k}\right),$$

$$s = k\ln Ch\left(\frac{v_{\max}t}{k}\right),$$

where $v_{\max} = \sqrt{\frac{a}{b}}$ is the maximum velocity of the avalanche; $k = \frac{1}{b}$ is a certain constant coefficient with dimensions of length; t is time. These equations correspond to the differential equation:

$$\frac{dv}{dt} = g(\sin\alpha - f\cos\alpha) - bv^2,$$

if we ignore the suspending effect of air in sufficiently compact snow.

In spite of the relative complexity of equations (9), (9a), and (9b), their use may be easier than a systematic application of the equation given in the Proceedings of Research Institute of Construction, or equations (10) and (10a) for straight sections, for which it would have been necessary to break up the profile of the slope into a number of straight sections where it is curved. Combined use of equations is also possible, if the path can be represented in the form of a few adjacent straight sections and arcs.

The distance travelled by avalanche snow is determined from equation (9a) by successive approximation. If it is essential to determine whether under given conditions the avalanche will reach a certain point at the foot of the slope, it is sufficient to calculate its velocity (to simplify the calculations, nomograms from adjusted points or grid nomograms with a transparent visor may be constructed). A minus sign in front of v^2 will indicate that the avalanche will not reach a given point.

Equation (9) is also valid for a convex section of the trajectory, if the radius of curvature is given a negative sign. In this case, it is essential to check the calculated velocities to determine if the avalanche will jump (break away from the substratum):

$$v^2 > g\rho\cos\alpha . \qquad (11)$$

In a free fall, an avalance is subject to air resistance only. The differential equations for a jumping avalanche in the form of a sufficiently compact mass of snow are as follows:

$$\frac{d^2x}{dt^2} = -kvv_x \quad \text{and} \quad \frac{d^2z}{dt^2} = g - kvv_z \qquad (12)$$

or

$$\frac{dv_x}{dx} = -kv \quad \text{and} \quad v_z\frac{dv_z}{dz} = g - kvv_z . \qquad (12a)$$

These equations will give the trajectory and the components of velocity at the point with the given coordinates x and z. The point of intersection of the trajectory with terrain is determined graphically.

Generally speaking, the easiest way to calculate the velocity of a jumping avalanche is by means of a very simple equation used abroad(3):

$$v^2 = 2gS\sin\alpha\frac{\gamma-\gamma_0}{\gamma} ,$$

where S is the length of the section, γ and γ_0 are unit weights of snow and air respectively, and α is the angle of slope of the section.

It is evident that this equation is equivalent to:

$$v^2 = 2gH\frac{\gamma-\gamma_0}{\gamma} , \qquad (13)$$

where H is the height of the fall of the avalanche.

In the case of sufficiently compact snow, we obtain a value close to the maximum velocity for a body falling in a vacuum:

$$v^2 = 2gH .$$

Equation (13) may be used, first of all, in the case of avalanches with a small mass and a large volume (powder snow avalanches); when calculating the velocity of avalanches of more compact snow, the values obtained will be on the high side. As far as the distance travelled by a jumping avalanche is concerned, the air resistance plays an important role and therefore the equations similar to (12) and (12a) may be useful.

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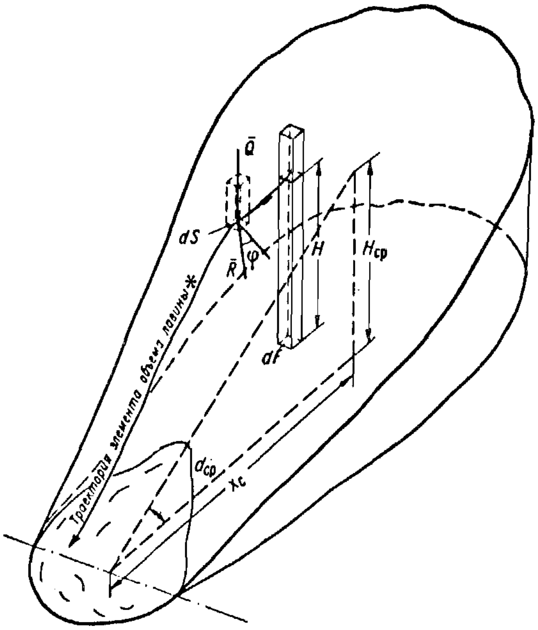
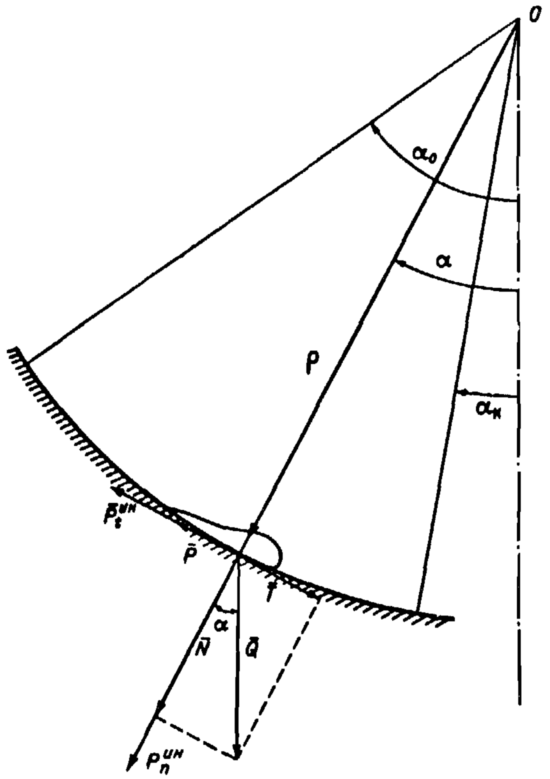


* Path of unit volume of avalanche

Fig. 1


0
α_0
α
ρ
$\alpha_к$
$\bar{P}_t^{ин}$
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α
$\bar{N}$
$\bar{Q}$
$P_n^{ин}$

Fig. 2

PREDICTION OF AVALANCHES

by

K.S. Losev

A description is given of a genetic classification of avalanches developed by the author. Existing methods of predicting the avalanche hazard are analysed and new methods suggested.

The development of methods for the prediction of avalanche hazards is an important problem, the solution of which would create safe conditions for work and traffic in avalanche-prone regions.

The term "prediction of avalanches" is interpreted by some authors (9,11) as the determination of the places of avalanche descent. Such interpretation does not correspond to the generally accepted meaning of the term "prediction" as used in meteorology and hydrology, where it means the ability to foresee the development of a phenomenon in a given place well before its actual occurrence. Therefore the term "prediction of avalanches" should be interpreted as a scientifically sound forecast of the time of formation, nature and size of avalanches.

It is essential to distinguish between the following aspects of the prediction of avalanches: 1) prediction of the time of occurrence of an avalanche (i.e. foreseeing in good time the moment when an avalanche will occur in a given avalanche-prone area); 2) the prediction of the beginning of the period of avalanche hazard (i.e. timely forecasts of the period when a dangerous situation arises in an avalanche-prone area and a slight additional disturbance of snow may cause an avalanche). Both types of predictions may be also used for a particular region where there are many avalanche sites. In this case they should be called regional forecasts of the time of avalanche descent, and a regional forecast of the onset of a period of avalanche hazard, respectively.

The predictions of avalanches may be subdivided into qualitative and quantitative predictions. The qualitative predictions do not make it possible to determine precisely the onset of the period of avalanche hazard, or the moment of descent. The quantitative predictions provide information on the onset of the danger period and the moment of descent.

For a systematic development of methods of predicting avalanches, it is essential to have a genetic classification of avalanches. An attempt to develop such classification was made by V.N. Akkuratov(2,3). His classification is the first genetic classification of avalanches and as such reveals a series of shortcomings. The genetic principle is not fully borne out in it. For example, the subdivision into classes (dry and wet avalanches) is based not on the genetic principle but on the condition of the snow. It follows from this classification that avalanches of new snow cannot be wet, while such avalanches are quite common in the Caucasus and the mountains of Central Asia. The classification does not account for all factors contributing to the formation of avalanches. Finally, the subdivsion of avalanches into types is by far not uniform. For example, together with the type of avalanches of new and drifting snow, which owe their origin directly to meteorological factors, the dry avalanche class contains also the type of avalanches resulting from metamorphism, i.e. avalanches which owe their origin to processes, which take place within the snow cover and are not directly connected with meteorological factors.

The genetic classification presented here (Table I) is an attempt to rectify the shortcomings of Akkuratov's classification.

The avalanches caused directly by meteorological factors are formed as a result of the following phenomena: overloading of slopes with snow during snowfalls and snowstorms, rain falling on the snow cover, reduction in the strength of the snow cover when temperatures rise during warm spells (Table II), or internal stresses caused by sharp drops in temperature.

The avalanches, caused directly by processes taking place within the snow cover in the absence of melting, result from metamorphism, which reduces the strength of layers, and from weakening of the snow cover by prolonged loading(6).

The avalanches caused directly by meteorological factors, as well as melting processes within the snow cover, result from weakening of the snow cover by melting.

The avalanches caused by incidental phenomena do not result from regular processes within the snow mass and meteorological factors, but from incidental phenomena such as earthquakes, underground blasting, frost heaving of soil, etc.

Avalanches formed as a result of a slight effect of some phenomenon on the snow cover cannot be included in this class. For example, avalanches are sometimes triggered by a loud shout, by snow falling from a tree, by animals crossing an avalanche-prone area, etc. The occurrence of such an avalanche was already prepared by meteorological conditions or processes taking place within the snow mass, and only a slight disturbance was required to set the snow mass into motion.

Under natural conditions, mixed types of avalanches are quite common, for example during snowfalls when a layer of depth hoar is present. With this combination, a relatively small increase in snow depth may be sufficient to cause collapse of the entire snow mass lying above the layer of depth hoar, which has a low cohesion. New snow in such cases provides an additional load resulting in the collapse of the old snow mass.

The classification given here is not final and should be enlarged as new data become available.

There are various methods of predicting avalanches (Table III), since the causes of formation of avalanches differ, as may be seen from their genetic classification.

The simplest methods are those based on the study of the surface condition of the snow cover. There are certain signs indicating that the snow cover on a slope is unstable:

1) Fractures in the snow cover indicate that stresses within the snow mass can no longer be neutralized by plastic deformation and result in the disturbance in the continuity of the snow cover which may start an avalanche. Fractures are characteristic of slab and dry snow.

2) Snow pellets, rolls and folding of the cover indicate that the snow on the slope is unstable. These forms are characteristic of wet snow.

3) Overhanging snow cornices are unstable and they may trigger an avalanche when they break. Large overhanging cornices on ridges are a sign of avalanche hazard.

4) A high moisture content points to weak internal cohesion of the snow cover and negligible cohesion with the underlying surface.

5) A dense wind crust (snow slab), which differs from the surrounding snow by a darker dull colour, may also indicate an avalanche hazard.

6) Large quantities (30 - 50 cm) of new or drifting snow indicate an avalanche hazard.

The aforementioned signs may be used in the field by exploration parties, tourists, mountaineers, and skiers. They render it possible to predict avalanches resulting from processes within the snow cover and from melting.

The method of probing and studying the stratigraphy of the snow cover has been in use for a long time. There are various methods to do this. The simplest of them is testing with the help of probes of various types. An ordinary ski pole may serve as a probe. Special probes are used in the Alps (Paulcke probe, Lindenman probe, Birger probe, etc.). Such probes give an indication of the condition of the snow cover: its depth, presence of layers with a very low resistance to the penetration of the probe, presence of voids, nature of underlying surface, etc. From the rate of penetration of the probe, the resistance of snow to penetration, sound which accompanies the penetration, depth of the snow cover, and nature of the underlying surface, an experienced observer can determine whether the snow cover on a slope is stable or unstable and then give the appropriate warnings, if such are warranted. It is evident that data obtained by means of the penetrometers are subject to human error. It is better to use hardness testers, which give an objective picture of the condition of the snow cover.

From data obtained with the help of a hardness tester, it is possible to construct a curve showing the change in snow hardness with depth. The analysis of the curve and of the corresponding stratigraphic profile of the snow renders it possible to establish the presence or absence of an avalanche hazard. Let us now examine the methods used for the prediction of avalanches in Czechoslovakia(13).

The Czechs use a cone-shaped hardness tester driven into snow by a weight. A detailed probing of the snow cover makes it possible to establish empirical relationships for prediction of avalanche hazards (Table IV).

The stratigraphy of the snow cover is determined simultaneously with probing. Combined diagrams showing the hardness and the stratigraphy render it possible to pinpoint the type of avalanche to expect. The Czechs have also developed standard diagrams showing the hardness and stratigraphy of the snow cover. By comparing them with diagrams obtained in the field, it is possible to determine the type of avalanche to expect. A similar method but without the use of a hardness tester has been developed in the Soviet Union by G.K. Tushinskii as early as 1949.

This method may be used mainly for predicting the avalanches resulting from processes taking place within the snow cover, from snowfalls and snowstorms, as well as from snow melting.

To predict avalanches resulting from weakening of the snow cover, it is essential to have graphical or tabular data on the reduction in the strength of snow with time. However, it is difficult to obtain such data in the field. Furthermore, these curves will vary with the change in temperature and type of snow, as well as metamorphism within the snow cover. Therefore it is essential to search for other methods of predicting avalanches of this type, not based on the strength curves. In this respect the study of settlement of the snow cover appears to be promising.

As is known, the settlement of snow occurs in two ways: 1) by way of gradual plastic deformation without destruction of the structure, and 2) by way of sudden jerky settlement with destruction of the structure. Observations have shown that the pressure of the overlying snow cover is very often not sufficient to destroy the layer containing depth hoar. As may be seen from Table V, the pressure from the snow cover up to 3 m deep does not exceed 110 g/cm^2, while the hardness of snow determined by means of hardness testers exceeds this value.

We should also consider that a hardness tester has a cone-shaped head and the hardness of snow measured with a flat plate would be higher. Nevertheless the settlement of snow occurs even though the hardness of the snow is considerably higher than the weight of overlying layers. This phenomenon may be explained by the reduction in the strength of snow under a constant load with time, which leads to the destruction of the structure and the settlement of snow. The settlement recorded by instruments will indicate the formation of weakened horizons. It is possible to create additional loads on the snow cover on experimental sections where recorders are situated, and in this way determine which loads will result in a settlement. This will make it possible to arrive at certain conclusions concerning the stability of the snow cover on a slope and the possibility of disturbing it.

The genetic classification leads to an important conclusion: any sharp change in the weather increases the avalanche hazard, and the sharper this change, the greater the likelihood of formation of avalanches. Any sharp change in the weather recorded by an observer, such as the beginning of a heavy snowfall, snowstorm, rain, or thaw, or the arrival of clear sunny weather, marks the beginning of a period of avalanche hazard.

It is also essential to utilize the meteorological forecasts of breaks in the weather. For this it is necessary to study the synoptic situations accompanied by heavy snowfalls, snowstorms, thaws, sharp drops in the temperature, rain, etc., which lead to the occurrence of avalanches.

In Central Asia, the most favourable weather conditions for abundant precipitation are as follows: 1) frontal activity along the southern and southwestern parts of Central Asia, when the area in which low pressure systems are forming on an intense globe-circling front extending to high-altitudes is located immediately above Central Asia; 2) frequent cyclones with subsequent regeneration along the fronts of the outbreaks of arctic air, when above the eastern part of Central Asia there is a superposition of three air masses: tropical, temperate and arctic. A detailed description of each of these processes and of what they indicate is given in the paper by V.A. Bugaev et al.(4).

The analysis of synoptic situations preceding and accompanying avalanche formation renders it possible to give a regional forecast for an entire mountain range, or for individual large sections of the latter, ahead of forecasts based on a particular phenomenon, for example, the beginning of a heavy snowfall.

The predictions of avalanches may be made directly from observations of meteorological elements and changes in the snow cover. This method is based on the fact that avalanche formation sets in not immediately after a change in the weather but after a certain time interval required for altering the interrelationships of forces within the snow cover under the influence of the change in the weather. This time interval renders it possible to evaluate these changes. In the case of avalanches directly related to meteorological factors, this time interval is short and therefore the range of the forecast will be short also. In the case of avalanches resulting from a combination of meteorological factors and processes within the snow cover, the range of forecasts will be longer. The theoretical basis of predictions derived from observations of meteorological elements is the well-known equation for the critical depth of snow:

$$h_{\text{к}} = \frac{C}{\gamma(\sin\alpha - f\cos\alpha)}. \qquad (1)$$

The use of equation (1) for the prediction of avalanches during snowfalls and snowstorms and an explanation of theory behind the empirical methods for the prediction of avalanches in the Khibiny Mountains has been described by K.S. Losev(6).

Let us examine the possibilities of using equation (1) for the prediction of other types of meteorological avalanches. It is known from observations that avalanches which descend during a warm spell are related to a rise in temperature which does not necessarily result in melting(9). It is known that the forces of cohesion within the snow mass depend on the temperature. Experiments (Table II) have shown that during a rise in the temperature from -16° to 0°, the shear resistance is reduced approximately by half. This is in good agreement with data obtained by V.N. Akkuratov on the relation between the ultimate tensile strength of the snow and the temperature, and with data obtained in Davos(1). Therefore, during a thaw, factor C in the right half of equation (1) is lower, and consequently formation of an avalanche requires a progressively smaller critical depth of snow. If K and n are coefficients that relate the rate of change in the shear strength to increase in temperature, and ν is the speed at which the zero temperature level progresses through the snow mass expressed in m/hr, then the equation for the prediction of avalanches during a thaw will be as follows:

$$T_{\text{лп}} = \frac{KC_t^n}{\nu\gamma(\sin\alpha - f\cos\alpha)}. \qquad (2)$$

However, the use of equation (2) is difficult at present, since K, n, and γ cannot be calculated as yet. Furthermore, equation (2) does not account for the melting of snow which may take place during a warm spell and will lead to a reduction of the cohesion within the snow mass. Because of this, the forecasts of avalanches resulting from a thaw may be made only for an entire region. In a general form, equation (2) may be expressed as follows:

$$T_{\text{лп}} = F(t_{\text{от}}, \Delta t_{\text{от}}, P), \qquad (3)$$

where t_{OT} is the highest temperature during the thaw, Δt_{OT} is the rate of increase in the temperature during the thaw, and P is the duration of the thaw. It is assumed that C, γ, f and α are constant. This relation forms the basis of a regional forecast during a thaw. If a thaw is forecasted, avalanches should be expected. The more pronounced the thaw, the greater the probability of avalanches, and the higher the number of the latter.

If results of long-term observations are available, the thaws may be subdivided into several types with respect to their duration, rate of increase in the temperature, the highest temperature recorded, or combination of all these factors. The relation between the type of the thaw and avalanche formation may then be determined. As an example of this type of analysis, we include some data on avalanches resulting from a rise in temperature in one of the regions of the Chatkal'skii Range (Table VI).

During a thaw, it is essential to consider also the nature of the weather and the humidity of air. If the humidity is high, it may lead to condensation, which will increase the temperature of the snow cover more rapidly.

Complex phenomena may be observed when rain falls on the surface of the snow cover. Experiments* (Table VII) have shown that a small increase in the water content may increase the cohesion within the snow mass. Evidently, film water which appears in the snow "binds" the snow particles even closer together; some snow settles and becomes more compact. Further increase in the water content loosens the bonds between snow particles, and the particles become suspended if the amount of water is increased. Experiments have shown that a snow column 20 cm high and 50 cm^2 in cross-section fell apart on oversaturation with moisture. It is possible to calculate the amount of water which penetrates to a given snow depth when rain falls on the surface of the snow cover. If the data on the relation between the shear strength and the amount of water in the snow are available, equation (1) may be used to calculate the critical depth of the snow and to predict the moment of avalanche descent. However, in practice, it is not possible to carry out such calculations at present, since the coefficient of permeability of snow and the relation between the amount of water in the snow and its shear strength are unknown. Nevertheless, there are certain empirical data which render it possible to predict the avalanches resulting from rainfall.

On the basis of observations carried out at avalanche stations in the U.S.A., Atwater(12) has established that a water content of about 10% corresponds to critical conditions. Consequently, if the intensity of the rainfall is known when it begins to rain, and assuming that it will not change later, the time interval between the beginning of the rainfall and the setting in of the dangerous period may be calculated from the following formula:

$$T_{\text{лп}} = \frac{\Delta H - \beta}{R}, \qquad (4)$$

---

* The shear strength of the snow cover was determined at about 0°C by the method proposed by G. G. Saatchan(8). Samples were wetted by means of a narrow funnel. The temperature of the water was 2 - 0°C.

where β is the free water content in the snow prior to the beginning of the rainfall, Δ is the critical water content in %, H is the water equivalent of the snow, and R is the intensity of the rainfall.

The methods of predicting avalanches resulting from the spring thaw are close to those described above. It follows from Atwater's argument concerning the critical free water content in the snow cover that after the beginning of melting, a hazardous situation will set in when the amount of melt water in the snow reaches Δ. Therefore, if we know the reserves of water in the snow in a given avalanche-prone area, the sum of mean positive daily temperatures from the beginning of melting $\sum t$, the amount of melting per degree of positive mean daily temperature of the air σ, and the expected mean daily temperatures for the next few days $t_1, t_2 \ldots, t_i \ldots, t_n$, it is a simple matter to determine the onset of the hazardous period from the following equation:

$$\Delta H - \sigma\left(\sum t + \sum_1^n t_i\right) = 0, \qquad (5)$$

where $\sum_1^n t_i$ is the sum of mean positive daily temperatures prior to the time of the forecast. The equation is solved by the selection method. t_1 is added first and if the sum is greater than zero, t_2, etc. are added until the sum is equal to zero. Let us assume that this will happen after adding t_n. Consequently the hazardous period will set in on the n-th day (counting from the day of the forecast).

The avalanches formed during a spring thaw with night frost differ from those described earlier by the fact that on cooling at night, a part of the free water contained in the snow is transformed into the solid state and a dense crust is formed on the surface of the snow which can sometimes support the weight of a man. These two facts are additional factors which favour the retention of snow on a slope. Therefore when using equation (5), it should be remembered that prior to the destruction of the crust the slope is relatively safe. The night crust is usually destroyed by noon and this is the beginning of a hazardous period. When predicting crust-type avalanches, it is also essential to consider the exposure of the slopes.

The mechanism of avalanches due to radiation thaws is similar to that of avalanches described earlier. Melting plays a decisive role in their formation. The author conducted special investigations on the formation of radiation avalanches on the southern slopes of the Kuraminskii range in January 1956. The observations were carried out on a clear sunny day in an avalanche-prone area facing south. The snow structure there was as follows. On top there was a layer of new snow 15 cm deep with unit weight of 0.18 g/cm^3, in which, on careful examination, it was possible to distinguish layers 1.5 to 3.0 cm thick. Next came a layer of old, fine-grained snow 27 cm deep; in the lower part of the profile it gave way to medium-grained snow with a unit weight of 0.32 g/cm^3. The mean daily temperature of the air was -4°C, and the maximum -1.6°C. On the day in question intensive heating by radiation commenced at 10 a.m. and this emphasized the layered structure of the new snow. By noon noticeable wet zones were formed at the layer boundaries, while individual sections of the uppermost layer in the upper part of the slope broke off and rolled down in the form of round lumps up to 10 cm in diameter. By 3 p.m. the most noticeable wet interlayer was formed on the boundary between new and old snow (evidently due to a hothouse effect), and half an hour later the layer of new snow came down in the form of a shield and formed an arching ridge at the foot of the slope.

No quantitative predictions of such avalanches can be made at present. However, on clear sunny days, when the air temperature is negative but close to zero, avalanche formation may be expected on slopes facing south. Our observations have shown that these avalanches descend in the middle of the day or in the afternoon.

A method of predicting avalanches resulting from a sharp drop in air temperature has been examined by V.N. Akkuratov(1).

Under actual conditions, the avalanches often result from a combination of factors, e.g., when a snowfall coincides with a thaw. In such cases, the predictions should account for both factors.

Let us examine a case where a layer with weak cohesion is formed as a result of internal processes within the snow cover. During snowfall, the layer of new snow will create an additional load that disturbs the equilibrium of the snow cover, causing a collapse along the weakened layer. Consequently, the time of avalanche formation will depend not only on the depth of new snow but also on that of old snow h_{CT}.

A weak layer can be easily detected by means of a hardness tester. If it is present, C and f must be determined daily. If it is found that C and f of the layer are lower than C and f at the contact between old and new snow, then sliding of snow along the plane of this layer is more likely. In such cases, the C and f values of the weak layer are used when estimating the onset of the hazardous period. The critical depth of snow will then be:

$$h_{\text{к}} = T_{\text{лп}} l - h_{\text{ст}}. \tag{6}$$

By substituting this equation into equation (1) and after certain modifications, we obtain:

$$T_{\text{лп}} = \frac{C}{l\gamma(\sin\alpha - f\cos\alpha)} - \frac{h_{\text{ст}}}{l}. \tag{7}$$

By assuming that C, γ, f and α are constant, we obtain:

$$T_{\text{лп}} = F(l,\ h_{\text{ст}}); \tag{8}$$

$$T_{\text{лп}} = F(R,\ h_{\text{ст}}). \tag{9}$$

A method of predicting the avalanche hazards has been developed in the U.S.A.$^{(14)}$, which takes into account a combination of factors and represents a further development of the aforementioned method. Ten factors are considered:

1) The depth of old snow. Slopes on which the depth of the snow cover reaches 60 - 90 cm may be regarded as hazardous.

2) The nature of the surface of old snow and the character of the latter. The avalanche may form when: a) there is an ice crust on the surface of the snow, or a snow slab with an underlayer of loose snow; b) a layer of depth hoar is present in old snow; c) the top layer consists of loose snow.

3) Depth of new snow. A hazardous situation sets in when the depth of new snow is about 30 cm.

4) Crystal type of new snow. Pellet snow, graupel, needles, and granular snow favour the formation of a hazardous snow slab. Fluffy, fibrous snow does not form hazardous layers, except when the snowfall is accompanied by strong wind. Stellar snow crystals lead to the formation of avalanches of loose snow.

5) Density of new snow. The average density of new snow is about 0.10 g/cm^3. If the density is lower, the hazard of avalanche formation increases. If it is higher, the hazard decreases.

6) Snowfall intensity. The avalanche hazard is high when the intensity is 2.5 cm/hr.

7) The precipitation intensity. When the precipitation intensity is 2.5 mm/hr and wind velocity is above the critical value, the possibility of avalanche formation is sharply increased. It is also important to consider the period of time during which the precipitation intensity is high. The "intensity factor" is the product of intensity in mm/hr by the duration of the period during which the given precipitation intensity is observed (in hours). The critical intensity factor is 1.00.

8) Wind speed. The critical wind speed is 7 - 8 m/sec. If it is higher, the avalanche hazard is increased.

9) The settlement of snow. When the rate of settlement of new snow is 15 - 20% per day, the snow cover becomes stable.

10) The air temperature. At about 0°C as well as during long periods of low temperatures the avalanche hazard is high. The hazard is especially great in the presence of strong winds which lead to the formation of dangerous snow slabs and layers of depth hoar.

Each of the ten factors is evaluated on a ten-point scale. The sum of all points indicates the extent of expected avalanche hazard. The sum of points may vary between 0 and 100. If the sum comes to 75 - 100, the avalanche hazard is great, if it lies between 0 and 30, the hazard is quite negligible.

An important disadvantage of the described method is the fact that each of the ten factors is given equal weight, while under actual conditions one, two or several factors may prove to be decisive.

Let us examine the following example. Let us assume that the depth of old snow is below 60 cm (i.e. 0 points), the air temperature is moderate and its role is insignificant (0 points), wind velocity is 3 - 5 m/sec (0 points), the surface of old snow is irregular and there are no layers of depth hoar (0 points), the density is normal - 0.1 gm/cm^3 (5 points); there is a heavy snowfall, the characteristics of which add up to 10 points (the expected depth of new snow, type of crystals, the snowfall intensity, the precipitation intensity, and the settlement). The sum of all points will then be 55, i.e. the possible avalanche hazard will be moderate to great. However, the situations close to the one above may result in avalanches of catastrophic proportions, as was the case in the Swiss Alps in January 1951, when the rate of increase in snow depth exceeded 4 cm/hr, while the "intensity factor" exceeded 4.8. A spell of warm weather prevailed in Switzerland at that time which increased the sum of all points to 65, but even this figure does not indicate an avalanche hazard of catastropic proportions.

It is evident from this example that the ten factors used in America for predicting the avalanche hazards are not equally important. They may be subdivided into two groups: 1) passive factors related to the condition of the snow (the depth of old snow, the nature of the surface of old snow and its structure, the density of new snow, the rate of its settlement, the crystal type of snow); and 2) active factors related to meteorological conditions (the depth of new snow, the snowfall intensity, the "intensity factor", the wind speed, the temperature). Hence it would have been better to rate the factors of the first group at, say, half the value of factors of the second group; for example, from 0 to 5 points (first group) and from 0 to 10 (second group). In this case, the total points would have varied between 0 and 75, so that a sum of 50 to 75 points would have indicated a very hazardous situation. Then, in the aforementioned example, the total points (without the thaw) would have been 52.5, and 62.5 with the thaw, i.e. the predictions would have been close to actual hazards. However, even this system of counting the points does not indicate that there is a catastrophic situation, as was the case in Switzerland in January 1951.

There is a special form of avalanches, or a special situation, which may be called catastrophic, or sporadic, according to G.K. Sulakvelidze(9).

This situation is characterized by an unusually large number of avalanches at places where they are not common, which bring down unusually large amounts of snow.

Catastrophic avalanches are infrequent avalanches which reach large proportions and are formed under unusual meteorological conditions. This was first pointed out by G.K. Sulakvedlidze(9). Therefore catastrophic avalanches should be expected when there are unusual meteorological conditions in a region. Let us examine some examples of such situations and avalanches.

As an example of a catastrophic avalanche in the Khibiny Mountains near the city of Kirovsk, we may cite the avalanche which came from a cirque on the northern slope of the Aikuaiventchorr Mountain on the 22nd of November, 1936. This was the largest avalanche between 1933 and 1941. According to various estimates its volume was 250,000 - 285,000 m^3(7). The circumstances of its formation were somewhat unusual for this region. Firstly, a southerly wind persisted for a long time, from December 12th to December 21st. Secondly, wind speed varied between 3 and 12 m/sec and on the night of December 21st increased to 20 m/sec. Thirdly, snowfalls occurred daily during that period which increased the snow depth by 40 cm. Such a combination of strong persistent wind blowing from a direction which was rather unusual for this region, long period of snowfall which resulted in an increase in snow depth unusually large for this region, and a cirque which created exceptional conditions for snow accumulation (under the circumstances) led to the formation of a sporadic avalanche.

As another example we may cite the avalanche which came down the southwestern and the southern slopes of a terrace near the town of Severo-Kuril'sk on the Kurile Islands (data from questionnaires). The terrace forms part of the Vetrenaya Mountain and has an area of 1200 - 1500 hectares. Its average elevation is 135 m above sea level. Its southern and southwestern slopes fall steeply towards Severo-Kuril'sk and the Second Kurile Strait. North and northwest winds, which prevail in this region sweep snow from the surface of the terrace onto the slope. Winds of force 8 form a snow cornice along the edge of the slope, which quickly increases in size when winds exceed this force. The cornice may be 4 to 6 m thick and the width may reach 20 to 25 m. On the 25th of December, 1959, during a wind of hurricane force with speed over 40 m/sec, the edge of the snow cover along the crest of the terrace broke off for a distance of about one kilometre due to overloading. According to local inhabitants, such a large snow slide had not been observed there for at least ten years.

In Western Caucasus, sporadic avalanche situations occurred in the winters of 1911-12, 1931-32, and 1962-63 (A.A. Nasimovich, 1938).

The analysis of all known catastrophic avalanche situations has shown that they are related to unusually heavy and prolonged snowfalls accompanied by strong wind. In fact, a sporadic avalanche situation requires a displacement of unusually large snow masses, often in places where no avalanches have been observed for a long time. In places where avalanches usually occur, large snow masses are accumulated as a result of heavy snowfalls and displacement during snow storms, while snow accumulations in unusual places are due mainly to unusual wind conditions. This leads to the possibility of predicting catastrophic avalanche situations.

It may be seen from the above discussion that at present qualitative predictions can be given for all types of avalanches, while quantitative predictions can be given for those avalanches of the 1st and 3rd classes which are related to meteorological factors and snow melting.

The greatest difficulties are encountered in predicting the avalanches of the 2nd class, which are related to such processes as recrystallization and reduction in the strength of the snow cover under a constant load. No quantitative descriptions of these processes, which would be adequate for prediction purposes, are available at present, although, for example, the recrystallization of snow has been studied for a period of many years. In this respect, much work remains to be done. An important problem is the development of criteria for the evaluation of the reliability of avalanche forecasts.

In general, avalanche forecasts are concerned with probabilities, i.e. predictions of phenomena that may or may not occur. In this respect they are similar to predictions of thunderstorms. Therefore it is hardly correct to regard as false the prediction of an avalanche hazard which was not followed by the descent of avalanches. The state of the snow cover on the slopes may be close to critical and a small external disturbance may be sufficient to set the snow mass in motion. Incidently, investigations being carried out in a hazardous zone may prove to be such a disturbance.

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Table I

Genetic classification of avalanches

Classes of avalanches	Types of avalanches	Time of occurrence	Nature of snow in the avalanche deposit
1. Avalanches caused directly by meteorological factors	1.1 Avalanches caused by snowfalls	Fall, winter, spring	Moist, dry, loose, fine lumps
	1.2 Avalanches caused by snow storms	Fall, winter	Dry, loose, small lumps, slabs
	1.3 Avalanches caused by rain falling on the snow	Spring	Wet, small lumps
	1.4 Avalanches caused by thaws	Fall, winter, early spring	Moist, small lumps, large lumps, slabs
	1.5 Avalanches caused by a sharp drop in air temperature	Winter	Dry, large lumps, slabs.
2. Avalanches caused directly by processes within the snow cover in the absence of melting	2.1 Avalanches caused by recrystallization of snow and formation of layers of depth hoar	Winter	Dry, large lumps, slabs, loose
	2.2 Avalanches caused by a reduction in the strength of the snow cover subjected to a prolonged load	Winter, spring	Dry, moist, loose, small lumps
3. Avalanches caused directly by meteorological factors and melting processes within the snow cover	3.1 Avalanches formed during radiation thaws	Winter, early spring	Moist, loose, small lumps
	3.2 Avalanches formed during spring thaws	Spring	Wet, small lumps, large lumps
	3.3 Avalanches formed during spring thaws with night frost	Spring	Moist, wet, small lumps, large lumps
4. Avalanches caused by incidental phenomena		Fall, winter, spring	All types of snow

Table II

Variation of instantaneous shear strength of snow with temperature

Type of snow	Unit weight g/cm^3	Instantaneous shear strength at -16°C, kg/dm^2	Instantaneous shear strength at 0°C, kg/dm^2
Dry, new	0.12	0.78	0.42
Dry, drifting	0.23	1.86	0.98
Fine-grained, firn-like	0.31	2.34	1.42

Table III

Methods of predicting avalanches

Method	Nature of forecast	Area for which the forecast is valid
Based on external condition of snow cover	Qualitative	Isolated area
Probing and examination of stratigraphy of snow cover	Qualitative	Isolated area, region
Based on sharp change in temperature	Qualitative	Region
Based on synoptic situation before and during the descent of avalanches	Quantitative	Region
Based on variation of individual meteorological elements	Quantitative	Isolated area, region
Based on variation of individual meteorological elements and changes taking place within the snow cover	Quantitative	Same

Table IV

Empirical relation between avalanche hazard and measurements by a conical hardness tester (14)

Hazard	Snow hardness, kg (determined by conical hardness tester)	Ratio of hardness of adjacent snow layers
1. Avalanche may form in immediate future	Below 1.5	Over 4
2. Avalanche may form on mechanical disturbance of the snow cover (additional impulse)	1.5 - 5.0	2.5 - 4
3. Almost no hazard	5.0 - 21	2.5 - 1.5
4. No hazard	Over 21	Below 1.5

Table V

Pressure exerted by snow of various depth on underlying layers (in kg/cm^2)

Unit weight, g/cm^3	Snow depth, m			
	1	2	3	4
0.20	0.020	0.040	0.060	0.080
0.25	0.025	0.050	0.075	0.100
0.30	0.030	0.060	0.090	0.120
0.35	0.035	0.070	0.105	0.140
0.35 (from 0 to 2 m) 0.40 (from 2 to 4 m)	0.035	0.070	0.110	0.150

Table VI

Avalanche formation in relation to intensity and duration of thaw

No. of cases	Maximum mean daily temp.	Av. rate of increase in positive temp. per day	Duration of thaw in days	No. of avalanches
1	4.8	2.4	2	3
2	5.1	2.6	2	8
3	8.8	2.4	4	17

Table VII

Relation between shear strength of snow and the moisture content

Type of snow	Shear strength of snow, kg/dm^2			
	Dry snow	Slightly moist snow	Wet snow, no free flowing water	Wet snow, free flowing water
Fine-grained, unit weight 0.26	0.575	0.780	0.425	0.350
New snow, unit weight 0.21	0.415	0.735	0.330	0.200
Drifted snow, fine-grained, unit weight 0.28	1.220	1.380	0.865	0.510
Medium-grained, unit weight 0.31	1.170	1.290	0.880	0.735

SOME PROBLEMS OF THE MOTION OF AVALANCHES AND OTHER ANALOGOUS PHENOMENA

by

K.S. Losev

Certain assumptions made in deriving the formulae of TNIIS, G.K. Sulakvelidze and D.N. Gongadze (5), and S.M. Kozik (3) are analyzed; the motion of avalanches is compared with certain other analogous phenomena in nature.

For the solution of many practical problems such as the location of structures in avalanche sites, the construction of avalanche defence structures, etc., the speed of motion of avalanches must be taken into account. This problem is extremely complex and, to date, no adequate solution has been found.

In the Soviet Union, three formulae for estimating the speed of avalanches have been put forward; these are the formulae of TNIIS$^{(4)}$, G.K. Sulakvelidze and D.N. Gongadze$^{(5)}$, and S.M. Kozik$^{(3)}$. The author attempts to evaluate the validity of the assumptions made in deriving the formulae and their range of application, but does not compare them or analyze their merits and defects.

The basic assumption made in deriving the indicated formulae is that the motion of an avalanche may be treated like that of a solid body. Is such an assumption justified? In the majority of cases, no. This is recognized by the authors themselves. Thus, S.M. Kozik approximates the motion of a wet avalanche to that of a viscous fluid, and finds as well that a powder snow avalanche also has some features in common with a fluid. Hence, the proposed formulae should not be used for estimating the properties of wet or powder snow avalanches. This leaves only avalanches of snow slabs and cornices. A study of the deposits of slab avalanches shows that the remains of the slabs, if, indeed, they are preserved, are simply inclusions in a powder snow avalanche. The latter is formed by the grinding and disintegration of the snow slabs in the process of their movement. These observations indicate that the proposed formulae apply only to the fall of cornices. In this connection, it should be mentioned that the TNIIS formula was checked experimentally by its originators precisely for the movement of cornices, which were sawn off by means of a cable and, naturally satisfactory results were obtained$^{(4)}$. Information about comparisons of the other formulae with field observations is not available.

The comparison of the motion of an avalanche to that of a fluid body is also an approximation insofar as the avalanche does not move like a fluid over its entire path. Two stages of motion must be distinguished: initial and fluid-like.

The initial motion may consist in the crumbling of loose snow, the sliding of a continuous layer or a layer broken by crevices; or, finally, the rolling descent of snow lumps. In all of these cases the motion is accelerated, new snow masses are involved, the avalanche acquires a more uniform mass and begins to flow as a current, or to move in the form of a stream of powder snow. This is familiar to everyone who has observed the motion of an avalanche. The illusion of motion in the form of a fluid is complete. Such a transition from the crumbling and movement of a layer to a flow or stream of snow is well described by M.I. Anisimov(2), who has observed avalanches over a period of many years.

It appears that for each type of snow there is a certain critical speed at which the change from initial to fluid-like motion takes place. The critical speed is apparently low, of the order of several metres per second. The energy of the avalanche is spent in the destruction of the initial structure and in turbulent mixing of the snow. Loose snow has the lowest critical speed. Anyone who has observed avalanches of loose snow knows that, soon after the start of the movement, a snow cloud appears, sometimes almost instantaneously, and the observer sees the fluid-like motion. Slab avalanches have the highest critical speed, since, for the disintegration process and the formation of a comparatively uniform snow mass, which includes fragments of snow slabs, a much larger force is needed than for avalanches of loose snow. The critical speed for slab avalanches may be estimated.

Snow slabs in motion are subject to air resistance and to impact and friction against the underlying surface. We shall assume that the disintegration of the snow slabs occurs simply as a result of air resistance. Then the speed at which the disintegration of the slabs begins may be determined by solving the inverse problem - at what wind speed does the displacement of snow of various degrees of strength begin? Similar observations have been conducted by many authors. In particular, V.N. Akkuratov(1) established for a snow density of 0.4 - 0.6 g/cm^3 (which corresponds to the density of the snow slabs) that drifting is initiated at a wind speed of 8 - 10 m/sec, and is already considerable at 20 m/sec. Thus, even at an avalanche speed of more than 10 m/sec, disintegration of the snow slabs can occur as a result of air resistance; impact and friction against the underlying surface accelerate the process. Thus, disintegration of the original structure of the slab avalanche and the transition to a fluid-like motion takes place at a speed of the order of 10 m/sec.

The fluid-like part of the motion proceeds like that of an eddy-flow in a viscous fluid. That the motion is turbulent is made manifest by the waves - sometimes frozen into the surface of the deposit itself - which appear on the surface of the avalanche. A clearly perceptible eddying motion can be observed in a powder avalanche.

An indication of the turbulent nature of avalanche motion in the fluid-like stage is the occurrence of various inclusions such as stones, tree fragments, lumps of snow, and the remains of snow slabs. Additional evidence is the damage to trees observed after the passage of avalanches from great heights. The formation of soil-containing debris cones is also caused by the suspension and turbulent intermixing of fine-grained soil in the avalanche. The suspension of heavy inclusions and fine-grained soil is also due to the avalanche flow possessing a certain viscosity.

Thus, if there is motion similar to that of a solid body, or if there is crumbling in the initial stage, a motion analogous to that of a viscous compressible liquid can occur subsequently. The transition from one form of motion to the other occurs after the destruction of the initial structure of the avalanche and the formation of a certain uniform mass and after a certain critical speed provisionally estimated as below 10 m/sec has been exceeded.

As a rule, an avalanche is characterized by an irregular movement. However, in isolated cases, there may be a uniform motion in individual sectors, providing the slope of the sector, the width and depth of the avalanche do not vary, and no snow is deposited or picked up. The uniform motion of a fluid is described by the Chezy formula.

A number of natural phenomena similar to the motion of avalanches in the fluid-like stage are known. These include: 1) katabatic winds, 2) turbidity currents in lakes, reservoirs and oceans, 3) mudflows.

We shall consider the formulae for calculating the motion of certain of these phenomena.

A number of formulae have been devised for calculating the motion of mudflows.

1. Vang's formula:

$$V_c = V_B \cdot \frac{1}{(1+1{,}7\alpha)}. \qquad (1)^*$$

Bearing in mind that the expression $\frac{1}{(1 + 1.7\ \alpha)}$ takes into account the ratio of the volume of detritus to the volume of water, Vang's formula may be written in the general form

$$V_c = C\sqrt{RI}\,(1-\gamma)^{\alpha}. \qquad (2)$$

Here, γ is the unit weight of the mudflow mass.

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* In formulae (1) - (10):

с = mudflow
в = water
Мп = turbidity current
л = avalanche
лп = powdery snow avalanche

2. M.A. Mostkov's formula:

$$V_c = k_c \sqrt{gh(i - i_m)}. \qquad (3)$$

Denoting $kg^{\frac{1}{2}}$ by c and considering that $i_m = f(\gamma,\eta)$ and $h = R$, we write this formula in the form:

$$V_c = c\sqrt{RI}(1-\gamma)^a(1-\eta)^b. \qquad (4)$$

3. S.M. Fleishman's formula:

$$V_c = V_B(1 - a); \qquad (5)$$

considering that $\alpha = f(\gamma,\eta)$, formula (5) may be written in the form

$$V_c = c\sqrt{RI}(1-\gamma)^a(1-\eta)^b. \qquad (6)$$

Kenan calculated the uniform motion of turbidity currents based on the Chezy formula. Johnson(7) also arrived at the Chezy formula, having proposed the following expression for calculating the motion of turbidity currents:

$$V_{мп} = D\sqrt{hIB(\sigma - \rho_0)\bar{\rho}}. \qquad (7)$$

Assuming that $D = c$ and $h = R$, and $B(\sigma - \rho_0)\bar{\rho} = f(\gamma)$, we obtain

$$V_{мп} = c\sqrt{RI}(1-\gamma)^a. \qquad (8)$$

By analogy with the above formulae, in order to calculate the uniform motion of an avalanche, we can write

$$V_л = c\sqrt{RI}(1-\gamma)^a(1-\eta)^b. \qquad (9)$$

Assuming that in the case of a powder snow avalanche the viscosity can be disregarded

$$V_{лп} = c\sqrt{RI}(1-\gamma)^a. \qquad (10)$$

Thus, the calculation of the motion and the model testing of snow avalanches are only parts of a much wider problem - the movement of gravity and drift impregnated flows. This type of motion is widely distributed in nature. It gives rise to intensive erosive activity, especially in mountainous regions. On sea and ocean beds it is the principal factor of erosion. The practical necessity of studying this type of motion is fully understood.

Some observational data on the indicated types of motion are given in Table I.

It is evident from the table that the energy of these phenomena varies. This is due mainly to the difference in the density of the given currents and the difference in the buoyancy effect (flows with open and closed surfaces).

All other conditions being equal, one would expect the greatest destruction from mudflows. However, if the actual scales of the phenomena are considered, greater destruction would be expected from avalanches than from mudflows, since avalanche paths have gradients 5 - 10 times steeper than mudflow paths, and the height of an avalanche front is measured in tens of metres. The scales of turbidity flows in the ocean are greater still. According to Johnson, the height of a turbidity front may reach hundreds of metres.

In conclusion, it should be emphasized that the important geophysical and geographical problem of studying the motion of turbidity and gravity flows, both on the earth's surface and under water is a general one which can only be resolved through the combined efforts of meteorologists, hydrologists and oceanographers.

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Table I

Phenomenon	Max. speeds, m/sec.	Predominant slope angles	Buoyancy	Max. density kg/m^3	Damage to man-made structures
Avalanches	up to 100	30 - 40°	May be disregarded	50 - 500	Destruction of major structures; soil erosion
Katabatic winds	up to 50	5 - 15	0.05 - 0.10	1.10	Destruction of some structures; erosion of soil of low cohesion
Turbidity flows	up to 50	5 - 20	0.10 - 0.20	1,300	Silt erosion; disruption of underwater cables
Mudflows	up to 12	3 - 10	May be disregarded	1,700	Destruction of major structures; extensive soil erosion

EXPERIENCE IN THE USE OF AERIAL PHOTOGRAPHS FOR MAPPING AVALANCHES AND PERENNIAL SNOW

by

K.V. Akif'eva and V.I. Kravtsova

This article presents a method of compiling avalanche maps from aerial photographs together with the results of a comparison of aerial photographic material from surveys conducted at different times of the year.

It is intended to compile a monograph-manual "Avalanches of the U.S.S.R", which will include avalanche distribution maps for individual mountainous regions and for the whole of the Soviet Union. This work will be carried out by the Snow and Ice Laboratory of the Faculty of Geography of the Moscow State University during the next few years.

It is proposed that the prime sources for the compilation of the manual and the avalanche maps should be aerial photographs and topographic maps. The intention is to compile large-scale maps from aerial photographs for standard sectors of different mountain systems, then, from the analysis of the conditions which cause avalanches in standard sectors, together with the analysis of topographic maps, climate, data obtained from literature and field observations, it will be possible to define the areas where avalanches could occur in a mountain system, and from this smaller scale maps will be compiled. In the compilation of large-scale maps, aerial photographs may, and should, be used, not only in the field but also in office processing. This method of compiling avalanche maps was selected on the basis of experience gained in field work and office processing in the Caucasus, the Northern Urals, the Khibiny Mountains and Central Asia. In these areas collaborators from the Snow and Ice Laboratory and the Air Photo Laboratory carried out air photo interpretation in the field and in the office for construction organizations and for scientific and methodological purposes in order to determine the degree of avalanche danger in various sectors, to locate possible construction sites, to ascertain the boundaries of avalanche areas and the lengths of avalanche paths. Methodological work on interpretation was also conducted.

A series of maps was compiled from the accumulated data: "A chart of avalanche hazards in construction areas in the Dombaiskii region" by K.V. Akif'eva and N.M. Malinovskaya; "A chart of avalanche hazards in nine construction areas in the Western Caucasus region", by S.M. Myagkovyi; "Avalanche-mud slide hazards in a sector of the Baksan River valley", by K.V. Akif'eva; "The avalanches of El'brus", by S.M. Myagkovyi; "The avalanche zone on the northern slopes of the Greater Caucasus", by E.A. Leonova;

"A chart of avalanche hazards in the far northern Urals", by N.L. Kondakova; "Avalanche hazards in the Chatkalo-Kuraminskie Uplands", by K.V. Akif'eva.

Experience shows that aerial photographs are convenient to use, both in preliminary and in detailed survey of areas subject to avalanche hazard. The remainder of this article is devoted mainly to the use of aerial photographs in preliminary surveys.

An air photo survey is a convenient basis for maps of avalanche sites.

It is possible to use small-scale aerial photographs to make larger scale charts for heavily wooded and rugged areas, but for treeless, uniform terrain this is difficult.

In order to determine avalanche sites from aerial photographs it is necessary to recognize avalanche identification features. Since the aerial survey is usually carried out during the summer, terrain favouring the occurrence of avalanches and traces of avalanche activity may be identified from photographs.

Conditions which indicate an avalanche hazard and which are reflected in the aerial photographs include:

1. Terrain: a) the incline of the slopes, b) their relative height, c) the forms of relief conducive to avalanche formation (erosion cuts, denudation funnels, deformed cirques and cirques slopes).

In analyzing the terrain for avalanche hazard, it is important that the interpreter should be experienced in field avalanche surveys. Field work on interpretation of avalanche sites in standard sectors is also a requisite. The use of topographic maps is a necessity.

2. Snow cover and features of its distribution connected with wind. Places where snow cornices form are potential sources of avalanches. Snow cornices persist for a long time, leaving behind unique forms of relief (flattened out depressions with waterlogged bottoms), thus making it possible to recognize avalanche hazards indirectly from summer photographs. Cornices may be identified by white, elongated snow patches located on the lee side of crests of ranges and water divides, as well as along the edge of plateaus. If there are no snow patches, the location of cornices may be identified by the dark strip of the waterlogged depression.

Analyzing the above-mentioned conditions from aerial photographs makes it possible to estimate only the possibility of avalanche occurrence in these places. The occurrence of an avalanche is also determined by the weather and the snow, factors which are not evident from aerial photographs.

The most reliable indications of actual avalanche occurrence are the traces of their activity. They appear on the photographs as

1) the remains of avalanche snow, which must be distinguished from snow patches from other sources.

2) evidence of avalanche action on vegetation (destruction of the grass cover, destruction and suppression of forest vegetation, the appearance of deciduous trees in place of coniferous trees, the different ages of trees in areas of avalanche cones of different ages, excessive wetness);

3) traces of the effects of wind blast on vegetation (seen only in forest zones on broken timber);

4) the presence of debris cones in cases where it is difficult to a assume any other cause of cone formation;

5) the presence of micro-relief formed by avalanches on debris cones and slide paths (trough-shaped cuts with ridges along the sides in the case of avalanches in the Khibiny and Caucasus Mountains, and a ridge-and-hollow micro-relief in the path of wet avalanches in the Western Tyan'-Shan).

A combination of all the signs of avalanche hazard is a rarity. Different combinations occur depending on the climate zone or the altitude in which the area is located, and also on the time of the survey, since the state of preservation of the traces of activity changes with time (the cornice and avalanche snow remnants melt, herbaceous vegetation appears, etc.).

It should be noted in identifying avalanche sites that, where some signs of avalanche descent are lacking, it is necessary to take into account the geographical features of the region. For example, it is well-known that avalanches occur in the Northern Urals, although there are no traces of them, and for this reason it is impossible to determine the avalanche distribution pattern without analysis of the wind regime. Knowing that prevailing winds are from west, we can assume that the avalanches occur mainly on slopes with eastern exposure. Another example is to be found in Zabaikal'e where the snowfall is light (i.e. it would appear that snowfall, which is usually the main cause of avalanches, is insufficient), but wind concentrates the snow in such a way that avalanches do occur.

Avalanche identification keys also vary in different mountain regions, although they depend mainly on the altitude and climate zone in which the avalanche develops.

In the alpine belt the hazard of avalanches is present on nearly all slopes. The paths most often followed by avalanches are rock gullies (chutes) and talus. Areas recently freed of snow appear light in aerial photographs. Here there are many patches of drift snow which must not be confused with avalanche deposits. Drift snow patches may be seen on valley floors, in the upper flat portions of valleys (usually in the vicinity of a pass) and in depressions between moraine ridges, in corries and cirques, whereas avalanche snow patches are located at the bottoms of slopes in the form of merged cones. Drift snow patches can be distinguished from avalanche snow patches, by their form, as well as by their location. Drift snow patches usually have smoother, rounder edges than the characterisitic irregular contours of avalanche snow patches.

In the alpine belt, there may be noticed on most summer photographs, traces of summer avalanches on the surface of the perennial snow (dark and white strips on light background) and avalanche cones at the bottoms of the slopes, or on glacier surfaces.

The subalpine belt. At the mouths of tributaries of principal valleys and along ravine bottoms, avalanche snow patches of considerable size remain for a long time, as do traces of cornices in the form of snow patches or small waterlogged grassless depressions. Avalanche traces are not visible for long on alluvial cones following the disappearance of the snow patches, since the ground is rapidly covered with herbaceous vegetation. In aerial photographs, grassless areas of detritus and debris cones recently freed of avalanche snow patches usually appear in a lighter shade than the surrounding grassed slopes. The wet portions of cones and areas of slopes adjacent to cornices are of a darker shade.

Spectrozonal photographs* taken with SN-2 film were used for avalanche identification in the subalpine belt. They provide especially clear definition of vegetation, which is a good indicator for determining the distance travelled by the avalanche: grassless areas appear greenish; grassy areas, reddish-brown; waterlogged areas, dark brown.

The forest zone. Here avalanches are always interpreted by traces of their effects, since avalanches destroy coniferous trees and have an inhibiting effect on deciduous trees. Avalanche paths in a partially wooded avalanche hazard area are identified by lighter strips on a dark background of coniferous forest. Small islands of forest which indicate avalanche-free sectors in avalanche hazard regions may be seen in the form of darker patches. Shrubs and deciduous forest growing in clearings made by avalanches have a finer pattern of a lighter shade than coniferous forest. Avalanche snow on debris cones in the forest zone is rarely observed as late as August and September when the photographic flights are usually carried out.

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* Translator's note: Spectrozonal photography is defined in the Great Soviet Encyclopaedia as the photography of objects in two different zones of the spectrum, including the invisible ultraviolet and infrared zones. Spectrozonal photography is based on the ability of an object to reflect different rays of the spectrum in varying degrees. This makes it possible to obtain two images on two specially sensitized photographic materials. When these images are correlated their details are revealed in great clarity as a result of the difference in image contrast.

The steppe zone. Here, avalanche identification keys are similar to those in the subalpine zone, but avalanches occur rarely and leave fewer traces in the form of snow patches, since at low altitudes the snow melts. Thus, avalanche interpretation from aerial photographs taken in the summer is particularly difficult in this zone.

The time at which the air photo survey is carried out is of great importance for successful interpretation. The results of five photo flights carried out in the spring and summer of 1959 in a sector of the Chatkalo-Kuraminskie Highlands were compared with those of a survey made at a different time of the year.

1. From aerial photographs taken at about the same time as a normal topographic survey (31st of July) it was possible to identify (a) a year-round avalanche danger zone, (b) a zone of avalanche danger in the winter and spring where traces of avalanche activity are well defined, (c) a zone of probable danger in the foothills where traces of avalanches had already disappeared and the forms of relief give rise to doubt as to the possibility of avalanches occurring.

2. The following emerged from an examination of photographs taken on a winter flight (10th of April): a) it was possible to discern all the avalanches which had occurred following the last snowfall and to analyze the nature of their rupture, the characteristics of their paths, and the nature and size of the debris cones; b) it was not possible to determine from these photographs all the possible places where avalanches could have occurred since the area was covered with snow and points of possible avalanche descent were obscured; c) traces of avalanches which had occurred prior to the last snowfall were hidden. An overall picture of the avalanche hazard was not apparent; d) avalanche traces in the foothills, near the snow line, showed up in great detail in the aerial photographs.

Thus, aerial photographs taken in the winter may be used for specific purposes, for ascertaining the pattern of avalanche activity on a particular date, and for determining the extent of avalanche hazard in foothills.

Photographs taken during spring and early summer make it possible to establish from avalanche snow patches the precise locations of avalanches which had occurred during the preceding winter in the middle sectors of the mountains. They do not provide a complete picture of all the possible avalanches.

Several photo flights made in the same year provide the most complete picture of avalanche activity in the preceding winter. However, since some avalanches occur very rarely, the flights made in any one year do not provide a full picture of the hazard in a region.

Work based on several photo flights carried out in one year can, to a certain extent, replace field work, when avalanche descents are determined at the site and their identification signs in the photographs are visible in the field. Since avalanches in winter photographs are fixed by date, then, even though their traces disappear before the end of the summer, the places where they occurred are known and it is possible, by analogy, to identify sites where avalanches did not occur during the past winter as sites where they may occur in future.

The maps of the avalanche hazard of the Chatkalo-Kuraminskii Highlands are based entirely on such an office interpretation of photographs taken on several flights in the same year. The interpretation of a series of photographs shows that: 1) Identification of avalanche sites based on a survey dated 31st of July, when the traces of many avalanches had already disappeared, were justified in the majority of cases. Summer photographs may serve as a reliable basis for compiling maps of avalanche hazard. 2) Probable avalanche sites that are not confirmed by winter photographs, are distributed irregularly: singly in the upper zone, in large numbers in the middle zone, and predominantly in the lower zone, below the snow line (10th of April). Some of the conjectured sites may be attributed to interpretation errors; some may be explained as follows: (a) certain avalanches are not triggered every year and their frequency of occurrence is unknown. Of course, some of the avalanches will occur in following years. This is most likely the case in the upper and middle zones; (b) by the time the photographic flights were carried out (31st of July and 10th of April) the traces of many small avalanches in the lower zone had already disappeared and, therefore, possible avalanche activity could not be confirmed. Photo flights over a period of several years or flights carried out at an earlier time may yield data on avalanche traces in the lower zones of this region.

The map, "An analysis of the interpretation of aerial photographs taken on different occasions", shows that, even in the spring of 1959 when catastrophic avalanche acitivity was recorded in the Chatkalo-Kuraminskii Highlands, avalanches did not occur at all possible sites: some of them occurred at other times during that year.

Using photographs taken on different flights during the same year, it is possible to zone an area by the degree of avalanche hazard (number of avalanches per linear kilometre, volume), by the nature of the avalanches and, partially, by time of occurrence.

Apart from the direct identification of avalanche sites, the interpretation of characteristics of a high mountain region which are linked in some way with avalanches, particularly the interpretation of the perennial snow fields, is of importance. Perennial snow, besides providing material for year-round avalanches, gives an indication of the conditions under which the snow cover is formed. Thus, for example, the snow surface relief makes it possible to determine the direction of the wind and drifting snow, and to evaluate the part played by wind, gravity and other forces in the redistribution of deposited snow.

During work on the IGY programme in the Air Photo Laboratory of the Faculty of Geography of the Moscow State University, considerable experience was gained in the interpretation of perennial snow. Numerous maps were compiled showing the overall glaciological features of one of the regions of the Caucasus and characterizing snow cover and avalanches as feeders of glaciers. One of these charts - snow cover distribution in the ablation period - shows the snow lines on two dates (the beginning and the end of the ablation period), thus revealing its dynamics during this period.

Two types of snow surface were distinguished: areas with an undisturbed surface where, obviously, the fallen snow accumulates without being redistributed, and areas where the surface has been disturbed by the action of the wind and gravitational processes and where the deposited snow is redistributed. Since it is very important to know the redistribution processes when studying accumulation, the map was marked to show snow surface relief forms which indicate these processes and the direction of their action combined into two groups - wind-induced (wind furrows, honeycomb relief, snow tongues on lee sides, snow cornices) and gravitational (snow creep, avalanches). Work on this map led to what in our opinion was an interesting conclusion - from the wind-induced forms of the snow relief it was possible to establish the direction of the surface wind and snow drifting, which by no means always correspond to the wind directions recorded by the meteorological stations.

The principal method of mapping was office interpretation of aerial photographs with selective field correction, the analysts having at their disposal aerial photographs taken on several flights in which different types of film were used for the purpose of making a comparative evaluation. As a result of this we were able to draw a number of conclusions concerning the methods used.

1. Comparison of the different photographic materials* demonstrated the superiority of glass diapositives for interpreting snow and ice surfaces. When viewing the photographs (under a stereoscope on a light table),

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* The following materials were used in the compilation of the charts: a) black and white prints from negatives obtained on "Panchrom" film, b) black and white glass diapositives from negatives obtained on "Panchrom" film, c) colour prints from negatives obtained on three-layered TN-1 colour film.

they permit the finest variations of optical densities in the picture to be noted. This conclusion conforms to an established pattern and is connected with the peculiar susceptibility of human eye to variations of small optical densities, as a result of which the bright surfaces of snow in photographs are interpreted most effectively when viewed with transmitted light.

2. A correlation between field work and office photo interpretation was established, which is of particular importance in high mountains where accessibility is difficult. Office interpretation of snow surfaces holds out great possibilities.

3. The effectiveness of repeated photographic flights was confirmed. This permits the stability of wind-induced forms of snow cover relief to be determined, as well as the dynamics of the snow line and the intensity and nature of the thawing process in different sectors. In this connection it would be interesting to make a comparison of aerial photographs taken at different times of the year in order to determine how accurately the wind-induced relief forms reflect the mean wind directions over a period of several years.

4. A test of the processing of the data from repeated air photo surveys was conducted. The relevant methods are as follows: (a) consecutive processing of the photographs of two flights on an SPR-2 stereoscope. This is the most accurate but most time-consuming method. Its drawback lies in the fact that the small visual field of the stereoscope does not take in a sufficiently large area for interpretation purposes. (b) Optical conversion of the photographs of one flight onto a base representing a clarified mosaic of the second flight, the converted contours being drawn directly onto the mosaic. This method may be employed when great accuracy of planform image is not a major consideration, when the only requirement is to correlate the change in contours for photographs taken on different flights.

A combination of these two methods was used in the compilation of the snow cover distribution chart.

Aerial photographs are of great importance in preliminary investigations of mountainous regions. They are documents which record the condition of a high mountain area on a specific date, permitting the most diverse information about avalanches and their attendant effects to be obtained under office conditions.

A considerable amount of time is saved by working with aerial photographs: the office interpretation of avalanches from 1 : 100,000 scale photographs taken on two flights covering an area of 2,500 km^2, takes 1.5 man-months. The field interpretation of such an area would take more than one field season.

It is evident that air photo survey materials should be widely used in the compilation of the avalanche catalogues drawn up by various institutions of the Hydrometeorological Service of the U.S.S.R.

AN ATTEMPT TO USE ANALYTICAL METHODS TO DETERMINE THE MAXIMUM SPREAD OF AVALANCHES

by
G.A. Vladimirova and A.D. Myagkova

This article describes an attempt to use petrographic, micromorphological, granulometric, spectrum and other analyses to determine the avalanche hazard in a given region.

One of the problems in the investigation of avalanche areas is to determine the maximum spread of avalanches at individual avalanche sites and the boundaries of the avalanche hazard zones.

It is common knowledge that methods of evaluating avalanche hazard based on regional-geographical features, such as the calculation of the maximum spread of avalanches, do not always yield sufficiently accurate results. In the Khibiny expedition undertaken by the Snow, Ice and Avalanche Laboratory of the Faculty of Geography of the Moscow State University an attempt was made to provide an accurate analytical method for regional-geographical investigations which combines a complex of analyses: petrographic, micromorphological, granulometric, spectrum, etc. During the first two years of work the task was to determine the validity of certain theoretical ideas concerning the properties of avalanche deposits and to find the principal qualitative characteristics of these properties.

Fragmental avalanche materials exist even when purely external landscape traces of avalanches have had time to disappear, and it has a number of unique properties:

1) a small area of distribution and a relatively shallow depth;

2) a petrographic composition determined by the petrography of the avalanche accumulation area;

3) a unique texture, also an increase in the size of the fragments from the top of the deposit to its periphery;

4) comparatively little evidence of weathering in the debris (recently carried down from the accumulation area) compared with neighbouring avalanche-free areas;

5) a unique micromorphological nature, in particular, the unavoidable presence of numerous remains of vegetation destroyed by the avalanche;

6) a complex stratigraphy, the presence of buried soil formed during periods of reduced avalanche activity;

7) a unique geochemical nature - as an expression of all the preceding characteristics;

8) the last and most important property for the purpose of determining the boundaries of the avalanche spread - a gradual and regular variation of all the enumerated properties from the top of the cone to is periphery.

Near the top of the cone, the character of the deposits is clearly expressed and may be easily identified. Moving down the cone, the deposits are less clearly defined, decrease in thickness and are gradually lost in the mass of the underlying deposits.

If we find quantitative characteristics of these or other properties of the sediments of that part of the cone where the avalanche features are clearly expressed, then by extrapolation we can find the point at which these characteristics disappear altogether and, moreover, establish the boundary of the avalanche deposits, i.e. of the avalanche hazard area.

Avalanche debris cones in the Yuksporiok River valley were selected for investigation in the first field season, and avalanche debris cones in the Kuniok River valley in the second season. The terrain of the avalanche sites in both valleys is typical of the Khibiny Mountains.

The upper boundary of avalanche sites is at the edges of large plateaus which support stony and moss-lichen tundra. Below, there is usually a belt of low bush tundra merging into mixed birch and spruce forest extending to the very bottom of the valley. Within the forest altitudinal belt, the vegetation of avalanche sites is clearly discernible in the characteristic form of "combings". Here, the original vegetation has been destroyed by avalanches and replaced by small-leaf trees (birch and willow) and herbaceous soil cover. In the Kuniok River valley, exposed stony cones located above the low bush tundra belt were singled out for investigation.

When studying loose deposits and their geochemical properties, it is necessary to take into consideration the characteristic features of soils formed from these deposits and intermixed with them. Like the vegetation cover of the region under consideration, the soil cover is also zoned in a vertical direction. In the forest belt, under a moss-low bush spruce cover which is characteristic of the slopes untouched by avalanches, there are well-developed podzolic humus-alluvial soils, typical of the soil cover of the Khibiny massif.

In several test holes in avalanche debris cones, these soils were found buried under avalanche and avalanche-mudflow deposits. These soils, approximately the same in depth as the present-day deposits, were formed on old avalanche deposits and thus provide evidence of a considerable reduction of avalanche activity for a certain period of time. It is necessary to make a careful study of the buried soils during a general analysis of the stratigraphy and lithology of the avalanche cones together with the paleographic conclusions derived therefrom before the results of the analyses can be interpreted. The present-day soil cover, which is being formed under secondary, small-leaf trees growing in place of the coniferous trees in an avalanche "combing", is made up of soddy-forest skeletal soils. On cones located above the forest belt in the Kuniok River valley the vegetation and soil covers are fragmentary. Grassless areas predominate on the surface of the cones. The soils here are thin, raw, soddy-skeletal with signs of humous alluvial content.

The geomorphological structure of the key avalanche sites are typical of this region. Denuded cones of irregular shape extending down the slope act as avalanche starting zones. Their axes, which are avalanche paths, are straight. The avalanche starting zones have various kinds of surface: rocky, partially sodded, covered with scree. The debris cones of avalanche sites have a more or less regular fan shape. In some cases the cone surface is scarred by mud-stream beds and intermittent streams of water.

The geological formation of the slopes of key avalanche sites is straightforward. The Yuksporiok and Kuniok River valleys cut through a body of alkaline intrusion in the Khibiny massif. In the valley of the Yuksporiok River the country rocks are represented by compact aegirine ristchorrites, apatite-nepheline rocks, compact urtites and trachytoid ijolites. Erratic, allogenic rocks deposited by the Fennoscandian ice cap in the form of moraine are represented by granite, granite gneiss and rocks of the Imandra-Varzuga series.

In the Kuniok River valley there are no erratic rocks, but the composition of moraine and local rocks is the same: ristchorrites (predominantly lavochorrites), spreusteinides, malignites, lujavrites, urtites, etc. The thin layers of detrital material deposited by avalanches had to be distinguished against a background of moraine deposits such as these. Moraine deposits, chaotic at first sight, have a clearly defined grain-size composition, which is an intricate function of the geological structure of regions overrun by glaciers and the bedrock topography. Under the conditions prevailing in the Khibiny Mountains, moraine is transformed by solifluction and rock slides. The petrographic-mineralogical composition of the moraine is related to its texture.

Observations and the collection of material in the key sectors were carried out in two cross-sections: 1) in the avalanche site, from the plateau through the avalanche starting zone and the runout zone; 2) on slopes not subject to avalanche activity. Test holes in these cross-sections disclosed a stratum of loose deposits extending down to the underlying moraine. Samples (10 dm^3) were taken from the soil-forming horizon. The first step in the processing of these samples was a mechanical analysis.

The sinking of the test holes, a careful study of the distribution of loose detrital material on the surface of the cones, collection of samples and their classification by granulometric analysis was the first step in our work in both of the past field seasons and constitutes a separate section in the objectives of the expedition; but, of course, it is closely interwoven with the geochemical investigations.

Some general remarks about the granulometric peculiarities of avalanche deposits will serve to underline its unique and easily recognizable character:

1) a generally high centent of particles larger than 10 mm,

2) a very much smaller content of medium-sized particles between 7 and 5 mm;

3) an increase in the content of 10 mm particles from the top of the cone to its periphery.

A petrographic analysis of the collected samples was carried out simultaneously with the mechanical analysis. This analysis was bound to confirm the assumption that the avalanche deposits are petrographically different from other loose deposits. The larger than 10 mm and 10 - 7 mm particles from all the main horizons were subjected to petrographic analysis. Each particle was broken and identified from a freshly chipped surface. The composition was determined from 25 - 40 to 100 identifications. These investigations showed that the petrographic composition of avalanche deposits is related to that of the starting zone and differs from the composition of the underlying moraines.

The complex of analytical studies of avalanche deposits included also a micromorphological analysis. Samples were taken from the main horizons by means of test holes in avalanche and non-avalanche sections of the Yuksporiok valley. Owing to the extreme friability of the material it was possible to make microsections of only five samples. It was impossible to draw conclusions of a general nature based on a study of these; although, on the whole, the tentative view concerning the uniqueness of the micromorphological nature of avalanche deposits is borne out: the mineral particles of these deposits have acute angles, their mineral content is local (nepheline, zircon, aegirine, apatite), the organic matter is coarse and allogenic.

In order to determine the geochemical character of the avalanche terminus, the sample particles, graded by size, were subjected to spectrum analysis. The content of trace elements was calculated as the weighted average of the contents by particle size.

As a result of the analyses it was found that an avalanche terminus of loose deposits consisting of country rock is distinguished by high contents of Sr and Zr, elements which are morphologically typical of the alkaline rocks of the Khibiny massif.

A characteristic of the non-avalanche moraines is an increased content of Cr, transported here in erratic granite. No regular pattern was detected in the distribution of other elements (Cu, Ni, Ca, etc.) in avalanche or non-avalanche deposits.

It was very interesting to trace the variations in the content of given trace elements in particles and strata in avalanche and non-avalanche test holes. Here, we kept in view the fact that weathering and soil-forming processes are intensive in the upper 20 cm layer, and that in a layer extending down to 50 cm, unweathered deposits predominate (sic).

In the upper layer (0 - 10 cm) of avalanche and non-avalanche deposits the pattern of trace element content is uniform. The Sr content is high in all the particles, with the exception of those under 1 mm. This is explained by the high mobility of Sr in an acid medium, which is characteristic of the local soils.

The content of Zr, which is resistant to weathering, is highest in 3 - 1 mm particles, where it is found in the form of mineral grains. An increased content of Ni, Co, Ba is characteristic of particles under 1 mm.

The pattern of trace element contents in avalanche and non-avalanche deposits differs sharply in the 0 - 50 cm layer. The contents of Sr and Zr, which are elements characteristic of nepheline syenites, are much lower in avalanche deposits than in non-avalanche deposits. The Zr content in 10 - 7 and 7 - 5 mm particles is particularly high. This is explained by the predominance of country rock.

A decrease in the Sr content and an increase in the Ni and Cr contents is characteristic of non-avalanche deposits.

A spectrum analysis of vegetation cuttings did not reveal any substantial difference in the trace element content in avalanche and non-avalanche areas, although it was found that the ash of plants from the latter contains more Cr. Although the rocks contain almost no silver, it is found in plants almost everywhere, a fact which is explained by the well-known capacity of vegetation to accumulate this element.

In order to obtain a picture of the loss and accumulation of elements in the process of rock weathering, we recorded those trace elements which were actually detected in 10 - 7 mm particles, and those which should have been contained in them according to the known petrographic composition of the deposits.

It was found that in avalanche deposits there is an accumulation of Sr amounting to a difference in content of a whole order. Hence, it may be concluded that Sr not only makes the geochemical character of the avalanche deposits unique on account of its high content in the country rocks, but also, in virtue of its geochemical properties, reinforces this character in the weathering process of the fragmental material. The geochemical singularity of avalanche deposits is not lessened but heightened by aging.

In general, the results of the analyses obtained by us make it possible to speak about an avalanche terminus of loose deposits having a unique character, including its geochemical character. In the next stage of the work it will be necessary to raise the question of the dimensional variability of the geochemical properties of the avalanche terminus, i.e. the question of specific criteria for determining the maximum spread of avalanches. In this connection, Sr, Zr and Cr are worthy of attention as possible indicator elements for the Khibiny massif in the Yuksporiok River valley.

The use of chemical, mineralogical-petrographic and other scientific data in avalanche studies, in addition to physical and mathematical data, increases the possibility of determining the boundaries of an avalanche terminus.

EXPERIMENT IN THE USE OF TERRESTRIAL STEREOPHOTOGRAMMETRY FOR ESTIMATING AVALANCHE HAZARD

by

V.M. Famintsev

This article describes an experiment in the compilation of a topographic map, using stereophotogrammetry.

Specialists at the Snow and Ice Laboratory of the Faculty of Geography, Moscow State University, are carrying out investigations aimed at determining the magnitude of avalanche hazard in mountainous regions. These investigations should be used as a basis for an avalanche hazard map. The available small-scale topographic maps of this region are not suitable for this purpose; the terrain is represented in a very generalized form and information on surface conditions is far from adequate for the purpose of characterizing avalanche activity.

Attempts to represent the nature of the avalanche activity in the given region as fully as possible have resulted in a demand for a topographic base with specific features and a decision to produce such a base by special means.

The Air Photo Laboratory in conjunction with the Snow and Ice Laboratory undertook the work of compiling the required topographic base by means of a terrestrial stereophotogrammetric survey.

The selection of the method of survey, was governed by the following considerations: 1) An air photo survey for mapping mountainous regions to a scale of 1 : 10,000 entails complex organization of field and office work. The geodetic field completion work entailed by air photo surveys of mountainous regions is always attended by great difficulties. Field checks of geodetic measurements and point identifications are complicated by the difficulties of travelling in a mountainous region. Air photo surveys of comparatively small areas (100 km^2) are inexpedient on account of these difficulties. 2) The topographic method (plane-table and tacheometric surveys) is also unsuitable, its principal drawback being that the subjective elements in the topographer's work are given too free a rein, particularly in depicting relief. The topographer maps the area on the basis of a certain number of arbitrary vertical points, the contour lines being interpolated by means of visual judgement. Topographic features are smoothed out in the plan view and fine detail is lost. Inaccessible areas are represented inaccurately in the plan. Unfavourable weather conditions, which are frequently encountered in the region of our work, also add to the difficulties. Furthermore, the accuracy of a topographic plan depends not only on the instrument and the individual characteristics of the topographer, but also on the degree of accuracy with which the rodman follows the contours and the relief.

Terrestrial photogrammetry has a number of advantages over the above methods. The processing procedures are arranged so that the accuracy of each step is controlled by the one which follows it. The human element is reduced to a minimum. The processing of the stereoscopic pairs, i.e. relief and contour plotting, is done under office conditions on an automatic instrument. Terrestrial stereophotogrammetry is far simpler than air photo survey, from the technical, as well as the organizational, point of view.

Terrestrial stereophotogrammetric survey materials to a scale of 1 : 10,000 may be utilized to compile a large-scale map without the need for additional field work. The survey photographs are of excellent quality and may be used for identification purposes in the compilation of special avalanche maps and as illustrative material.

As far as cost is concerned, a terrestrial stereophotogrammetric survey in a mountainous area in a small tract of land is considerably cheaper than an air photo survey and two to three times cheaper than a topographic survey. A map compiled by the terrestrial stereophotogrammetric method has the following advantages: 1) exceptionally detailed contouring; 2) highly accurate contouring of inaccessible (rocky, swampy, etc.) sectors; 3) a degree of detail practically unattainable with other mapping methods.

The Khibiny expedition was entrusted with the task of producing a topographic base for the future mapping of avalanche indicators - landform characteristics determined by geomorphological, geochemical, geobotanical and other methods. This topographic base differs from government topographic maps in the following respects:

a) Relief: The relief is shown by contour lines at 20 m intervals. This increase in the contour interval, compared with that of the government topographic maps, arises from the need to leave the topographic base free for the insertion of additional special material. In this connection the drawing of the contour lines acquires a special significance. Altitudes are inserted at characteristic bends in the terrain and at water surfaces. Prominent features in the form of individual rocks are marked. Scarps, water holes and tectonic fissures are indicated by different symbols. Terrain of rolling hills and hollows not expressed by contour lines is designated by a special symbol.

b) Hydrography: Rivers and streams (including those which dry up), fords and crossings, waterfalls and rapids, and springs are marked on the map.

c) Nature of surface: The surfaces of slopes are extremely varied. Alternations of exposed bed-rock, talus, mudflows - this is by no means a full description of the physico-geographical phenomena in the area of operation.

Outcrops of bed-rock are denoted by black contour lines. In some places the bed-rock is covered by a thin layer of fragmentary material through which it can be discerned. In this case, brown triangles are drawn between the mountain contours within the appropriate bed-rock configuration.

Large and small areas of fragmentary material, both on the slopes and in the foothills are indicated by the legend "rock streams".

Fragmentary material deposited by avalanches, mudflows, gravitational washdown; steep banks undercut by rivers; moraine intersected by streams of water, i.e. any fragmentary material which appears "fresh", or rather, rock debris which does not have a covering of desert varnish, is designated by the legend "recent fragmentary material".

d) Vegetation: Vegetation is a very important component of the landscape. The most characteristic sign of avalanche activity is the presence of avalanche combings - trees that have been broken or bent by the passage of avalanches. As a rule, young shoots appear in the area of the combing. This is indicated on the map by a special legend: "broken trees in avalanche combings with young growth . In certain, specially stipulated cases, this may be indicated by vectors representing trees lying separately.

Wooded areas (usually mixed forest), open woodland and brush are denoted by the normal symbols. The brush symbol occurs frequently on the topographic map of the region in which we are working. We are careful not to simplify the contour representing the upper limit of scrub, i.e. we do not straighten it out. As a rule it has a festooned appearance. In the majority of cases these festoons emphasize the presence either of outcrops of bed-rock, or more frequently, rock streams. In some cases the festoon-like appearance of the upper limits of scrub indicates a high degree of avalanche danger on that slope.

"Tundra vegetation" implies different varieties of tundra vegetation; to subdivide it into its various components would be practically impossible.

e) Other designations: Wooden buildings, the ruins of wooden buildings, roads (tractor), tracks, and all the other things which are of little interest to the client or to those carrying out the survey.

A map compiled in this way, in addition to its standard content, contains specific information which will assist glaciogeomorphological specialists to evaluate avalanche conditions in the region in question.

During three months of field work carried out in 1962 in unfavourable weather conditions, approximately 40 km^2 of terrain were photographed, compared with 60 km^2 in two months in 1963. In the latter case the region was familiar to the surveyor and the weather conditions were favourable.

During the office processing period of 1962 - 1963 approximately 25% of the entire survey area was processed. It is proposed to complete another 50% in 1963 - 1964. The remaining 25% represent sectors hidden behind folds in the landscape which did not appear on the field photographs. These so-called "blanks" will be incorporated later either by means of supplementary photogrammetric or plane-table (tacheometric) surveys.

The completed portion of the plan was field-inspected for errors in photo-interpreting the nature of the surface, the state of the vegetation cover, contour boundaries, etc.

In the 1963 field period the checking (field editing) was done on a prepared chart board, mainly for the purpose of clarifying the special content of the uncompleted map. The check showed that details on the plan based solely on field photographs were absolutely correct. More detailed editing will be carried out for the whole of the given area in subsequent field seasons.

Terrestrial stereophotogrammetry is also being used for the solution of other special problems: 1) a large-scale survey of several run-out zones makes it possible to ascertain the number of fragments, and thus their distribution pattern, on a stereoautograph under office conditions; 2) repeated field camera surveys permit determination of the annual increment of fragmentary material in the above-mentioned run-out zones; 3) variations in the surface area of melting snow on mountain slopes also show up well in a successive series of surveys of the same slope.

Maps with a 5 m contour interval are now being produced on a stereo-autograph.

Cartometric work is being carried out with such maps for the purpose of determining certain parameters of avalanche systems, namely, length of chute, size of avalanche accumulation area, longitudinal and cross-sectional profiles, etc.

This by no means represents a full account of the use of terrestrial stereophotogrammetry as a measuring technique in the evaluation of avalanche hazards.

THE STUDY OF THE MECHANISM OF MOTION OF AVALANCHES BY STEREOPHOTOGRAMMETRIC METHODS

by

A.V. Bryukhanov

This article deals with the question of the feasibility of using terrestrial stereophotogrammetry in studying the motion of avalanches.

Further development of the theory of motion of snow avalanches and the improvement of calculation formulae are, at the present time, unthinkable without a detailed study of the motion of avalanches and precise definitions of the parameters of their motion in space and time.

Almost all the methods of observing the process of avalanche motion in nature which avalanche specialists employ today are, as a rule, based on visual determination of the elements of avalanche motion, and are therefore characterized by their subjective nature and by a lack of precision.

Qualitatively new data, free from these defects may be obtained by studying the motion of avalanche by means of terrestrial stereophotogrammetry, using special, automatic, synchronized equipment with remote control.

As is known, ground stereo surveys make it possible to determine an object's position in space, its shape and dimensions from photographs (stereopairs). If we photograph a moving avalanche (observing all the requirements of terrestrial photogrammetry) using two synchronized cameras with a time interval of 1 - 2 seconds between exposures, the process of motion of the snow mass will be fixed by a series of stereoscopic photographs which, when specially processed with stereoscopic instruments, will show the spatial coordinates of the avalanche at specific instants of time, and variations in the shape and size of the avalanche mass while in motion.

Thus, stereoscopic photographs of a moving avalanche make it possible to determine the parameters of avalanche motion (velocity, trajectory, spread) and the deformation of an avalanche mass in motion, these values being expressed by the respective measurements of the spatial coordinates of the avalanche.

From the same photographs we can determine the geometrical elements of the slope, the volume of snow which was brought down and deposited by the avalanche, and a number of other factors.

Since 1962 the Ice, Snow and Avalanche Laboratory and the Air Photo Laboratory of Moscow State University have been working on the design of special apparata for stereo surveys of moving avalanches and the systematization of field work and office processing.

As we know, ground stereo surveys for measurement purposes call for an extremely high degree of accuracy in the execution of the field work, as well as in the manufacture of the survey equipment. Suffice it to say that the inner orientation elements (focal distance, the position of the principal point) of field cameras used in the topographic stereo survey of ground forms should be known to within one hundredth of a millimetre, and the outer orientation of the camera (angle of incidence, horizontal position of axes) should be determined to an accuracy of several seconds.

Besides these general requirements, an automatic synchronized apparatus suitable for stereoscopic photography of avalanches must also satisfy a number of special requirements arising out of the need to operate two cameras simultaneously with a small interval of time between exposures. The above-mentioned laboratories carried out a special analysis of the requirements for such an apparatus. This analysis served as a basis for experimental design work on cameras for stereophotography of avalanches.

The best combination of apparatus for photographing avalanches is, in our view, an arrangement consisting of two automatic synchronized cameras with f = 180 mm and a picture size of 13 cm x 18 cm, fitted with a special command-synchronizing device. These cameras should be fitted with central shutters which obviate motion aberration when photographing fast-moving objects and which give exposures of 1/50 to 1/2,000 sec. The lenses of the cameras must have identical optical characteristics, including a maximum permissible distortion of 0.02 mm at the edge of the image field. The focal lengths of the cameras should not differ from each other by more than 0.11 mm. Aerial film of the appropriate size with a high resolution and a sensitivity of 200 - 500 GOST* units should be used. The operational cycle of the cameras (backwinding of the film, cocking of the shutters, film flattening and exposure) should not occupy more than 1.5 sec. The capacity of the film magazine should be sufficient for 5 minutes continuous operation, the smallest interval of time between exposures being 1.5 sec, which corresponds to 200 frames, or approximately 40 m of film.

The cameras should be fitted with appropriate attachments for inserting frame counter and time readings directly onto the film. The command synchronizing device and console should permit remotely controlled photography with bases up to 1,000 m. The shutters must be synchronized to within 1/50 sec. The time interval between exposures must be constant, accurate to the order of 0.2 sec.

These, briefly, are the special requirements of apparata intended for use in the stereophotography of moving avalanches. If all these requirements are fulfilled, the parameters of avalanche motion may be determined with a fairly high degree of accuracy.

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* Translators note: All-Union State Standard.

The probable error in determining the spatial coordinates of an avalanche was calculated for distances of 2,000 m from a basis of 180 m and with a 3 second interval between exposures. The velocity of the avalanche was assumed to be 40 m/sec. Errors in determining the spatial coordinates of the avalanche M_y, M_x, M_z were found to be ±5.0, 2.2 and 1.5 m, respectively. The error in determining the path traversed by the avalanche during 3 seconds of camera coverage proved to be $M_s \approx \pm 7.2$ m. And, finally, the error in determining the speed of motion by processing adjacent stereopairs was found to be $M_v \approx \pm 2.4$ m/sec. It should be noted that the above errors are mainly due to inaccuracies in photographic measurements, which sharply reduce accuracy in determining the spatial coordinates of the avalanche.

Where it is possible to increase the precision of stereoscopic viewing* of the image of the avalanche body, a much greater degree of accuracy is obtained in the final results. It should be noted that the question of the accuracy of stereoscopic viewing of the photographic image of an avalanche mass has not been studied by anyone. In all our calculations we have assumed this factor to be equal to 0.05 mm, which corresponds to the precision of stereoscopic viewing of a cloud. There is every reason to suppose that for avalanches this figure can be reduced to 0.03 mm, thus increasing the accuracy of the final results by a factor of approximately 1.6.

In 1962 we constructed a working model of an apparatus for stereophotography of avalanches from AFA-39 aerial cameras. With the exception of the focal length and frame size, this apparatus (Fig. 1) meets all the requirements enumerated above. It has the following basic characteristics: focal length of cameras, 100 mm; frame size, 7 cm x 8 cm; magazine capacity, 200 frames; operational cycle, 0.7 sec; smallest interval of time between exposures, 1.5 secs. The entire set of equipment was adapted for manual transportation and rapid assembly. Field tests of this equipment which were carried out in the Khibiny Mountains in the winter of 1962-63 confirmed its reliability in the field in below-zero air temperatures and also the high degree of accuracy of the results obtained with it.

Ways of making further improvements to the apparatus were found as a result of a survey carried out in the Khibiny Mountains.

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* vizirovanie - viewing, sighting (Transl.)

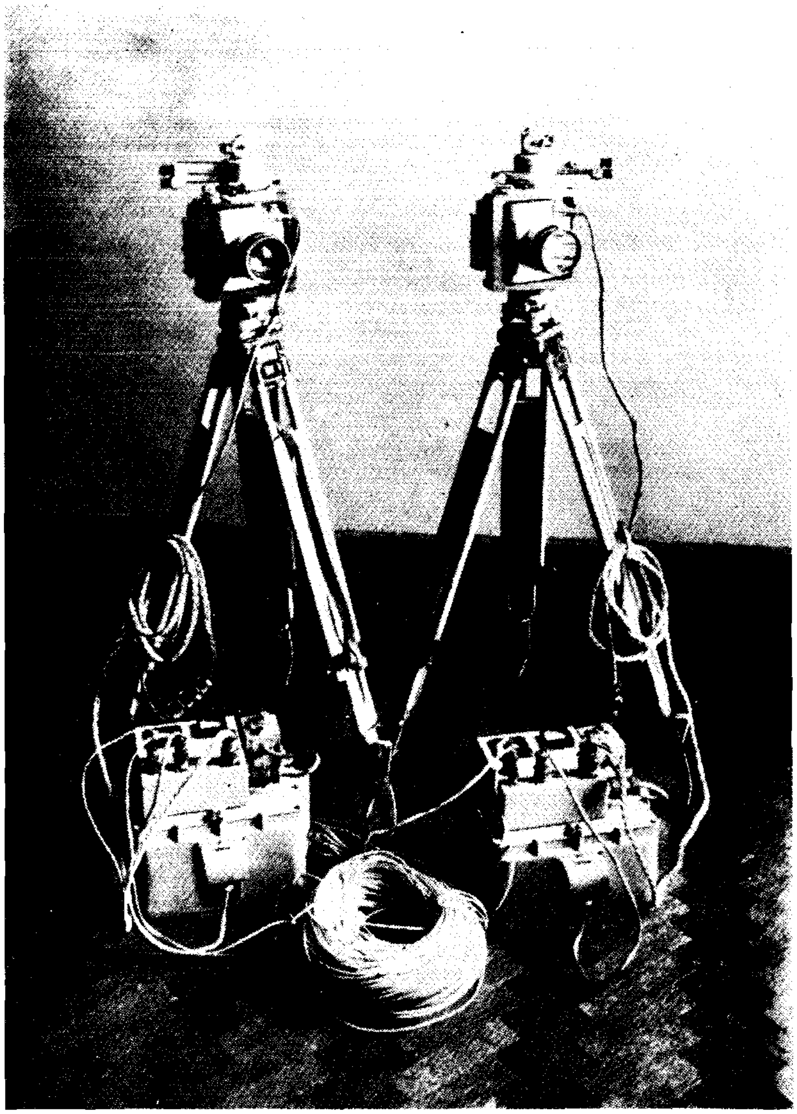

Fig. 1

General view of the apparatus for taking stereo photographs of avalanches

AVALANCHE DEFENCE OF INDUSTRIAL SITES

by
V.S. Kozhevnikov

This article describes the principal measures which require to be undertaken to combat avalanche hazards in the vicinity of an industrial plant.

The rapid growth of industry in the U.S.S.R., particularly in the post-war years, has led to the opening up of new sites in mountain areas. Here considerable difficulties are encountered in the construction and operation of industrial plants, highways, railways, power and communication lines. In addition to problems of a general nature, man has to contend with the danger of avalanches. The tragic results of avalanches are well known. Statistics show that even in a small country like Switzerland as many as 100 people are killed each year by avalanches, and Switzerland is a country where avalanche counter-measures are well-developed.

Avalanches occur at irregular intervals. It is practically impossible to forecast where and how frequently avalanches will occur. We can only say that small avalanches are more frequent than large ones, the latter occurring at intervals of a hundred years or more. Thus, in Switzerland in January 1951, there were instances of buildings which were constructed more than 500 years ago being destroyed by avalanches.

Considerable expense is involved in the setting up of 100% effective avalanche protection for an industrial site. For example, the erection of snow-retaining barriers in an avalanche accumulation area costs from 5 to 7 thousand rubles per hectare. The area of an average-sized avalanche site is usually of the order of several scores of hectares, but an industrial plant may be threatened by avalanches from several avalanche sites. The cost per linear metre of snow shed for road protection is sometimes higher than that of the road itself, and 20-30% of the entire length of the road passing through the avalanche areas has to be protected.

From the above we can gauge how serious the problem of protecting industrial sites from avalanches has become.

All avalanche protection measures being applied at present fall into two main groups - engineering and temporary.

The decision as to which of the two types of avalanche defence measures to adopt is dictated by the existing physico-geographical conditions and the nature of the work being carried on at the site to be protected. However, experience shows that a combination of both types of protection is the most effective. In this case, engineering measures, since they are the most reliable (though costly) are used to protect the vital or more dangerous sectors, where there is the possibility of frequent large-scale avalanches resulting in accidents and heavy material loss. Temporary measures are implemented for the protection of industrial sites which can be closed down for several days or upon which avalanches can descend without inflicting much damage. Usually these are secondary sectors of industrial sites, roads, mines, etc.

Engineering Defences

Engineering defences take the form of man-made structures of varying degrees of complexity, arranged to absorb the impact of avalanches.

The defence structures in current use are divided into four groups according to functional characteristics:

a) structures which prevent sliding of snow in places where avalanches originate (barriers, benches, terraces, bridges, nets, pickets, etc.), so-called supporting structures;

b) structures which allow avalanches to pass over the protected site (galleries, sheds);

c) structures which deflect avalanches away from the protected site (diverting dams);

d) structures which stop avalanches before they reach the site (catching dams, braking wedges, etc.).

The feasibility of employing one or another of these structures depends both on the physico-geographical conditions prevailing in the region, and on the nature of the object which is to be protected (its geometrical dimensions, its position in relation to potential avalanches, and on a number of other factors). Thus, structures suitable for one set of conditions may not be suitable for another.

Following is a short description of the basic types of avalanche defence structures, the conditions under which they function and special features of their design and operation. Questions which have been adequately dealt with in published works are not discussed in this article.

Structures which prevent the movement of snow in places where avalanches originate (supporting structures). This group includes a large number of structures of different types the sole purpose of which is to reinforce the snow cover on the slopes and prevent it from collapsing and producing avalanches. The structures cover the entire area in which snow may slide. In practice this is accomplished by constructing on the slope a large number of structures of a single type (e.g. barriers) in a specific pattern.

This group contains three types of structures, each acting on the snow in a different way:

a) structures of the retaining wall type (walls, barriers, bridges, nets, fences);

b) pile type structures (pickets, pyramids, etc.);

c) terraces.

Retaining wall type structures are individual units, 10-20 m in length and 20-40 m apart, covering the entire avalanche area in checkerboard fashion (Fig. 1). They take the form of retaining walls (dry or mortar); massive barriers of wood, metal, or reinforced concrete (in Switzerland prefabricated reinforced concrete barriers are called bridges); fences, nets of wide nylon strips on metal supports, etc. Barriers and other structures of this type serve to eliminate excessive internal stress in the snow due to the tangential component of the weight of the snow. The question of barrier design has been adequately dealt with by G.K. Tushinskii(14). Here it is only necessary to discuss certain particularly important questions related to the planning of such structures.

G.K. Tushinskii suggests that we take as the load per running metre of barrier, or structure similar to it

$$P=\gamma hl(\sin\alpha - f\cos\alpha) - Cl, \tag{1}$$

where P is the load per running metre of structure in kilograms; γ is the unit weight of snow in kg/m^3; h is the depth of the snow in metres; l is the distance between the structures in metres; f is the coefficient of friction; C is the cohesion in kg/m^2; α is the incline of the slope in degrees.

Numerous observations show that firm snow layers adhere to soil with a strength of at least 100-200 kg/m^2. The coefficient of friction for snow with respect to soil is fairly constant, varying on either side of 0.3.

The second most important question in planning such structures is the percentage of openings in the supporting surface. At present it is accepted as 50% with an aperture width of 100-200 mm. Observations show that an aperture 200 mm in width does not retain the snow effectively. At the same time, when the width of the support surface element of the barrier is reduced to 50-75 mm the percentage of openings can safely be increased to 75% by leaving apertures 150 mm in width. A barrier with such a percentage of openings has real prospects in windy regions, since it will separate only small amounts of snow during blizzards. However, construction of such barriers entails the use of new synthetic materials, a problem which in our view has been successfully resolved by the French engineer Labourdigue with his nylon avalanche defence nets.

The third problem is the height of the structures. It goes without saying that the height of the structures should be greater than the maximum depth of the snow. If drifts accumulate at two or three structures, avalanches will form from the snow lying on top of them. In determining the depth of the snow, it is necessary to take into account, not only the snow deposited at the time of precipitation, but snow drifted and deposited by wind, the normal direction of which will be altered by the presence of the avalanche defence structures. In addition to theoretical calculations, the total accumulation of snow should be determined empirically both from traces left in the avalanche area and from winter observations on small experimental groups of avalanche defence structures. In practice, structures which separate snow from the air flow (barrier, fence and bridge types) in regions subject to snowdrifts are inefficient.

Apart from the depth of the snow, the height of the barrier is affected by its position in relation to the slope. In order to retain a given depth of snow a vertical barrier must be higher than one placed at right angles to the slope. Calculations shows that where the angle formed by the plane of the barrier and the slope is equal to 90 ± 10^{0}, the possibility of the snow creeping over the barrier is eliminated. Furthermore, the positioning of the barrier at this angle simplifies the structure considerably. In this case pressure supports are used instead of tension stays.

In observations carried out in 1956, small snow slides were recorded on one occasion only, and this occurrence was preceded by a snowfall lasting five days, which yielded more than 1 m of new snow.

The erection of barriers in a windy region at angle of 120^{0} to the slope yielded negative results. As observations show, even when the direction of the drifting snow is in line with the barriers, individual barriers are completely snowed up after a few snowstorms (Fig. 2). In such sectors, almost immediately after the barriers are covered with snow, the danger of avalanche formation arises. Small avalanches are not stopped by the lower rows of barriers, and as they continue to move deeper snow horizons are involved, resulting in destruction of the barriers further down the slope (Fig. 3). Finally, the avalanche, containing a large quantity of the fragments of smashed barriers, breaks away from the barrier-covered zone of the accumulation area.

In conclusion, we should mention another feature of such structures. Large accumulations of snow in the form of caps may form on the upper edge of the structures during very heavy snowfalls. If the snow is very plastic, a day or two after the snowfall, these snowcaps, in sliding from the upper edge of the structure, form "garlands" and "catkins" which hang from the barriers (see Fig. 4). Later on they separate and fall onto the snow below the barriers, sometimes causing avalanches. Therefore, where defensive structures of this type are employed, the possibility of the formation of such "garlands" should be investigated. If they do form they should be destroyed in good time, bearing in mind that in doing so, it is possible to start an avalanche. A positive factor directly associated with supporting structures is the natural regrowth of shrubs in protected zones. This has been observed in certain regions.

Pile type structures - pickets, pyramids, posts, etc. These are also arranged in checkerboard fashion, but at closer intervals than structures of the retaining wall type. To date there is not even an elementary theory for calculating such structures. One stake per square metre of surface has been recommended by various investigators. The strengthening effect results from the formation of zones with sharply contrasting snow properties around the stakes or pyramids. This is explained by the fact that the stake, acting on the snow, changes its structure. In order to increase the effectiveness of the stakes or pyramids on the snow they should be made of metal and painted black. The height of the stakes is determined in the same way as the height of barriers.

Despite the frequent reference to the possibility of using these structures as defences, the author knows of no experiments to determine their practicability. Tree-planting, which perhaps falls into this category, is the only measure of this kind known to be of practical use in avalanche accumulation areas. However, tree-plantations retain the snow efficiently only when the undergrowth among the trees is well-developed at the height of the prevailing snow cover. Tree thickets without an undergrowth of shrubs are in many cases incapable of retaining the snow.

Terraces. Defences of this type consist of terraces arranged at specific distances, one below the other, down the entire slope of the avalanche accumulation area. The principle involved here is that an avalanche which originates on a small sector of the slope between terraces must remain on a terrace. For this reason, both the distance between terraces and their width are calculated. The formula usually used for these calculations is one of those employed in determining the distance travelled by avalanches.

Structurally, terraces may vary widely. However, for practical purposes, they can only be constructed on slopes with sufficiently deep, unconsolidated soil.

A feature of terraces is that they require to be cleared of accumulated snow throughout the entire winter. A terrace strewn with avalanche snow or covered with drifting snow is not fulfilling its purpose, i.e. does not prevent avalanches.

Structures which permit avalanches to pass over objects. These are used for the protection of linear objects, principally roads of all types. They usually take the form of different kinds of tunnels and sheds, the structure of which varies widely. The only important stipulation is that the structure is capable of withstanding the loads resulting from the passage of avalanches and that the entrances at the ends are not blocked by avalanche snow. Since anti-avalanche tunnels and sheds are constructed in mountain regions which are, as a rule, subject to earthquakes, the most suitable materials for such structures are metal and wood, which stand up to seismic shocks better than other materials.

The structure must be capable of withstanding the following loads during the descent of an avalanche: the impact on the roof, the normal pressure due to weight of avalanche snow which remains on the roof of the structure, and the tangential stress exerted on the roof of the structure as a result of the friction of the avalanche against the roof. Formulae for determining all three loads may be found in avalanche manuals. The following points should be noted:

1) In calculating the strength of the structure, the seismicity of the region should also be taken into consideration; however, it is not practicable to design the structure for simultaneous avalanche impact and seismic shock. The likelihood of this happening while people are in the shed is so slight that it is not worth serious consideration.

2) Determination of the depth of avalanche snow on the roof of the shed should be based on the fact that in a unit of time practically one and the same volume of snow, which is equal to the constant product of the avalanche cross-section and speed, must pass any point of the avalanche slide path. Essentially, the cross-sectional area of the avalanche body is determined from avalanche traces at several points of the descent channel. The travelling speed at these points is determined by calculation. From the resulting products, which, if the correct points are selected, should be approximately uniform, and from the travelling speed of the avalanche on the roof of the shed, the cross-section of the avalanche body and then the depth of the passing avalanche are determined.

3) The force of the avalanche impact on the roof of the shed depends on the angle between the roof and the slope. The smaller the difference between the angle of incline of the slope and that of the roof, the weaker the impact. The best combination is obtained when the roof is a continuation of the slope. In this case there is no impact. If a back-fill with the same surface incline as the roof is placed between the shed and the slope, the impact force of the avalanche on the roof of the structure is reduced.

The degree of effectiveness in this case depends on many factors, though in most cases it depends on the properties of the fill.

Structures which deflect avalanches to the side of the protected site. These consist of various kinds of diverting dams. They are arranged in such a way that an avalanche, on meeting a wall, changes its course and veers to one side of the protected site. A prerequisite for the construction of such defences is the existence of an area into which the avalanche can be sidetracked.

In planning these structures it is necessary to place them as far as possible from the protected site, where feasible at points where the avalanche travelling speed is average and where the angle at which the dike meets the avalanche is smallest. If the avalanche is travelling at a high speed when it meets the dike, part of it may spill over the structure. In this case, the further the dike is away from the protected site, the better, since the snow which has spilled over the dike may be halted before it reaches the site. Where a dike is erected in an area in which avalanches have a low travelling speed, the avalanche may stop before reaching the dike. In this case, avalanches which occur later may easily pass over the dike and damage objects within the protected site. The smaller the angle at which the dike meets the avalanche, the weaker the impact of the avalanche on the dike and the less chance there is of avalanche snow spilling over the dike.

The design of such structures consists in determining the force of the avalanche impact on them and selecting the correct height. A dike which is intended to cope with average travelling speeds and which meets the avalanche at an angle of 30° or less, should be 2 - 3 times higher than the maximum depth of moving wet snow and no less than 4 - 5 times the depth of moving dry snow. In addition to this, the frontal wall of the dike should be vertical or almost vertical. Only under these conditions can the dike be expected to function effectively.

Structures which stop avalanches in front of the protected site. These consist of defence dikes and various types of retarding structures, the sole purpose of which is to stop the avalanche at the approaches to the defended site.

The defence dikes should be erected at points where the speed of the avalanche drops considerably. These are usually peripheral areas of alluvial cones. Under no circumstances should dikes be constructed in descent channels, at points of maximum avalanche velocity. The length of the dikes should be such as to eliminate any possibility of the avalanche passing round the sides of the structure.

Calculations are restricted to determining the force of impact on the dike and selecting the correct height of the structure. Here we must take into consideration not only the need to create a snow reservoir basin, where the snow from all the avalanches stopped by the dike must be deposited, but the possibility of snow spilling over the dike. The risk of snow spilling over the dike can be discounted only when the length of a horizontal line from the top of the dike to its point of intersection with the surface of the slope is such as to indicate that the structure is capable of completely halting an avalanche. If for any reason it is impossible to comply with this recommendation, the following procedure may be adopted. The height of the dike is assumed to be the same as that needed to form a snow reservoir basin; but a little below the first dike, a second, duplicate dike is constructed. This will hold the avalanche snow which spills over the main dike; and since it is travelling fairly slowly (in relation to all the avalanche snow), the dimensions of the second dike should be considerably smaller than those of the first.

Dikes may be constructed of very different materials, but earth or stone dikes with concrete lining on the upper slope are the most reliable. Here we reiterate that the steeper the upper slope of the dike, the less chance there is of snow spilling over the structure. The defence dike at the settlement of Yuksporiok in the Khibiny Mountains is an example of a well-designed structure. It is 10 metres high, constructed of earth; the upper slope has a batter of 1 : 6 and is lined with reinforced concrete slabs. The pit from which the earth was taken for the construction of the dike is situated in front of the dike in the form of a ditch, as a result of which the effective height of the structure is considerably increased. The dike is located on the decreasing branch of the avalanche velocity curve.

Braking structures consist of various types of braking wedges and lattices. In the Soviet Union these were first used in the Khibiny Mountains. Heretofore, they took the form of cribs with two elongated walls forming a rib. Such cribs were arranged in checkerboard fashion in the paths of avalanches, the rib facing the avalanche. In Switzerland they use special latticed braking wedges of sectional reinforced concrete. Recently, Switzerland, Austria, the U.S.A. and Canada have begun using earth mounds. In planning protective measures for the Trans-Canada Highway, the use of earth mounds 4.5 - 7.5 m high and with 18 - 24 m between their centres was recommended. Sometimes such structures are arranged in the form of massive grids.

The purpose of all these structures is the creation of large-scale turbulence in the movement of the avalanche, a drastic reduction in the travelling speed of the avalanche and its arrest before reaching the protected site. The theoretical basis for calculating such structures is still being worked out, and for this reason it is impossible to deal with the subject here. It should be borne in mind that braking structures must be placed at points where the avalanche speed is greatest, where their resistance to movement is most effective. Moreover, avalanches should not be stopped in sectors of the system, since this will result in a levelling of the artificially created unevenness and subsequent avalanches will encounter no resistance.

Maximum effectiveness of a defence system consisting of a complex of engineering structures is obtained when the avalanche hazard threatening the defended area is fully known in the planning stage. At this time, not only is it possible to select the correct type of defence structures, but to make full use of all the defence advantages to be gained from correctly locating the objects within the protected area, i.e. by locating the objects in such a way that only the minimum demands are made on the defence structures (by locating industrial objects on water-divides between avalanche accumulation areas, in the shelter of large rock outcrops or trees, which eliminate the possibility of avalanches, by erecting buildings and other structures from the water-divide to the foothills, etc.). It is impossible to give a universal formula for the correct siting of an object to be defended in a region subject to avalanche hazard. This can be done only after careful study of the physico-geographical conditions of the site in question, the nature of the object and its function. Such investigations are best carried out by combined groups of avalanche specialists, and persons who plan the projected complex and are familiar with the interrelationship of its individual links.

Like every engineering structure, avalanche defence structures call for careful observation and periodical repair. Only then can they be expected to fulfil their function effectively. The repair work should ensure that the structures are in a permanent state of operational readiness; the frequency and nature of the repair work varies for different structures. The defences should be repaired in summer and autumn, taking into account the possibility that they will have to function without a breakdown throughout the entire winter, since it is impossible to carry out repair work in winter; otherwise the construction and repair of such structures is meaningless, because a defence structure in a state of disrepair is useless.

Temporary Avalanche Defence Measures

Temporary avalanche defence measures are in effect throughout the entire life of the industrial plant. Their number may change from year to year, depending on a number of factors. These measures cover a wide range of activities - predicting the time of avalanche occurrences, breaking up and dusting the snow, constructing emergency storage rooms, organizing safe travel, first aid, etc., etc.

Notwithstanding their apparent diversity, these operations may be summarized under the following headings: a) determination of the time and place of avalanche occurrences; b) preventive measures within the avalanche accumulation area (blasting and dusting of the snow, reducing snow accumulation in avalanche areas); c) precautionary measures within the working area of the plant, i.e. safeguards against the possibility of personnel and transport being caught by avalanches; d) salvage and rescue work.

The aim of all continuing avalanche defence measures is to ensure complete safety and uninterrupted operation of the plant at minimal expense.

As past experience has shown, all the applied temperary avalanche defence measures are closely interrelated. The volume and efficiency of certain measures determine the extent of the need for additional precautions.

Determination of the time and place of avalanche occurrence. None of the engineering and temporary avalanche defence measures will prove effective unless they are oriented in relation to the time and place of avalanche occurrence. This is obvious. In order to close off hazardous areas it is necessary to know where they are located. It is only possible to organize safe road travel when the precise time and place of possible avalanche occurrences are known. Therefore, special attention should be paid to the forecasting of avalanche hazard, since an error here may nullify all avalanche defence work.

At the present time the forecasting of avalanche hazard is carried out in two stages. In the first stage, usually during surveys, or in the initial period of development of a region, a general evaluation of the avalanche hazard is made, without reference to time of occurrence. This is done by forming a conclusion about the extent of the avalanche hazard in the region or by compiling a report on an avalanche survey in the region. A forecast of the first stage is used as the basis for selecting the safest sites and for planning avalanche defences. In the second stage, which covers the entire period of exploitation of the mountain site, a specific evaluation of the avalanche hazard is made every day during the winter by determining the time of onset and termination of the hazardous periods. The second stage or temporary forecast serves to ensure the safe, uninterrupted operation of the plant through the application of routine avalanche defence measures.

The first stage of avalanche forecasting. In the first stage an overall estimate of the avalanche hazards is made when evaluating the sector or region to be developed. The evaluation report usually consists of a textual portion and an avalanche map. Places where avalanches may originate, their maximum volumes, slide paths, the terminal points of avalanche deposits and the conditions which give rise to avalanche formation are indicated in the report. The times of avalanche activity are not indicated at this stage.

The scale of the avalanche map depends on the phase and character of the industrial development of the given mountain region.

Evaluating the extent of avalanche danger in a particular region is a matter of vital importance. The initial work usually consists in the collection of recorded information (mainly meteorological), winter and summer field observations, the processing of the resulting data, the compilation and formalization of the maps and the report.

Sufficiently detailed accounts of all aspects of this work are contained in the available literature. However, the author would like to dwell on two very important points relating to the compilation of the evaluation report, namely recording traces of avalanche activity and drawing the avalanche map.

Recording traces of avalanche activity. The field work usually begins with geomorphological investigations, during which traces of avalanche activity are recorded. As a rule, however, insufficient attention is paid to these traces, whereas from their nature it is possible to determine with a fair degree of accuracy the following characteristics:

1) the frequency of avalanche occurrences (annually or at intervals);

2) the distance travelled by avalanches (particularly large ones);

3) the average depth of snow in an avalanche accumulation area over a period of several years;

4) the height of the moving avalanche front;

5) most frequent location of sliding surface (inside the snow cover on the ground);

6) areas from which the snow breaks away;

7) the depth of avalanche snow on the roof of the avalanche defence structure.

Thus, avalanche snow covered with mineral debris indicates that an avalanche occurred during the past winter. Deposits of debris occurring only in places and only on the largest blocks and boulders indicate an avalanche occurrence in the past 2 - 3 years. The growth of undeformed shrubs of the barberry variety in the presence of inhibited tree growth is indicative of periodical avalanche occurrences every few years, and the presence of younger tree growth among the old denotes a periodicity measured in decades.

The list of questions enumerated above to which answers can be obtained by analyzing traces of avalanche activity, speaks for itself. Therefore, when conducting avalanche investigations, it is important to draw up a detailed and careful description of avalanche traces observed in the winter as well as in the summer. It is pointed out that, during the process of developing a mountainous region, man frequently destroys all traces of avalanche activity.

Most significant in the mountainous regions of Central Asia are: inhibited vegetation, traces of avalanche ploughing and abrasion, deposits of debris (Fig. 5), scratches on rocks and stones, the occurrence of desert varnish.

The work of mapping and describing traces of avalanche activity should be approached with great care. In many regions, particularly Central Asia, a number of physico-geographical phenomena which are completely unrelated to avalanche activity, leaves traces very similar to those left by avalanches. Thus, rock-slide and slopewash debris cones display a number of characteristics which are distinctive of debris cones originating from soil deposited by avalanches. Outflows of subsurface water are frequently observed in the vicinity of geological faults; as a result of this, denser green vegetation develops. Under certain conditions such areas may be mistaken for places where avalanche firn has melted. Mud-flows or mud and rock streams leave scratches and abrasions on rocks.

Avalanche map. The avalanche hazard map forms the main portion of the evaluation report. It must provide a clear answer to the question of whether or not danger exists at any point indicated on the map and, if so, how real and serious the threat is. The maps being compiled at present do not, as a rule, provide complete answers to all the questions which arise. However, this is understandable. In the majority of cases avalanche paths are indicated on the maps by arrows, and areas from which snow may be released during the formation of large avalanches are outlined. Such maps do not indicate the frequency with which avalanches may occur, or the degree of danger present in the areas between the arrows; neither do they indicate the different levels of avalanche hazard in meteorologically normal and abnormal years. This difference may be very substantial. As an example we may cite the Dukant Snow Avalanche Station region of observations, where during different winters the following numbers of avalanches and slides were recorded: 1952-53 - 120, 1953-54 - 226, 1954-55 - 93, 1955-56 - 67, 1956-57 - 62, 1957-58 - 19, 1958-59 - 13, 1959-60 - 23, 1960-61 - 4.

The methods and means of avalanche defence vary, depending on the frequency and size of the avalanches. This also changes the requirements for evaluating the degree of avalanche hazard.

The following sequence of map compilation procedures is suggested. First a geomorphological survey of the area is made. The results of the survey should be incorporated in geomorphological vegetation and lithological maps, as well as maps of avalanche traces, winter avalanche observations, snow accumulations, and for large areas, a climatic chart. Individual maps may be combined, depending on the quantity of factual material and the amount of topographical data shown on them. Then, on the basis of calculated data and collected factual material, an avalanche spread map is prepared. The resulting set of maps will serve as a basis for the compilation of avalanche hazard maps.

An avalanche chart is a map of a surveyed region the entire area of which is broken down into separate sectors or regions that differ from each other in avalanche conditions. In delineating the sectors, the following should be taken into consideration: a) frequency and volumes of avalanches; b) causes of avalanches; c) weather and climatic factors; d) degree of avalanche hazard and defence methods. The shapes and dimensions of the sectors depends solely upon the avalanche conditions within the sectors and their configurations may be extremely varied.

Using conventional map symbols, the following should be recorded for each delineated sector: a) the principal geomorphological features of the sector; b) the conditions under which avalanches form; c) the anticipated avalanche dimensions and frequency; d) the degree of hazard present in the sector; e) possible avalanche defence measures.

Here we should be guided by past experience of normal and abnormal avalanche activity. In addition to hazardous areas, safe areas should also be accurately marked on the chart.

Second stage of avalanche forecasting, or temporary forecasting, covers the entire period during which the mountain region is being exploited. Collaborators at avalanche stations, avalanche defence sections, etc., make a regular evaluation of the prevailing avalanche conditions in the region based on special snow and meteorological observations. The principal object of the work conducted at these stations is to determine the onset and termination of periods of avalanche danger, i.e. to determine the periods when avalanches are possible and inevitable. To produce a more accurate forecast, to indicate specifically in which accumulation areas avalanches will occur today and in which tomorrow, is not feasible in most cases, although, after several years operation, stations are capable of forecasting to within several hours the failure of snow masses for certain types of avalanches (snowstorm avalanches at the "Apatit" Combine). At the same time as they forecast the onset of a period of avalanche danger, the stations should indicate the point at which the failure of the snow cover (which may not take place) is anticipated, the approximate sizes of the avalanches, their spread and terminal points. Indeed not only the fact of the failure of the snow itself is important, but how the snow fractures and the amount of snow involved.

A small avalanche starting well inside a large avalanche accumulation area poses practically no threat to structures located in the vicinity of the run-out zone, since such an avalanche will not reach the run-out zone. At the same time a small avalanche from an erosion scar may damage traffic moving along a road.

The second task of avalanche stations is to devise and implement day-to-day avalanche defence measures. In this connection the station takes on the responsibility of working out the necessary programme of avalanche defence measures, and ensuring that they are observed, and sometimes the supervision of certain activities (snow blasting, rescue work, etc.). It is clear that the volume of avalanche defence measures depends entirely on the quality of the avalanche forecast. The more accurate the forecast, the fewer the routine avalanche defence measures.

At present there is no generally accepted method of avalanche forecasting. The existing procedures were worked out for different regions and, as a rule, are unsuitable for other regions. Avalanches originate as a result of the increase in depth of a snow layer and the internal stresses which build up in the layer. The start of an avalanche is determined by the mechanical properties of the snow. On the basis of the fact that the mechanical properties of snow are taken into consideration when determining the degree of stability of a snow layer on a slope, all methods of forecasting avalanches are divided into two main groups: the indirect and direct methods of determining the stability of a snow layer on a slope.

The theoretical premise of indirect methods is the assumption that a change in meteorological conditions will always cause a change in the physico-mechanical properties of the snow, thus affecting the stability of the snow on the slope. Indirect forecasting is generally known as background forecasting and is based on the relationship between meteorological elements and avalanche occurrences. Thus, for example, the method of forecasting snowstorm avalanches now being used by the avalanche defence department of the "Apatit" Combine is based on the relationship between the time of onset of avalanche hazard and the quantity of drifting snow deposited by the storm. Such indirect methods of forecasting may be used only under precisely defined physico-geographical conditions. Given the same qualitative characteristics, avalanche formation processes have a markedly dissimilar quantitative character in different physico-geographical conditions. An attempt by a snow avalanche station of the Directorate of the Hydrometeorological Service*, Uzbek S.S.R., to use the method of forecasting snowstorm

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* UGMS

avalanches now being used in the Khibiny Mountains proved unsuccessful.

The theoretical premise of the direct method of determining the stability of a snow layer on a slope is the assumption that two groups of forces act on the snow layer: the forces which retain the snow on the slope (P_1) and the forces which tend to cause the snow to slide down the slope (P_2). Depending on their relationship, the snow will be in either a stable or an unstable condition. The ratio of these forces (K) is always equal to or greater than unity; its value indicates the degree of stability of the snow on the slope. We may designate this the coefficient of stability of the snow layer. It is determined by the following formula:

$$K = \frac{P_1}{P_2} = \frac{\gamma h \cos\alpha \cdot f + C}{\gamma h \sin\alpha}, \qquad (2)$$

where γ is the weight per unit volume of snow in kg/m^3; h is the depth of the snow layer in metres; α is the angle of incline of the sliding surface in degrees; f is the coefficient of internal friction; C is cohesion in kg/m^2.

Where K is greater than 1.5 - 2 for avalanche accumulation areas threatening roads, and where K is greater than 2 - 3 for accumulation areas threatening industrial and residential sites, the situation may be considered safe. Where the safety factor is less than the indicated values, hazardous conditions exist.

The formula given above is, with certain additions and refinements, the basis for all direct methods of avalanche forecasting. The following have been formulated in the Soviet Union:

a) G.G. Saatchan's formula (1936)$^{(12)}$ expressing the relationship between the depth of snow cover occurring in a state of maximum equilibrium and the angles of incline of the surface:

$$h = \frac{\frac{C}{\gamma}}{\sin\alpha - f\cos\alpha - \frac{n}{\gamma l}}, \qquad (3)$$

where n is the tensile strength in kg/m^2; l is the length of the fracture line in metres.

b) V.N. Akkuratov's formula$^{(1)}$ for determining the critical depth of the snow:

$$h = \frac{0{,}374\, C l f_{\text{ск}}}{0{,}375\, C l \gamma (\sin\beta - A\cos\beta) + \alpha (t_1 - t_2) f_{\text{раз}}}, \qquad (4)$$

where h is the depth of the snow mass in metres; f_{ck} is the ultimate shear strength between snow layers, or the zone of failure in t/m^2; $f_{\text{paз}}$ is the ultimate tensile strength of the snow mass in t/m^2; l is the length of the slope in metres; γ is the density of the snow; β is the angle of incline of the slope in degrees; A is the coefficient of static friction; α is the coefficient of linear expansion of the snow; t_1 is the average temperature in degrees of the snow mass in the previous period; t_2 is the average temperature in degrees of the snow mass at the time when its stability on the slope was determined.

c) The lavinogram (sic) method of A.G. Balabuev and G,K. Sulakvelidze(6) is based on the formula

$$h = \frac{C_3 Z T}{\gamma^2 T \frac{\sin(\alpha - \varphi)}{\cos \varphi} - [2C_2 l - C_1 T]}, \qquad (5)$$

where h is the critical depth of snow in metres at which a break away of snow may occur; γ is the density of the snow; Z is the length of the layer in metres; T is the width of the avalanche at the fracture line in metres; α is the angle of incline of the slope in degrees; φ is the angle of internal friction in degrees*; C_1 is the tensile strength in kg/dm^2; C_2 is the shear strength in kg/dm^2; C_3 is the tensile strength along the sides of the avalanche in kg/dm^2.

In all these formulae the coefficient of stability is assumed to be equal to unity.

The tensile strength value, for the majority of nascent avalanches, comprises no more than 1 - 2% of the principal acting forces, and with present methods of determining the mechanical properties of snow it is practically impossible to allow for them.

Avalanche forecasting is based on the determination of the physico-mechanical properties of the snow in layers and on additional mathematical processing of the data. During the processing, the critical depth of the snow is determined, and this is compared with the actual or anticipated depth. If the actual or anticipated depth is considerably less than the calculated critical depth, the snow on the slope is assumed to be stable. If the actual depth proves to be close to the calculated critical, it is assumed that the snow is in an unstable condition.

The relationship between the avalanche station and the enterprise being served may vary considerably. The station may be one of the departments of the plant itself, as for example, the avalanche defence section of the "Apatit" Combine, or it may be independent of the plant. In any case, it is important that the programme of avalanche defence measures, supervision of its implementation, and avalanche forecasting be the responsibility of one and the same organization. Otherwise miscalculations are unavoidable, which, in the final analysis, may have serious consequences.

Preventive measures in avalanche accumulation areas. These are special measures, the purpose of which is the elimination or diminution of avalanche hazards. This work includes: a) the artificial release of avalanches;

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* Translator's note: β in Russian text; probably an error.

b) altering the properties of the snow in order to strengthen it; c) altering the snow accumulation regime.

The artificial release of avalanches or the dislodging of snow from accumulation areas is intended to eliminate the possibility of the sudden occurrence of large avalanches - sometimes of massive proportions - by inducing several smaller avalanches at predetermined times. This is done by firing at the accumulation area with mortars (Switzerland, U.S.S.R.), recoilless guns (U.S.A.), special rockets (Switzerland, Austria), by blasting the snow with explosive charges and by dislodging cornices. The successful release of accumulations of blizzard snow by firing at it with 120 mm mortars occurs when there is a weakened horizon in the snow mass, or when contact between layers has an ultimate shear strength (cohesion) not exceeding 220 kg/m^2. The release of snow by blasting it with explosive charges placed on the upper slopes is successful when the coefficient of stability, determined from formula (2), is found to be 1.5 - 2 and the difference between P_1 and P_2 forces does not exceed 250 - 300 kg/m^2. The charges should be placed along the fracture line in one or two strips. The size of the unit charge is determined by experimental blasting, since the properties of snow vary so widely. The weight of the unit charge is assumed to be such as will produce a hole, the diameter of which is equal to twice the depth of the snow. For dry plastic snow, the unit weight of which is 0.25 - 0.3 g/cm^3, the size of the charge is approximately 4 kg of explosive per metre of snow depth. The distance between charges is taken as being equal to the diameter of the hole. If the charges are laid in two strips, the size of the charge is halved. The distance between the strips is 2 - 3 times the diameter of the hole. An example of a successful release of snow is shown in Figure 6.

Snow may be released by exploding a single large charge at the foot of the slope when the difference between the P_1 and P_2 forces does not exceed 50 - 70 kg/m^2. Normally the charge is at least 150 - 200 kg. This method is used only for slopes with a concave cross-sectional profile, i.e. where the maximum steepness of the slope occurs near the water divide.

The release of cornices as a method of unloading slopes covering a large area has not been accepted, and for a number of reasons it cannot be recommended as a method of combatting avalanches.

In recent times the U.S.A. has used supersonic aircraft to overfly avalanche areas. Avalanches are triggered by the shock wave from the aircraft. This method is still in the experimental stage.

Preventive measures undertaken to change the properties of the snow for the purpose of strengthening it, consist in periodical shooting and blasting operations or the dusting of the snow in accumulation areas.

Areas of increased stability are formed at the points where shells explode in the snow during preventive firing at avalanche accumulation sites. These relatively stable areas act as piles which hold the snow on the slope. The frequency of these firing operations, which depends on the prevailing physico-geographical conditions, varies considerably. It should not be such as to allow the condition of the snow to deteriorate, i.e. to become unstable. The number of shells fired at the area to be stabilized is, according to V.N. Akkuratov, approximately 100 per hectare.

Preventive snow blasting is based on the same principle, but instead of individual charges, series of charges placed across the avalanche accumulation area at 100 - 200 m intervals are exploded. The charges are laid on the surface of the snow. The size of a single charge should be such that the depth of the resulting crater will be 10 - 15 cm less than the depth of the snow. The distance between individual charges is taken as 1.5 - 2 times the diameter of the crater. The charges are detonated electrically. Under the conditions prevailing in Central Asia blasting is carried out two or three times a month.

People may be permitted on the slopes of the avalanche accumulation site for the purpose of laying charges and setting up detonation rigs only when the coefficient of stability, determined by formula (2) is at least 2 - 3 and the difference between P_1 and P_2 forces no less than 100 kg/m^2. The calculations must incorporate the weight of the man (assumed to be 100 - 120 kg, allowing for skis, clothes and pack of explosives), which is added to the weight of the snow γh.

Blackening or dusting of the snow produces changes in the properties of the treated surface, which result in a marked increase of the cohesive forces on the contact which forms on the blackened surface; it also results in acceleration of thawing in the periods when the blackened surface is not covered by snow. Excessive water saturation of the snow during the accelerated thawing process may add considerably to the danger of avalanches. In order to avoid this it is advisable to blacken, not the entire danger area, but individual strips 20 - 30 m in width interspersed by untreated strips of the same width. Coal, slag, diesel oil, etc. may be used as a blackening agent. The optimum grain size of the dust is 0.2 - 0.3 mm. Finer dust is scattered by the wind and will cover the entire avalanche area uniformly. The dust is spread at the rate of 5 - 10 t/km^2, usually by an AN-2 aircraft, several times a month.

There are two methods of combatting avalanches by changing the snow accumulation regime. The first is the deposit of drifting snow outside the danger zone. The second is the formation of a very uneven layer of snow over the entire danger zone in the form of individual drifts surrounded by snowless areas. In the first case, light latticed fences (of the type used for railways) are set up along the edges of the avalanche accumulation area. These cause the snow to be deposited outside the danger zone. The second method entails the erection of solid fences across the entire danger zone in order to change the wind flux. The wind flux should be conducive to the accumulation of snow in the form of separate drifts, the areas between the drifts remaining clear of snow. Both methods are intended to reduce substantially the danger of avalanche occurrences.

The main purpose of all preventive measures carried out within the working area is to eliminate completely the possibility of personnel and traffic being hit by avalanches and to render help in the event of a disaster.

This is accomplished by partially or completely restricting access to certain sectors both for personnel and transport. To this end: a) dangerous sectors are isolated in the autumn and a plan is worked out for their use; b) talks and instructions on avalanche hazards and safety measures are given to workers and residents; c) dangerous sectors are fenced off and warning notices posted; d) necessary reserves and stocks of tools are accumulated; e) shelters are constructed alonside roads and paths; f) strict control is exercised over the movement of all personnel, etc.

The measures enumerated above, as well as a number of less important items, are, after careful study, incorporated in a single emergency plan for units of the enterprise. This plan clearly specifies where, when and what to do and who should do it in the event of danger; the interdependence of the units; emergency signals; conditions in which avalanches are most likely to occur; safe and unsafe places; the organization and conduct of emergency rescue work, etc. After the emergency plan has been approved by the head of the enterprise, all work at the site during winter is carried out in strict conformity with the emergency plan.

Emergency rescue work is carried out for the purpose of rendering assistance to avalanche victims. The key to success in this work, which should be directed by an avalanche expert, is precise organization. Scrupulous observation of every safety rule is vital, since while carrying out rescue operations, people work in sectors where a second avalanche may be expected, and consequently they may be caught a second time. In such a case, strict adherence to the safety rules makes the search for victims much easier.

In conclusion, it is reiterated that in order to ensure the effective avalanche defence of industrial enterprises in mountainous regions, two basic questions must be resolved:

1) the formulation and verification in practice of an avalanche forecasting method;

2) the development of design principles for avalanche defence structures.

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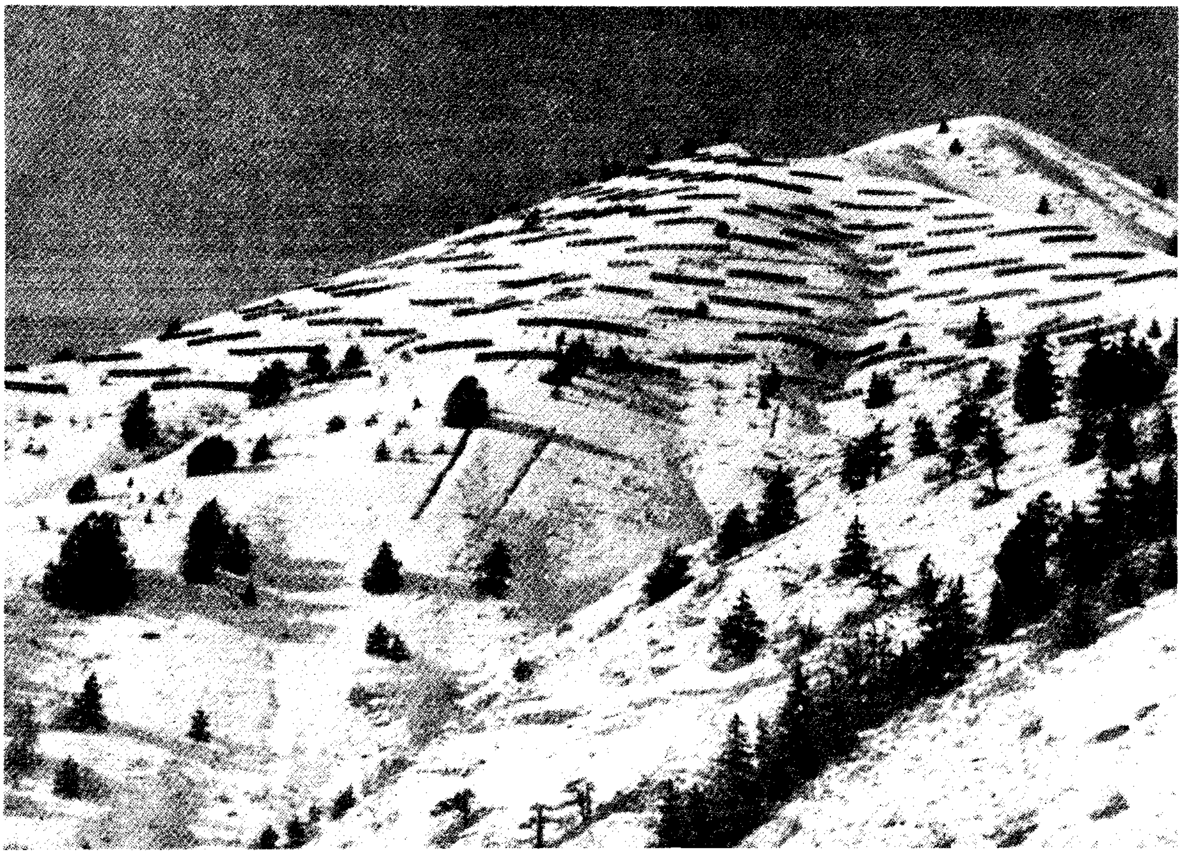


Fig. 1

Avalanche defence slope

Fig. 2
Snowed-up defence slope

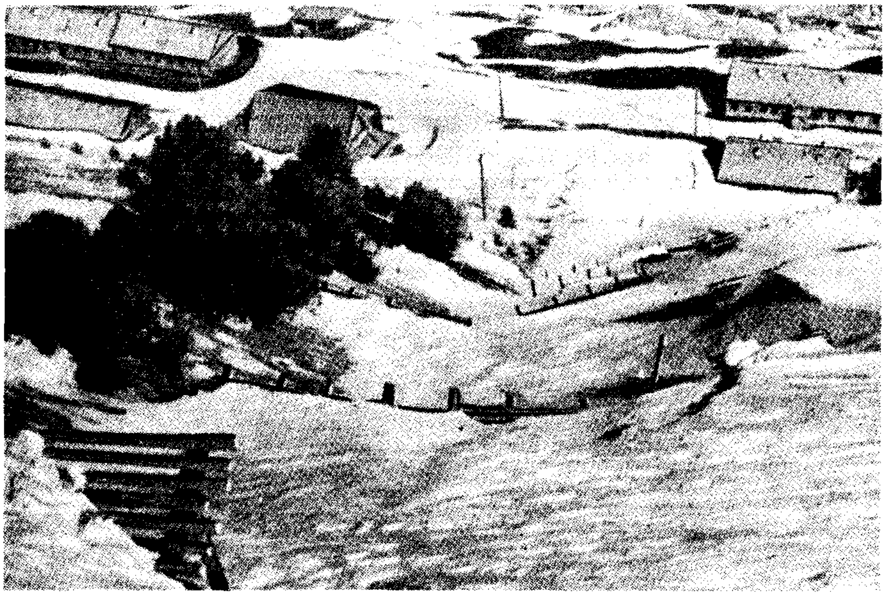


Fig. 3
Destruction of barriers by an avalanche which occurred inside the defence field

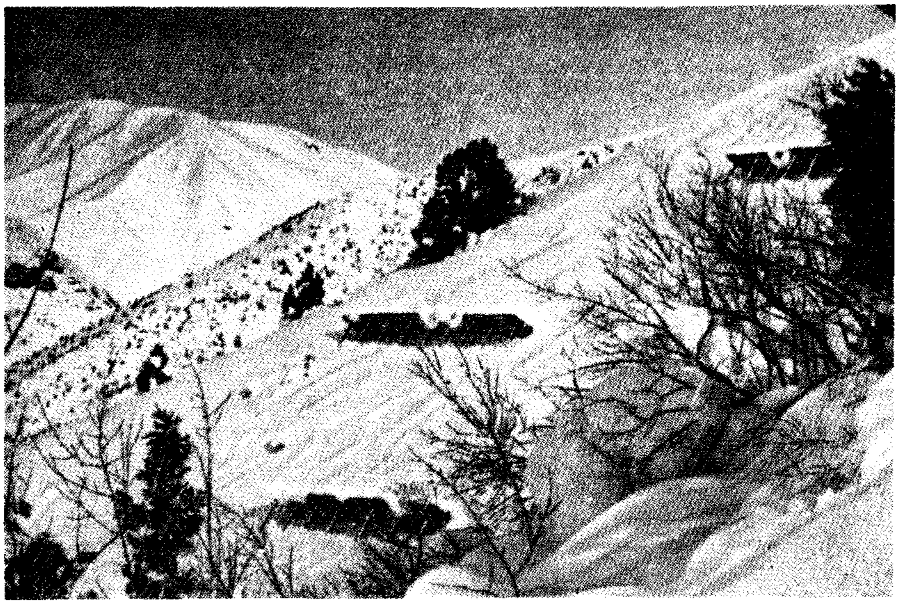


Fig. 4
Formation of snow "catkins" from freshly fallen snow on barrier edges

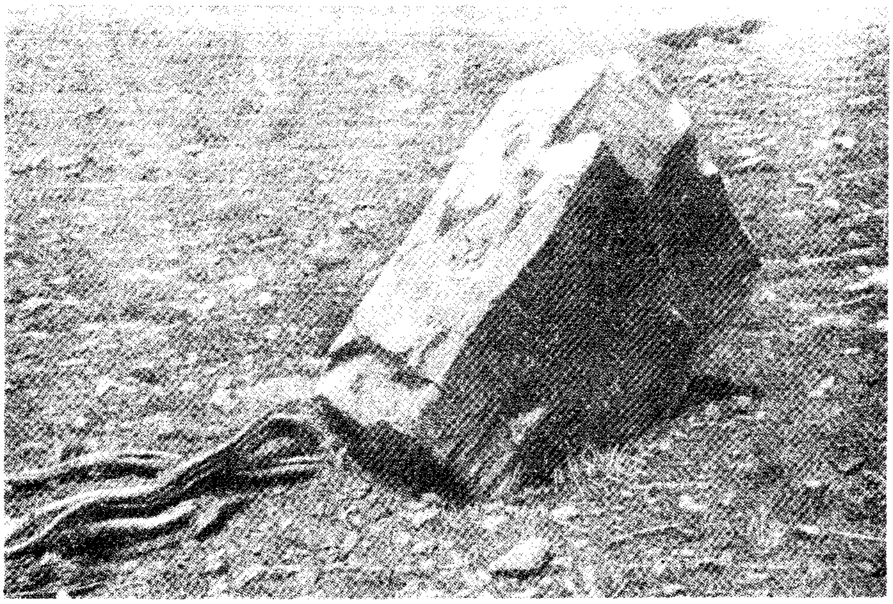
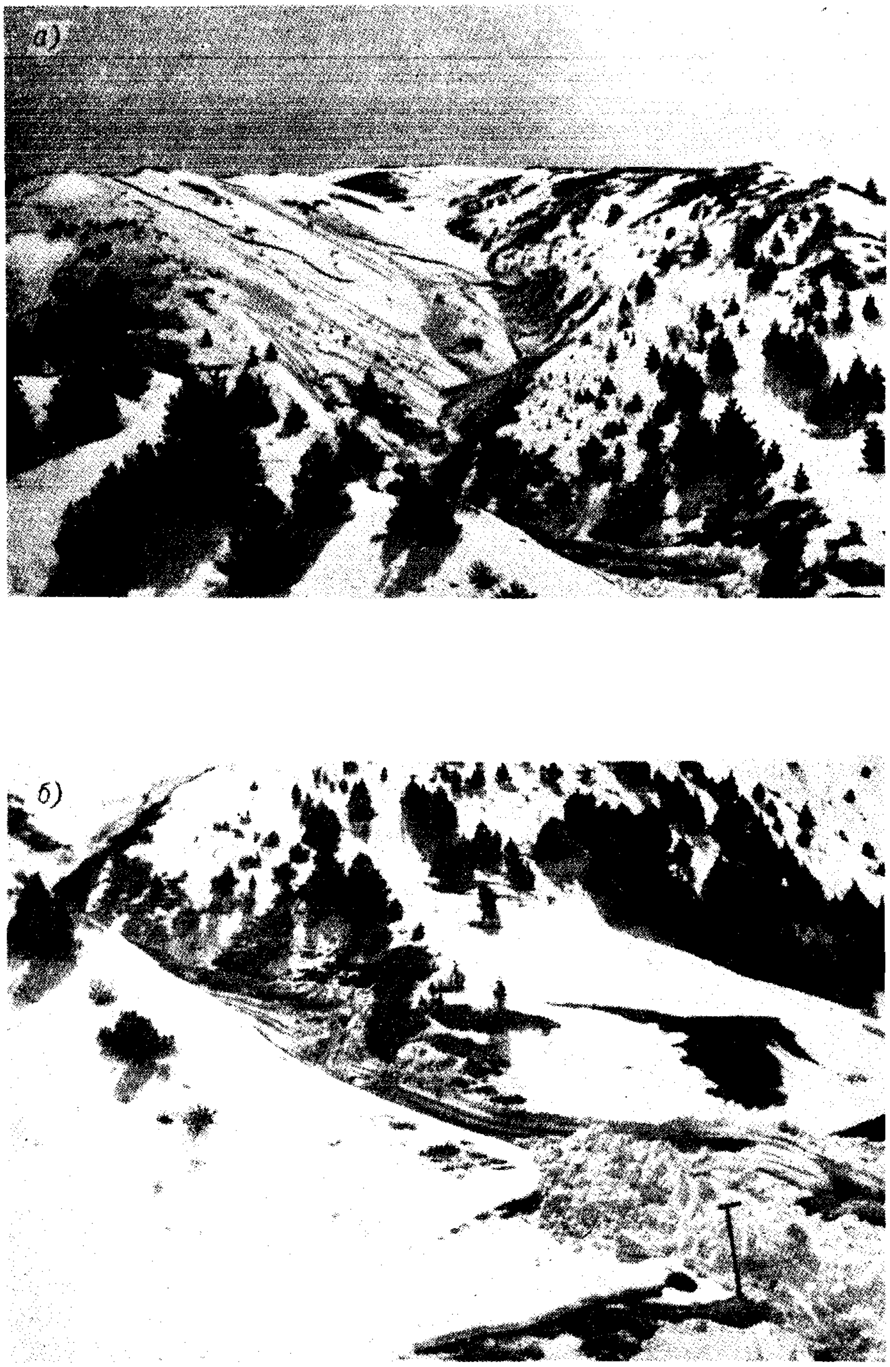


Fig. 5
Rock transported by an avalanche with avalanche debris



a)

b)

Fig. 6a and b

Snow blasting with explosive charges when the coefficient of safety of the snow layer is approximately 1.5

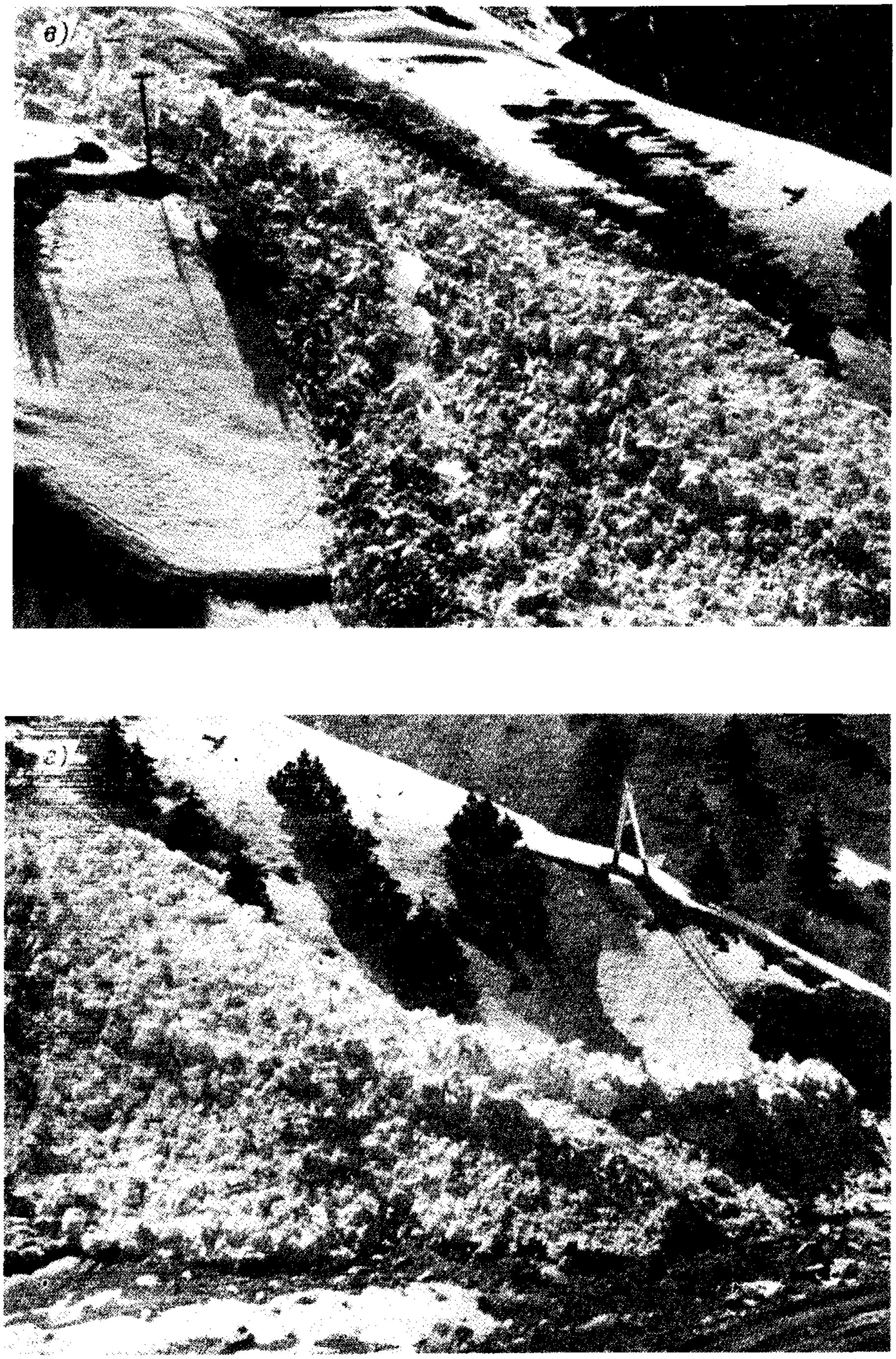


Fig. 6c and d

Snow blasting with explosive charges when the coefficient of safety of the snow layer is approximately 1.5

THE SLOW CREEP OF SNOW ON SLOPES

by

A.I. Korolev

The nature of the movement and velocity distribution in the slow creep and settlement of snow on a slope is demonstrated in work on a specimen of experimental material; also shown is the influence exerted on the velocity of the creep by certain natural and man-made factors (daily temperature fluctuation, micro-relief of the ground surface, support by downhill snow mass, vibrations caused by explosions, etc.).

The presence of pulsation in creep and snow compaction curves permit the conclusion that deformations of snow cover correspond to deformations of an elastico-plastic body.

General Information

In order to discover the nature of slow snow creep on a slope the Dukant Snow Avalanche Station employed an apparatus which hitherto had not been used to study the properties of snow. The principal component of the apparatus is a microindicator (a mechanical dial gauge) accurate to the order of 0.001 mm. The indicator is mounted in a housing on a stake driven into the soil on the slope.

Plywood strips 100 cm long and 3 cm wide serve as the data units. A plexiglass plate fastened at one end of the strip forms a unique terminal. The width of the plate is the same as the width of the data unit. The free end of the plate is bent at right angles to the plane of the plate itself, thus forming a small stand on which the leg of the gauge is rested.

To set up the instrument in the snow it is necessary to dig a test-pit. The data unit is inserted into the upper (working) wall of the test-pit at the selected level, parallel to the slope, in such a way that the plastic tip projects 2 - 3 cm from the wall. A metal stake with sockets for the gauge is inserted into the ground opposite the data unit.

The temperature and moisture regime, which was disturbed when the data unit was inserted, returned to its original state soon after the apparatus had been placed in the snow. The data unit froze into the adjacent snow layers and moved with them down the slope. As it moved it displaced the leg of the gauge and the indicator needle indicated the track followed by the given section of snow during a specific interval of time. Naturally, the size of the section, the displacement of which was recorded by the device, corresponds to the size of the data unit.

As a rule, readings were taken every two hours. In addition to these basic observations, continuous observations, each lasting from several minutes to half an hour, were carried out at different times of the day.

The observations were conducted during the periods from the 5th to the 23rd of February and from the 10th to the 13th of March, 1963.

The Nature of Slow Snow Creep

The unit section, which is found in a given medium at depth z and located on a surface with an angle of incline α, is subject to a given pressure P of that part of the medium above the level of z. Since the given medium is located on an inclined plane, the normal pressure P acting on the section is broken down into components, one of which creates shear stress F.

The magnitude of the shear stress in the general case is

$$F = zd\sin\alpha, \qquad (1)$$

where d is the unit weight of the medium.

Where the medium is subject to the laws of viscous fluid (or gas), the displacement of the unit section under the influence of external force F will conform to Newton's law for viscous fluids

$$F = \frac{dv}{dz} s\eta. \qquad (2)$$

Here $\frac{dv}{dz}$ is the gradient of the speed of motion of the layers of fluid which are displaced in relation to one another; s is the area of the layers of fluid; η is the proportionality factor.

A peculiarity of viscous bodies is the unlimited deformation on application of even the smallest loads. Then, all other conditions being equal, where F = const one would expect a smooth, continuous displacement of the selected section down the inclined plane.

Unlike viscous bodies, the displacement of particles of an elastico-plastic body on an inclined plane occurs only in the presence of a specific collision force which is capable of overcoming the elastic stresses originating in the body. Depending on the magnitude of the applied force, reversible elastic deformation, non-reversible plastic dislocation or failure of the body will result.

Snow stratification on a mountain slope corresponds to the conditions under which the models cited above are found on an inclined slope.

To which of the models do the mechanical properties of a snow cover more closely correspond: viscous fluid or a plastic body? Long-term continuous observations, conducted with an instrument which accelerates 1,000 times the scale of the creep rate, has made it possible to obtain a clear picture of the behaviour of microscopic movements of a snow cover. Of particular interest is the irregular behaviour of snow creep. We shall assume that at any given moment during the observations we observe a barely discernible, even movement of the snow layer of the order of 0.5 - 2 microns/minute. This rate is maintained for a period of 1 - 5 minutes, depending on the structure of the snow, then it increases: the data unit travels 1 - 3 microns in several seconds. The end of the accelerated phase is marked by a sudden jerky movement, the magnitude of which varies from several microns to several tens of microns. After such a jump, the indicator needle, as a rule, remains absolutely motionless. The data unit remains stationary for a period varying between several seconds and several minutes. Then the indicator begins to move again, barely perceptibly, from division to division. (Its rate of movement at this stage approximates that of the hour hand of a large wall clock). The entire process is then repeated. The phenomenon of creeping snow is often marked by certain deviations from the normal course of microscopic movements; for instance a sudden jump may last for several seconds; the stationary indicator period is sometimes absent, and a rapid shift is followed by a slow creeping movement, and so on.

Undoubtedly, when individual snow grains and crystals move in relation to each other, regular movements also occur, especially in wet snow. However, generally speaking, the instruments almost invariably indicated that the nature of snow creep is highly erratic, despite the fact that the large size of the data unit tended to level out the jumps and halts in the movement. This is not characteristic of viscous deformations.

It should be noted that an extension of the periods between observations results in a levelling out of the curve on the velocity graph. Here the laws of probability come into play. The greater the number of positive and negative accelerations involved in the process of movement during each individual interval of time, the closer the average velocity during this interval approximates the overall average velocity of the snow creep.

Such a purely statistical levelling of the velocities of motion cannot serve as a basis for equating the properties of a snow cover to those of a viscous fluid.

A snow cover, considered as a special form of sedimentary rock, represents a multiphase disperse system. The principal component which determines the mechanical properties of snow is ice. However, the high porosity of a snow cover makes it impossible to make any kind of analogy between the mechanical properties of snow and those of ice. The openness of the ice skeleton of a snow cover, which is absent in glacial ice, is conducive to irregular distribution of the external loads in the snow mass. These stresses reach maximum values at the contacts of the particles and in the narrow cross-sections of the links between adjacent granules. It is precisely here that the grains start to move, when the external forces exceed the elastic limit of the ice (ultimate shear stress). If, however, the stresses increase further and go beyond the stress limit (temporary resistance to shear), the result will be brittle deformation and a sudden spasmodic displacement of the affected area in relation to less strained areas. The displaced section will then fall into a more stable position, the stresses inside it become attenuated, its rate of motion decreases and sometimes movement ceases altogether. The redistribution of the material in the snow mass is accompanied by a redistribution of the stresses. The greatest stresses are now exerted on the adjacent sections, which consequently increase the magnitude and rate of deformation. Thus, section by section, the snow moves down the slope in successive stages of creep and consolidation. Consequently, the snow cover, insofar as its mechanical properties are concerned, must be considered an elastico-plastic body in which brittle fracture plays an important role in deformation.

An example of snow creep characteristics is provided by data obtained during an independent period in which observations were conducted at more frequent intervals (Table I).

Settlement of Snow on Consolidation and Acoustic Phenomena in Snow

Unevenness of snow deformation is even more pronounced during the vertical subsidence of a snow cover than during creep. Observations of snow settlement, which are of interest both as control and independent tests, were carried out in parallel with the creep observations.

The observations were conducted in March at a horizontal test site both on the surface and inside the snow mass, the overall depth of the snow being 110 cm. In this case, the data units were thin strips of plexiglass measuring 5 x 10 cm. The strips were well perforated in order to reduce their weight. The microindicator was mounted on an inverted L-shaped bracket stand directly over the surface of the snow; a steel spoke linked it with the data unit. Since the layer of snow in question receded from the instrument when it settled, the indicator needle moved from large values on the scale to smaller ones. Consequently, the readings were taken in the reverse order.

Large momentary movements of the order of several tens of microns were recorded more frequently during snow compaction than was the case with creep. Individual jumps were extremely large, 150 - 200 microns.

Similar "collapses" of individual sections of snow, occurring at the rate of 1 - 3 instances per hour, were accompanied by well-defined noise effects, which always occur in the brittle failure of ice particles. A microphone placed on a slope among stones underneath the snow and connected via an amplifier to an electromagnetic recorded, picked up noises and crackling which originated in the snow 24 hours a day. Numerous occurrences at the rate of 1 or 2 per hour were recorded on the tape.

In working with instruments, the functional principle of which is based on the acoustic properties of snow, it is necessary to take into account the presence in the snow of the frequent crackling which occurs during brittle failures and the spasmodic subsidences of certain areas and aggregates of ice granules in the snow cover, since these noises may interfere with the functioning of these instruments.

An example of snow settlement characteristics is provided by data obtained during an independent period in which observations were made at more frequent intervals (Table II).

Velocity Distribution Inside Snow Cover

In nature two types of bodies have their own movement (sic): glaciers and snow cover.

In glaciers the velocity distribution of ice in a vertical profile generally conforms to the parabolic law. The maximum vertical gradient of the travelling speed is usually observed in the lower layers of a glacier. As the pressure decreases towards the surface of the glacier, so does the velocity gradient(3).

The reason for this pattern is closely linked with the monolithic nature and structural uniformity of a glacier compared with that of a snow cover. The vertical gradient of velocities in a glacier depends mainly on the amount of pressure and thrust of the overlying ice masses, since the structure, temperature and density of the ice in the main body of the glacier remain substantially unchanged for long periods. Unlike glaciers, a snow cover contains extremely diverse types of snow at one and the same time (new, compacted, fine-grained, etc.). Each type of snow is characterized by its own specific structure and physical properties. A change in structure is accompanied by changes in the physical properties of snow, including plasticity.

Observations were conducted in the period from the 5th to the 23rd of February to determine the variations in the velocity of snow creep with time. The absolute altitude of the observation site was 2,230 m, exposure, north; angle of slope, 28 - 30°, structure of snow at start of observations: 1) bottom layer (00 - 20 cm) - coarse-grained dry snow with large quantity of depth hoar crystals up to 3 mm in size, unit weight 0.31 - 0.33 g/cm^3; 2) 20 - 53 cm layer fine-grained dry snow with an admixture of medium-grained snow; diameter of grains 0.5 - 1.5 mm, unit weight 0.29 - 0.31 g/cm^3; 53 - 70 cm layer - fine-grained snow, unit weight 0.24 - 0.25 g/cm^3.

The top layer was lightly compacted new snow with a unit weight of 0.15 - 0.18 g/cm^3. The overall depth of the snow cover was 78 - 83 cm. The structure of the snow at the conclusion of the observations was as follows: 1) the bottom layer of coarse-grained snow, as previously, consisted of a large amount of depth hoar; there was no noticeable differences in thickness and unit weight; 2) the second layer had turned into medium-grained snow, the unit weight of which had increased to 0.31 - 0.32 g/cm^3. Its depth had decreased by 5 - 6 cm due to compaction. The upper part of this layer, at the 47 - 48 cm level, had acquired a yellowish tinge.

The depth of the top layers had increased slightly as a result of new snowfalls.

In the first half of the observation period there was a marginal decrease in the overall depth of the snow cover. In the second half, following several snowfalls, it had increased to 90 - 100 cm.

The temperature of the lower layers fell 1 - 3°C. During the first days of the observations; by the end of the period it had risen to the initial level (Table III).

As is evident from Table III, during the test period the temperature of the snow and the overall depth of the snow cover fluctuated on either side of the initial values. The unit weight varied only on the side of increase. As the snow "aged" it also manifested a uniform tendency to granular coarsening.

A steady drop in creep velocity was apparent against the changing background of the snow parameters indicated above. In two weeks the velocity had dropped from 0.9 - 1.0 $\cdot$ 10^{-6} to 0.5 - 0.6 $\cdot$ 10^{-6} cm/sec, i.e. by almost half. Thus, the principal factor in changes of the plastic properties of snow is structural change and, to a certain extent, the change in unit weight which accompanies it.

In addition to indicators other means were used to study the velocity of snow creep. Lines of light wooden planks or laths erected on the surface of the snow is one method which was frequently recommended. The ends of the lines are secured by permanent bench marks.

At prescribed intervals the distance travelled by the laths (which move with the snow) is measured and the creep velocity of the surface layer of snow determined. This method was rejected because it grossly distorts the real picture of snow creep. In the first place, an accurate idea of the movement of the individual horizons inside the snow mass cannot be obtained by means of a rigid wooden plank, since this movement does not conform to the linear velocity distribution in a vertical cross-section. Secondly, and no less important, however light the wooden plank, it will always indicate an exaggerated snow creep velocity. Two factors are involved here which are not always taken into account by investigators: 1) The dead weight of the lath. As soon as the centre of gravity of the upright lath shifts (as a result of snow creep) from a vertical line passing through its base, the weight of the lath immediately imposes an additional load on that part of the snow cover which lies under it. The higher the lath rises above the surface of the snow, the greater the leverage, the greater the pressure it can exert on the snow and the more it deforms it. If a lath is inserted vertically into the snow as far as it will go, the dead weight effect of the lath is reduced to a minimum as a result of the shortening of the lever arm. 2) The effect of snow contraction during consolidation and, linked to this, the increase of pressure exerted by the overlying snow on the slanting lath.

When the lath is in a vertical position on a horizontal site it is, of course, completely unaffected by the pressure of the upper layers. The line of gravitational force is parallel to the axis of the lath. The tangential forces created by the uneven subsidence of snow around the lath are usually self-neutralizing.

On a slope, however, the interaction of the snow cover and the vertical plank will be quite different. Under the influence of the tangential forces which cause the snow to creep down the slope, the lath will deviate from the vertical and assume a certain angle to the direction of the pressure created during settlement of the snow. One of the elements of the pressures directed normally to the axis of the lath will exert an additional force on the lath. According to formula (1), this force will be directly proportional to the angle of incline of the lath.

Under the influence of force F, the rate of increase of the angle of incline of the lath immediately increases, which, in turn, entails an increase of force F. The lath will be bent down the slope at an ever-increasing rate until it assumes a horizontal position. The angle of the lath α will, with each instant, differ more markedly from the natural angle of displacement φ of the layer of creeping snow under the given conditions. Moreover, if the effect of the first factor (the weight of the lath) is reduced in proportion to the relative increase of the part of the lath buried in the snow, the effect of the second factor will increase.

Thus, the use of light wooden laths for creep measurement results inevitably in exaggeration of the creep rate, which is extremely difficult to take into account.

In order to obtain a more general picture of snow creep over an extended period of time, the station used paper tapes stuck vertically into the snow with a long, narrow ruler. Where the snow layers were compacted the tape crumpled easily, forming light folds. Using this method, it was possible to obtain a completely realistic picture of the relative movements of the various layers of snow down the slope. Still more effective and convenient to use are linen tape measures. These are the standard centimetre tapes used by tailors. The fact that they are marked off in centimetres facilitates the reading of velocity gradients and permits the settlement of the snow layers to be gauged at the same time as the creep. Observations of the deviations of the tapes from their original vertical positions reveal a marked difference in the rate of movement of the snow at various times during the winter.

The first test, in which a group of three tapes was used, took place in the first half of the winter (the tapes were inserted on the 20th of December, 1962, and dug up on the 5th of February, 1963) on a 25^{0} slope with a western exposure. During this period the average rate of movement of the snow in a layer 40 cm from the ground was $3.2 \cdot 10^{-6}$ cm/sec. The second test with a set of tapes inserted in the same place was carried out in the second half of the winter (the tapes were inserted on the 8th of February and dug up on the 6th of March, 1963). The average rate of movement at the same depth was found to be $0.2 \cdot 10^{-6}$ cm/sec. Thus, the rate of snow creep in the second half of the winter had decreased to one sixteenth of the rate measured in the first half of the winter.

The results of these observations on the distribution of velocities in the vertical profile of a snow mass confirm G.K. Tushinskii's(2) conclusion about the differences in the plastic properties of snow layers with different structures.

In order to obtain factual data on the distribution of the rate of movement in relation to the snow structure, micro-creep instruments were placed at different levels in the snow mass in a vertical profile:
1) 30 - 32 cm data unit - centre of layer of coarse-grained snow; 2) 40 - 44 cm data unit - upper part of layer of coarse-grained snow; 3) 50 - 55 cm data unit - lower part of layer of fine-grained snow.

The observation site was a 29 - 30^{0} slope with a northern exposure and an absolute altitude of 2,230 m. The observations were conducted on the 22nd and 23rd of February.

As is evident from Table IV, the rate of creep in a homogeneous layer increases uniformly in proportion to the distance away from the ground. The velocity gradient in the 00 - 31 cm layer is the same as that in the 31 - 42 cm layer.

However, in the transitional stage from a coarse-grained to a fine-grained layer of snow the rate increases sharply. The velocity gradient here is increased by more than seven times.

In this case, even when the instruments were placed in one vertical plane and the measurements taken simultaneously, the movement of certain layers in relation to the others was found to be highly erratic. In other words, the movement of different layers of snow in the same vertical plane is extremely uneven.

Observations of the movement of snow by means of tapes supports the theory that during an extended period the average rate of creep in a homogeneous layer increases uniformly the further away the layer is from the ground. In transition to a layer of a different structure the rate of creep decreases sharply.

As a rule, layers of coarse-grained snow occur in the lower sections of the snow mass. Finer-grained snow is found nearer the surface. Under such conditions the tapes are bent at increasingly large angles as they pass into the upper layers of new snow, clearly demonstrating the increased rate of movement of more recent snow which has not yet become coarse-grained. Sometimes, however, the maximum speeds do not occur in the upper layer but somewhere in the middle or lower portions of the snow mass. In this case, it turns out that the more plastic layer consists of somewhat smaller grains than those of the layers on either side of it. Such an "inversion" is possible in the following two cases:

1) Several periods of alternate warm spells and snowfalls (a very frequent occurrence in Central Asia), result in the formation of a thick coarse-grained layer of thermal crusts which have blended together.

Under this, a layer of snow of finer grain structure can be preserved for a long time.

2) "Reverse" metamorphism of the snow is frequently observed in the second half of the winter. A layer of coarse-grained snow is retransformed into a layer of medium-grained structure. Such a "rejuvenated" layer acquires considerable mobility compared with adjacent layers.

Again, all this is indicative of the close relationship between the plastic properties of snow and its structure.

Large velocity gradients are rarely noted in thermal crusts. However, it is not unusual to observe a general shifting of the crust together with all the overlying strata over the layer of loose snow underneath the crust.

The velocity distribution of snow in a horizontal plane presents a picture that is every bit as complex.

Two micro-indicators, mounted side by side at the same distance from the soil in one and the same layer, register different snow movement rates. Instances have been recorded of a slowly moving section suddenly increasing its speed and overtaking an adjacent section of snow.

Observations made with paper tapes confirm the inference that the creep rate in different sectors of a slope varies greatly. Thus, tapes places on a 29 - 30° slope with a northern exposure, at an absolute altitude of 2,230 m, between the 8th of February and the 6th of March, the overall depth of the snow being a little over a metre, indicated the different distances travelled by various sections of the snow cover (Table V). It is obvious that the micro-relief of the underlying surface (paths, protuberances, hollows, etc.) has a considerable effect on the movement of the snow.

It is evident from Table V that the difference in speeds of individual sections of snow may be reckoned in factors of ten.

A somewhat smaller, though still considerable, velocity spread was indicated by tapes placed in different conditions during the same period.

What were the maximum snow creep velocities observed in the vicinity of the station? It is difficult to speak about a maximum rate of movement in connection with snow because of the intermittent nature of snow creep. We can speak about an average speed over an extended period. Certainly, the upper layers of snow move the fastest.

Maximum speeds of $16 \cdot 10^{-6}$ cm/sec (average for 25 minutes) and $17 \cdot 10^{-6}$ cm/sec (average for 8 minutes) were recorded in the top layer itself (compacted at the time of observation). The observations were conducted on a 25° slope with a northeastern exposure at an absolute altitude of 2,000 m in March, during the middle of the day, in a layer 108 cm from the ground, the overall depth of the snow being 118 cm.

Thus, if such a high rate of movement were to be maintained, the snow would travel 1.5 cm/day. In fact, however, the maximum distances travelled by the most mobile snow layers during this part of the winter are approximately half that figure (0.6 - 0.8 cm/day). The lower maximum average rate of snow creep is explained by the fact that during the colder night periods both the rate of even plastic deformations and the number and magnitude of momentary movements decrease.

This applies only to the upper 10 - 15 cm layer of the snow cover, which is affected by the colder night temperatures; it has no bearing on the underlying layers.

Daily Variations in the Rate of Snow Creep

The daily variations in the rate of snow creep are directly related to the temperature variations in the snow cover. The daily range of air temperature fluctuations in the vicinity of the avalanche station during the observation period was generally speaking, 6 - 8°C.

Several large sweeps of temperature fluctuations were recorded on the surface of the snow cover (10 - 14°C). In isolated instances the difference between the day and night temperatures was as much as 20°C.

A snow cover, especially a layer of dry, loose snow, is an excellent heat insulator. Daily temperature fluctuations do not as a rule penetrate deeper than 20 - 25 cm, and even then there is considerable attenuation. Daily temperature variations in the lower layers are negligible or nonexistent. Where the depth of the snow cover is 1 m or more, it can be assumed that the temperature of the greater part of the snow mass does not vary. Consequently, in this part of the snow cover we do not expect to find large fluctuations in the creep rate during the course of a day.

This conclusion is supported by the results of observations of layers the temperature of which remained constant throughout the 24-hour period.

Relatively small temperature fluctuations extend over longer periods than a day inside the snow mass. For example, on the 5th of February the temperature of the snow layer 20 - 40 cm from the ground dropped 1 - 1.5°C; by the 20th of February it had risen to its original level (Table III). Despite the temperature fluctuations of this layer, its rate of creep continued to decrease uniformly throughout the entire observation period. Thus, under natural conditions, minor temperature variations in deep layers of snow have much less effect on the plastic properties of snow than other factors.

In order to find the relationship between temperature and rate of snow creep, observations were conducted in the upper 10 cm layer of compacted snow. The overall thickness of the snow at the time of the observations was 118 cm. The data unit was placed at a height of 108 cm from the soil. The results of these observations (Table VI) indicate that the creep rate tends to slow up during the cold part of the day. Until further observations have been carried out it is impossible to be more specific about the effect of temperature on the creep rate of the upper layers of snow.

How Snow Creep is Affected by Vibrations

A blast was set off in order to release the snow on the slope where the creep observations were conducted. The distance between the lines of explosive (ammonia dynamite) and the site of the micro-indicator apparatus was 200 - 250 m. Three hundred kilograms of explosive were used. The ground vibration and shock wave following the explosion were distinctly felt by an observer standing by the micro-indicators.

The snow cover did not react immediately to the explosion. The indicator needles of three gauges placed at different levels in the snow flickered at the instant of the explosion and then returned to their previous positions. The blast did not cause the snow to move a single micron. The effect of the blast was reflected in the state of the snow cover some time afterwards. Between one and one and a half hours after the explosion the creep rate had increased by a factor of 3 - 4 (Table VII).

The effect of the blast on the creep rate of the lower layer of snow was particularly marked. One and a half to two hours after the explosion the creep rate dropped to its original level.

Small shocks in the immediate vicinity of the observation sites cause sudden, comparatively large movements of snow. A hand or finger pressed lightly on the snow 30 - 40 cm from the data unit produces an immediate response in the form of a 10 - 20 micron movement of the layer.

After a sudden movement the layer ceases to creep for 1 - 1.5 minutes; then the snow begins to move again at the same rate and in the same manner as before.

The reason for such a complex reaction to vibration should be sought in the peculiarities of the elastico-plastic properties of snow.

As has already been pointed out, because of the high porosity of snow the stresses in it are distributed irregularly. Sections in which large stresses develop are more often subject to plastic deformations and brittle failure and they move at a fast rate. However, as a whole, the forces impelling the snow downwards are neutralized by the forces resisting movement (friction, cohesion, the support of the underlying sections of the snow cover), the result of which is an average rate of movement of the particles.

An explosion or impact introduces additional large, but short-term loads into the balanced system of forces in the snow. The dynamic equilibrium is disturbed. The effect of these additional loads on the snow will differ, depending on the distance from the site of the explosion (impact). On the one hand, at fairly large distances from the source of the shock the snow cover is either completely unaffected or is subjected to a negligible reversible deformation which is below the elastic limit. On the other hand, in the immediate vicinity of the source of the shock, considerable stresses occur in the snow, and these exceed the strength of the snow (ice). The bonds between the particles are destroyed. Certain sections will suddenly move a greater or lesser distance, depending on the structure of the snow and the force of the shock. Between these two extremes there is a transitional area in which the stresses created by the shock are still great enough to overcome the elastic limit, but do not exceed the strength. This is the region of plastic deformations.

Different investigators give different values for the elastic limit of ice. In the opinion of B.P. Veinberg and other research workers, the most likely figure is 0.5 kg/cm^2, which was obtained by Fabian(1). The ultimate strength of ice is 10 kg/cm^2. Between these extremes there is a pretty extensive range of stresses for plastic deformations. In this range, an explosion destroys the weakest contacts and bonds between the particles. A certain number of granules or aggregates of snow are momentarily displaced. The stronger bonds between the remaining particles are left intact and these, as a result of the displacement of the granules with weak bonds, will be subjected to an additional load which will cause stresses exceeding the plastic limit of snow. For a certain time the snow cover acquires the property of viscosity, i.e. the capacity to increase plastic deformations without an increase in the load.

Thus, the short-term effect on snow of an explosion or other type of shock, which expresses itself in the form of a spasmodic movement of the snow in the region of the shock source, will change at a certain distance from the source into a prolonged plastic flow.

The Influence of the Support of Underlying Snow on the Creep Rate of Snow

Two creep recording instruments were placed in the snow cover in a test-pit approximately 4 m in length running across the slope. The data unit of one of them was inserted in the snow at the same angle as the pit, as near as possible to the side wall. The other, a control instrument, was placed in the central part of the working wall of the pit, at the maximum distance from the side walls.

The data units of both instruments were located at the same level - 42 - 43 cm from the ground. The instruments remained in this position for approximately 36 hours. Readings were taken regularly every 1 - 2 hours. Then the pit was widened so that the data unit in the corner was left at some distance from the side wall. The average velocity of the snow supported by the snow on the downhill side was $1.16 \cdot 10^{-6}$ cm/sec, and the average velocity of unsupported snow in the same sector was $1.64 \cdot 10^{-6}$ cm/sec.

Thus, for free creep the rate of movement was approximately one and a half times as great. It should be noted that, after the test-pit was widened, the control instrument also indicated an increase in the creep rate of the snow.

Conclusion

1. A snow cover, like highly porous sedimentary rock, is, in terms of its mechanical properties, subject to the laws of an elastico-plastic body. Snow creeps slowly down a slope in an irregular, intermittent fashion. Spasmodic movements of individual sections of a snow cover alternate with complete cessation of creep. The rate of plastic deformation of the snow changes continuously.

2. Spasmodic movements of elementary sections of the snow associated with brittle failure in the most taut sections of the cover are accompanied by a definite acoustic effect which should be taken into consideration when working in snow with acoustic instruments.

3. Both in longitudinal and in cross-sectional profiles, other conditions being equal, the creep rates of various sectors of snow may differ from each other by a factor of several tens. This appears to be closely linked with the micro-relief conditions of the slope.

4. Under natural conditions the rate of snow creep depends largely on the structure of the snow. The larger the granules, the smaller (in terms of one or two decimals) the movements.

5. The daily velocity fluctuation in the main body of the snow cover is quite insignificant in view of the small range of temperature fluctuations.

6. The effect of short-duration shocks on the rate of snow creep is felt in the form of instantaneous movements near the source of the shock and in the form of accelerated rates of movement at specific intervals of time in areas further away from the source.

7. Sections of the snow cover located lower down the slope offer resistance to the creeping movement of the sections above them, thus creating a support. With the removal of this support the rate of snow creep is increased 1 1/2 - 2 times.

References

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3. Shumskii, P.A. Osnovy strukturnogo ledovedeniya (Principles of structural ice science). Moscow, 1955.

Table I

Data of observations conducted at increased frequency during the period 4:00 to 4:28 p.m. on 22nd February, 1963. Height of data unit above ground 49 cm, overall depth 115 cm, exposure northeast, absolute altitude 2,230 m; initial reading 628 microns

	Time					Time			
No.	hr	min	sec	Reading	No.	hr	min	sec	Reading
1	16	00	00	628.0	28	16	18	00	640.5
2	16	01	00	628.0	29	16	18	15	641.0
3	16	02	00	628.1	30	16	19	00	641.2
4	16	03	00	628.1	31	16	19	15	641.3
5	16	04	00	628.2	32	16	19	30	642.2
6	16	05	00	628.2	33	16	20	00	644.0
7	16	06	00	628.3	34	16	20	15	644.2
8	16	08	00	628.3	35	16	20	30	644.8
9	16	09	00	628.4	36	16	20	45	645.0
10	16	10	00	628.4	37	16	21	00	645.4
11	16	10	30	628.8	38	16	21	15	646.0
12	16	10	50	628.9	39	16	21	30	646.1
13	16	11	00	629.0	40	16	21	45	646.2
14	16	12	00	629.5	41	16	22	00	646.3
15	16	12	30	630.0	42	16	22	30	646.3
16	16	13	10	631.0	43	16	22	45	646.5
17	16	14	00	632.0	44	16	23	00	646.9
18	16	14	30	638.0	45	16	23	15	647.0
19	16	15	00	638.0	46	16	23	30	647.1
20	16	15	20	638.2	47	16	23	45	649.2
21	16	15	30	638.4	48	16	24	00	650.0
22	16	15	45	638.9	49	16	25	00	651.0
23	16	16	15	639.0	50	16	25	30	651.3
24	16	17	00	639.2	51	16	26	00	651.6
25	16	17	15	639.6	52	16	27	00	652.5
26	16	17	30	640.0	53	16	28	00	653.2
27	16	17	45	640.0					

Table II

Data of observations conducted at increased frequency during the period 2:18 to 2:43 p.m. on 12th March, 1963. Height of data unit above ground 87 cm, overall height 110 cm, exposure northeast, absolute altitude 2,000 m; initial reading 423.4 microns

	Time					Time					Time			
No.	hr	min	sec	Reading	No.	hr	min	sec	Reading	No.	hr	min	sec	Reading
1	14	18	00	423.4	26	14	26	30	310.0	51	14	36	48	180.0
2	14	18	30	423.3	27	14	27	00	309.0	52	14	36	50	145.1
3	14	19	00	423.2	28	14	27	15	308.0	53	14	37	00	145.0
4	14	20	00	423.1	29	14	27	30	307.0	54	14	37	10	140.0
5	14	20	10	423.1	30	14	27	31	302.0	55	14	37	20	125.6
6	14	20	11	413.0	31	14	28	30	301.9	56	14	38	00	125.5
7	14	20	11	395.0	32	14	29	00	301.8	57	14	38	15	125.3
8	14	20	14	390.0	33	14	29	30	301.6	58	14	38	30	125.1
9	14	20	15	377.0	34	14	29	33	287.2	59	14	38	30	119.0
10	14	21	00	376.0	35	14	29	45	285.0	60	14	38	45	118.9
11	14	22	00	375.0	36	14	30	00	285.0	61	14	39	00	110.0
12	14	22	15	370.0	37	14	31	00	285.0	62	14	40	30	109.0
13	14	23	00	370.0	38	14	32	00	285.0	63	14	40	45	109.6
14	14	23	01	333.0	39	14	34	00	285.0	64	14	40	46	108.0
15	14	23	10	330.0	40	14	35	00	284.9	65	14	40	47	107.0
16	14	23	13	325.0	41	14	35	00	212.0	66	14	40	48	105.0
17	14	23	15	325.0	42	14	35	02	208.2	67	14	40	49	102.5
18	14	23	16	324.0	43	14	35	10	206.0	68	14	40	50	102.0
19	14	23	17	321.0	44	14	35	20	202.0	69	14	40	51	101.0
20	14	24	00	320.8	45	14	35	30	202.0	70	14	40	52	100.9
21	14	25	00	320.6	46	14	35	45	195.0	71	14	41	00	100.5
22	14	25	30	320.6	47	14	36	10	190.0	72	14	42	00	100.5
23	14	26	00	320.5	48	14	36	20	185.0	73	14	42	30	100.0
24	14	26	10	320.0	49	14	36	30	183.0	74	14	42	45	97.0
25	14	26	11	310.0	50	14	36	40	183.0	75	14	43	00	97.0

Table III

Variation in depth of snow cover and temperature of lower layers of snow during period 5th - 23rd February, 1963

Date	Depth of snow, cm	Temp. of snow °C		Date	Depth of snow, cm	Temp. of snow °C	
		20 cm	40 cm			20 cm	40 cm
5	79	-0.8	-1.3	15	82	-0.6	-1.0
6	78	-0.8	-1.6	16	82	-0.6	-1.0
7	77	-1.2	-2.6	17	100	-0.6	-1.0
8	76	-1.4	-2.6	18	95	-0.5	-1.0
9	73	-1.5	-2.9	19	94	-0.6	-1.1
10	67	-1.7	-3.6	20	91	-0.6	-1.2
11	80	-1.8	-3.7	21	90	-0.7	-1.4
12	65	-1.5	-4.2	22	89	-0.9	-1.7
13	65	-1.8	-2.7	23	88	-1.1	-1.9
14	72	-0.9	-1.0				

Table IV

Rate of snow creep in different layers

Level of layer, cm	Rate, cm/sec	Velocity gradient between layers, sec^{-1}
31 (30-32)	$0.6 \cdot 10^{-6}$	$0.02 \cdot 10^{-6}$
42 (40-44)	$0.8 \cdot 10^{-6}$	$0.02 \cdot 10^{-6}$
50 (50-55)	$1.8 \cdot 10^{-6}$	$0.14 \cdot 10^{-6}$

Table V

Distances in centimetres travelled by various sections of snow during the period 8th February to 6th March, 1963

No. of tape	Height of snow layer above ground	
	40 cm	70 cm
1	3.0	4.8
2	0.5	1.0
3	16.0	22.0

Table VI

Relationship between creep rate and temperature of snow (compacted)

No.	Time observ. started		Duration of observ.		Air temp. °C	Temp. of snow surface °C	Av. creep rate cm/sec	Remarks
	hr	min	min	sec				
					11/3/1963			
1	12	00	1	00	3.6	00	$16.6\cdot10^{-6}$	
2	12	10	5	30	3.6	00	$12.1\cdot10^{-6}$	
3	12	35	25	00	3.5	00	$16.0\cdot10^{-6}$	
4	13	00	3	30	3.5	00	$14.3\cdot10^{-6}$	
5	13	05	2	25	3.5	00	$13.8\cdot10^{-6}$	Sunset.
6	16	00	2	06	3.0	-0.5	$15.1\cdot10^{-6}$	Intermittent movements.
7	16	30	2	13	2.0	-3.0	$32.3\cdot10^{-6}$	
8	16	32	5	31	2.0	-3.0	$10.9\cdot10^{-6}$	
					12/3/1963			
9	6	40	1	50	1.7	-13.0	$10.9\cdot10^{-6}$	
10	7	00	4	30	1.6	-13.0	$11.1\cdot10^{-6}$	Temp. at level of data unit - 7°C. Sunrise.
11	7	10	2	55	1.6	- 6.0	$8.6\cdot10^{-6}$	
12	10	40	5	20	4.0	00	$15.7\cdot10^{-6}$	

Table VII

Results of observations on the effect of an explosion on the creep rate of snow

Ht. of layer above ground,	Creep rate, cm/sec		
	Before explosion	Av. during 1 1/2 hr after explosion	Av. during 24 hr after explosion
31	$0.54\cdot10^{-6}$	$2.6\cdot10^{-6}$	$1.0\cdot10^{-6}$
42	$1.6\cdot10^{-6}$	$3.5\cdot10^{-6}$	$1.4\cdot10^{-6}$
43	$2.0\cdot10^{-6}$	$4.0\cdot10^{-6}$	$1.4\ 10^{-6}$

EXPERIMENT IN THE ARTIFICIAL DUSTING OF SNOW IN AVALANCHE ACCUMULATION AREAS AS A METHOD OF COMBATTING THE DANGER OF AVALANCHES

by

Yu. N. Emel'yanov and A.I. Korolev

Three questions are examined in this article: 1) the spraying of coal dust on the slopes of an avalanche accumulation area by aircraft; 2) the effect of artificial dusting on the physico-mechanical properties of the snow; 3) the feasibility of artificial dusting of the snow in avalanche accumulation areas to prevent avalanches.

In January 1963 snow covered slopes in the region served by the Dukant Snow Avalanche Station were sprayed with coal dust from an AN-2 aircraft belonging to Agricultural Aviation. Here we were governed by the following considerations: a) dusting accelerates the ablation of snow on the slopes, thereby reducing the threat of avalanches; b) the more intense thawing of the blackened snow during the day and freezing at night cements the snow cover to a much greater degree than would be the case if the natural conditions were not interfered with. This would also reduce the possibility of avalanche formation.

The sprayed area is an oval-shaped avalanche cirque, the lower portion of which is narrower than the top. Its length is 1,200 - 1,250 m, its maximum width from the crest of one slope to the crest of the opposite slope is more than 300 m, its minimal width (at the mouth) 75 m, and its area 24 hectares. Having a general western orientation, the right slope of the avalanche area is exposed to the south, the left to the north. The angle of the slopes is 30 - 35°. The average angle of incline of the discharge channel is 23 - 28°.

Since the coal dust was not sifted beforehand, a considerable quantity of large particles was found among the fine particles. It was felt that dusting the snow with such a mixture would be less effective than dusting with the same quantity of sifted dust; therefore, the quantity of dust per unit of area to be treated was increased to approximately 50 g/m^2.

The aircraft dropped one ton of coal dust on the avalanche area in four consecutive passes on each flight. More than 10 tons of coal were dropped in 9 flights. The dust was laid across the avalanche area in straight lines from altitudes of up to 40 m.

Analysis of the grain size composition of the dust showed that 2/3 of it consisted of particles less than 1 mm in diameter and the remaining third of larger particles (from 1 to 10 mm). If we take into account the larger pieces of coal, which were ignored in sampling tests, it can be estimated roughly that the ratio by weight of unsorted coal dust in terms of particles smaller an larger than 1 mm is 1 : 1.

The Distribution of Coal Dust by Aerial Spraying on the Slopes of the Avalanche Accumulation Area

As a result of the dusting, the avalanche accumulation area was covered by bands of coal dust up to 15 m wide, separated by lighter, somewhat narrower intervals of snow (up to 10 m wide). These bands are clearly visible in the morning and evening when the sun is hidden behind the crest of the mountains. At these times the dusted slopes appear greyish and stand out clearly against the white slopes of the neighbouring avalanche areas. Darker strips of dust resulting from uneven spraying are clearly visible against this ash-grey background.

It is interesting to note that the instant the slopes are illuminated by the sun's rays, the colour of the dusted slopes is absolutely indistinguishable from the surrounding, untreated slopes when viewed from a distance.

It is assumed that if the dust had been sprayed from an altitude greater than 40 m, the result would have been a more uniform application.

The distribution of dust within individual bands, which was also uneven, depended on the orientation of the slopes. The slope with the southern exposure was blackened more evenly than the slope with the northern exposure. Wind action as a factor in uneven distribution is excluded in the present case, since the wind velocity over both slopes on the day of application did not exceed 1 - 2 m/sec.

The reason for the more uniform dusting on the southern slope is that the snow cover here is usually covered by a uniformly rough sun crust caused by intensive solar radiation. The rough surface of the snow prevents the dust from rolling and from being blown away by the wind. Dust sprayed on the southern slopes remains in its original position. The northern slopes receive considerably less solar radiation. In periods of increased wind activity, the loose, dry snow is carried from one place to another. Numerous patches with a denser and more polished surface of wind crust are formed. A wind crust surface rarely retains coal dust. The dust rolls to the edges of the smooth patches, outlining light islands of snow cover in black. The slope takes on a spotted appearance. A certain amount of the dust is blown by the wind into concave forms of micro-relief: grooves formed by lumps of snow which have rolled down the slopes, wild animal tracks, etc.

In order to ascertain the degree of uniformity achieved in spraying the dust, samples of dusted snow were taken. At representative points the upper layer of snow, up to 2 cm deep, is taken from a unit area. The snow is melted and the residue filtered out on a technical balance.

The results of these observations are given in Table I.

As is evident from Table I, the dust on the surface of the avalanche accumulation area is distributed unevenly. The quantity of dust per square metre of snow cover varies from a fraction of a gram for sectors at the edge of the treated area, to 100 g in certain sectors inside the area.

The Influence of Artificial Blackening of Snow Cover on the Physico-Mechanical Properties of the Snow in the Event that Fresh Snow Falls on the Blackened Surface

Shortly after the snow in the avalanche accumulation area had been sprayed with coal dust, fresh snow fell on the blackened surface and the acceleration of surface thawing was interrupted. This raises the question of the effect on the physico-mechanical properties of the snow of a dusted layer covered by a layer of fresh snow. Would the blackened layer facilitate the strengthening of the bonds in the snow or, on the other hand, reduce the stability of the snow cover on the slope? In order to resolve this question, special observations were conducted at the Dukant Snow Avalanche Station.

At the end of January two sites measuring 5 x 5 m were prepared to artificial blackening under conditions similar to those in the dusted avalanche area. One of them was situated on a small plateau with an almost horizontal surface, the other, with a 30^{0} angle of incline, was located on the northeastern slope of the avalanche area adjacent to the plateau. The sites were blackened with fine (crushed) coal dust applied at the rate of 20 g/m^2. Comparative observations were carried out simultaneously at untouched control sites alongside the treated areas. Absolutely identical geomorphological and meteorological conditions at the sites ensured comparability of the observation data. Apart from this, since sites were located on a shaded slope and on a plateau illuminated by the horizontal rays of the sun throughout the greater part of the day, it was possible to ascertain the effect of artificial dusting on the properties of a snow cover subjected to greater amounts of solar radiation.

The snow cover depth at the site with a northeastern exposure was 70 - 72 cm and at the horizontal site, 50 cm when the dust was applied.

The layer of dust at both sites was covered by drifting and fresh snow in the two days following application, which meant that it was in a state similar to that of the dust layer in the avalanche area which had been sprayed from the air (the latter had been covered by fresh snow several days earlier). Observations were carried out periodically and completed on the 5th of April. By this time the layer of snow covering the blackened surface at the horizontal site had completely disappeared and the underlying layers had begun to melt. The depth of the snow cover on the northeastern slope had also decreased considerably.

The results of the observations (Tables II and III) indicate the following:

1. The change in the depth of the snow layer underneath the coal dust at the test sites was in fact (allowing for variations due to irregularities in the underlying surface) no different from that of the corresponding layer at the control site. The same applies to the change in the depth of the snow above the layer of dust.

2. Throughout the entire period of the observations the volumetric weight of the snow at the dusted sites remained the same (within the limits imposed by the degree of accuracy of the balance) as that of the snow at the control sites.

3. Shear strength at the contact of the fresh snow with the blackened layer was equal to, or a little less than, the shear strength at the contact of the same snow with an untreated layer.

It should be noted that failure of snow samples, both at the dusted test sites and at the control sites usually occurred, not on the dusted horizon, but somewhat lower, in the loose layer directly below the blackened surface (or the layer corresponding to it at the control site).

4. The structure of the snow (from visual observations) in the control test-pit did not differ in any way from that of the snow in the test-pit at the experimental site, apart from dark bands of stains from the dust which occurred in the underlying layers of the snow mass in test-pits at the blackened site on the 19th of March and subsequently.

However, some interesting peculiarities were discovered in the texture of the snow mass which, in all probability, appeared as a result of dusting. We shall examine the data of observations conducted on the 19th of March, 1963.

Horizontal Site

a) Dusted site. A 7 - 9 cm layer of coarse-grained snow darkened by seeping moisture lay directly under the layer of coal dust. Underneath, it terminated in a half-decayed (possibly re-forming) ice layer. This layer, 2 - 3 mm thick, was not solid, but made up of separate laminae (lenses).

b) Control site. A layer of coarse-grained snow approximately 10 cm thick lay directly underneath the surface corresponding to the blackened horizon. Underneath, it terminated in a solid layer of ice 3 - 5 cm thick running along the entire wall of the test pit without interruption.

The texture of the snow above the blackened surface in no way differed from the texture of the same layer of snow at the control site.

Northeastern Exposure

a) Dusted site. A layer of fine-grained snow, 25 cm thick, lay directly on top of the blackened horizon. A poorly defined, discontinuous layer of iced firn, which in places changed to thin ice lenses, had formed 7 cm above the film of dust.

b) Control site. A layer of fine-grained snow, approximately 25 cm thick, lay directly on top of the horizon corresponding to the film of dust. Seven centimetres above the horizon corresponding to the film of dust a clearly defined, continuous layer of ice had formed.

The texture of the snow below the blackened surface was identical to the texture of the snow comprising the same layer at the control site.

Thus, in comparison with the control site, there was less intensive formation of ice layers in the snow directly adjacent to the dust layer in the stratigraphy of the snow mass at the dusted sites. At the horizontal site a weakened ice layer was noted in the layer below the coal dust, while on the slope with the northeastern exposure a weakened ice layer was found in the layer above the coal dust.

The reason for the peculiar way in which ice layers formed at the dusted sites remains unclear.

No other peculiarities in the stratigraphy of the dusted snow mass were detected during visual observations.

Thus, the results of our attempts to find out how spraying the snow cover with coal dust affects the physico-mechanical properties of snow, when the dusted surface is covered by subsequent snowfalls, showed that no noticeable changes in the depth and volumetric weight of the snow cover occur as a consequence of dusting, nor did dusting result in any observable strengthening of the bonds in the snow. On the contrary, a certain decrease of shear strength was noted in the layer of snow subjected to dusting. This is indicated by the fact that an avalanche occurred in the accumulation area which had been sprayed with coal dust from the air. The avalanche occurred presumably on the 9th or 10th of March, shortly after the snowfall of the 6th - 9th of March, which yielded a total of 33 mm of precipitation.

At first only the freshly fallen snow was involved in the avalanche. The tail of the avalanche in this sector consisted of lumps of pure white snow. However, having travelled a third of its path, approximately 130 m, the avalanche took hold of the underlying 20 cm layer of old snow, including the dusted surface. From this point on the avalanche moved on the zone of low strength which had formed directly underneath the coal dust. This was indicated by the changed colour of the lumps of snow in the tail of the avalanche. Without exception the lumps were covered by a layer of snow blackened by the coal dust. The snow layer below the blackened, low strength zone was untouched by the avalanche.

Thus, instead of reinforcing the "cementation" process and consolidating the snow on the slope, artificial dusting of the snow cover resulted in a certain loosening and weakening of the bonds in the layer immediately underneath the dusted surface. Therefore, spraying avalanche accumulation sites with coal dust as a means of preventing avalanche occurrences is ineffectual and inefficient under the conditions described above.

Table I

The quantity of coal dust which fell on 1 m^2 of snow cover

No. of sample	Exposure	Absol. alt., m	Amt. of dust g/m^2	No. of sample	Exposure	Absol. alt., m	Amt. of dust g/m^2
1	South	2,010	1.0	6	West	2,000	44.2
2	South	2,135	29.1	7	West	2,015	0.3
3	South	2,220	32.1	8	West	1,800	0.2
4	South	2,220	8.0	9	North	2,050	92.3
5	West	2,040	67.0	10	North	2,025	3.0

Note:

1. Sample 7 was taken at the crest of the right side of the avalanche accumulation area at the edge of the dusted area.
2. Sample 8 was taken at the mouth of the avalanche accumulation area outside the dusted area.
3. Sample 10 was taken from a wind crust surface.

Table II

The effect of artificial dusting on the physico-mechanical properties of snow when fresh snow falls on a blackened surface. Horizontal site

Serial No.	Date	Depth of snow layer under given horizon		Depth of snow layer above given horizon		Unit wt. g/cm^3 upper layer / lower layer		Cohesion kg/m^2 above dusted horizon / at contact with dust layer	
		dusted	control	dusted	control	dusted	control	dusted	control
1	5/II 1963	47	48	45	46	0.25 0.35	0.29 0.36	567 608 906	450 888 1,000
2	19/III	45	47	39	34	0.34 0.38	0.38 0.38	675 >1,000	650 >1,000
3	31/III	43	44	15	14	0.48 0.36 0.38*	- - 0.37*	-	-
4	5/IV	33	40	melted	melted	- 0.41	- 0.38	>1000 (h =20 см) 877 (h =19 см) 570 (soil)	>1000 (h = 20 см) 7—7 (h = 19 см) 580 (soil)

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* Average weight by volume of the entire snow mass

Table III

The effect of artificial dusting on the physico-mechanical properties of snow when fresh snow falls on the blackened surface.
Slope with northeastern exposure, angle of slope 30°

Serial No.	Date	Depth of snow layer under given horizon		Depth of snow layer above given horizon		Unit wt. g/cm^3 upper layer / lower layer		Cohesion, kg/m^2 above dusted horizon / at contact with dust layer	
		dusted	control	dusted	control	dusted	control	dusted	control
1	5/II 1963	72	72	45	46	0.26 0.28	0.27 0.28	790 412 400	850 860 365
2	19/III	65	65	56	56	0.29 0.34	0.28 0.32	375 768 800	362 830 730
3	5/IV	65	65	28	26	0.40 0.28	0.41 0.31	196 1,000 392	255 1,000 405

EXPERIENCE IN THE ELIMINATION OF AVALANCHE DANGERS IN THE TIEN-SHAN REGION

by

N.V. Maksimov

This article interprets the results of an evaluation of the work on snow and avalanche investigations in the Kirghiz SSR, gives characteristics of meteorological phenomena which cause avalanches and describes experience in the elimination of avalanche hazards.

Snow avalanches represent a serious hazard for personnel, the planning and construction of trunk routes, power transmission lines, etc., in mountainous regions. The construction of objects in such areas necessitates special programmes for the investigation of snow avalanches directed towards a study of avalanche forecasting and the planning of engineering defences. Plans have been made for large-scale development of all sectors of industry and agriculture, and expansion of the mining and extractive industry is envisaged. As is known, most of the non-ferrous metal deposits in the Tien-Shan Mountains are located in avalanche areas. This has an adverse effect on the economy of enterprises exploiting these deposits and creates dangerous conditions for the workers.

Failure to take sufficient account of avalanche hazards in the construction of roads and the selection of cattle trails increases work costs, results in needless expenditure of funds and labour and sometimes to fatal accidents. The Directorate of Hydrometeorological Services of the Kirghiz SSR has for 10 years been conducting snow measurement work on a large scale in the mountains of Kirghizstan. Snow-measuring detachments and parties encounter avalanches with increasing frequency during field expeditions in the winter. Personnel of the Hydrometeorological Service, who have had considerable practical experience in the Tien-Shan Mountains and are familiar with the orography and the meteorological conditions of the region, usually manage to avoid accidents. Geological parties and detachments working in the mountains without guides and not knowing the conditions prevailing in highland and alpine regions are in a less fortunate position.

During the last 4 - 5 years alone, approximately 900 avalanches of different types were recorded. The volume of these avalanches varied between 1,000 and 6,000,000 m^3.

In examining avalanche conditions, it is necessary to consider the individual elements of avalanche activity attributable to a complex of physico-geographical processes. The duration of the avalanche danger period is approximately six months (December to May). The earliest avalanche was recorded on the southern slopes of the Kirghiz Range on the 26th of

November, 1959. Its volume was 8,920 m^3. The latest avalanche was recorded at the beginning of June 1960 in the Susamyr River basin (southern slope of the Kirghiz Range). Its volume was 1,280 m^3.

Expeditionary observations have shown that the most dangerous regions in Kirghizstan are the northern and southern slopes of the Kirghiz Range, spurs of the Talas, Chatkal', Fergana, Chon-Alai, Kugart, Susamyr, Moldo-Tau, Terskei-Alatau ranges, the region of the Pobeda and Khan-Tengri peaks.

The largest and greatest numbers of avalanches were recorded in the basins of the rivers Padshaata (6,400,000 m^3, February 1952), Karadar'ya (2,400,000 m^3, March 1956), Susamyr, southern side of Tyuya-Ashu Pass (1,125,000 m^3, March 1959), Ters (900,000 m^3, January 1961), Gavasai (750,000 m^3), Isfairam (600,000 m^3, March 1955), Aflatun (525,000 m^3, March 1959), Talas (140,000 m^3, March 1958), Yassy (46,000 m^3, March 1959), Bol'shaya Kzylsu (180,000 m^3, May 1958).

The period of maximum avalanche activity occurs at the end of March and the beginning of April. The frequency of avalanche occurrences depends mainly on the geomorphological features of the avalanche accumulation area.

Avalanches are observed most frequently on 25 - 45^0 slopes with a herbaceous cover. Most of the recorded avalanches were of the flowing type (65%); 23% sliding, 12% airborne and miscellaneous avalanches. The greatest number of avalanches occur in the altitude zones 1,600 - 2,200 m and 2,200 - 3,500 m above sea level.

The principal causes of avalanches in Kirghizstan are:

a) intensive precipitation;
b) thermal contraction and mechanical overloading of the snow by fresh or drifting snow;
c) weakening of the bounds in the snow resulting from evaporation and recrystallization of the snow;
d) sudden changes in the air temperature;
e) solar radiation which substantially alters the internal cohesion in the snow.

A brief analysis of the conditions of avalanche occurrence conducted by specialized snow avalanche stations revealed the essential nature of the processes of avalanche formation and the reasons for the occurrence of various genetic types of avalanches.

In the regions served by these stations more than 300 avalanches with various genetic characteristics and volumes of 1,000 to 1,125,000 m^3 were recorded over a period of 3 years.

Most avalanches (71%) are attributable to freshly fallen snow; the remaining 29% is made up of the following types: destructive metamorphisms

12%, drifting snow 3%, thermal contraction 9%, and 5% miscellaneous, the formation of which is affected by several factors. For example, avalanches are caused by thermal contraction of the snow and by the mechanical effect of the wind on the slope, usually with minimal bonding between the freshly fallen and the old snow. In this case there are three genetic characteristics, the most important being thermal contraction of the snow.

In order to provide systematic and practical assistance to organizations concerned with avalanche defence measures, the Directorate of Hydrometeorological Services of the Kirghiz SSR has since 1957-1958 considered it necessary to expand the programme of avalanche observations. Four specialized snow avalanche stations were set up in Kirghizstan to study the physico-mechanical properties of the snow, its temperature regime, stratigraphy and microstructure. In mountain regions where access is difficult, the investigation of snow and snow avalanches by means of helicopters was initiated, the volume of expeditionary work on the study of hazardous regions from reports submitted by national economic organizations was increased, and experiments were begun to determine the feasibility of releasing avalanches as a preventive measure.

The Directorate of Hydrometeorological Services of the Kirghiz SSR proposed that a system of avalanche forecasting be worked out, that the degree of avalanche hazard be evaluated and recommendations for avalanche defence measures be submitted for a number of industrial installations and enterprises within the shortest possible time. In addition, it was necessary to assure uninterrupted round-the-clock operation of transport, pits and adits located in danger zones. Lack of previous experience in this type of work was a serious obstacle in the way of a solution to this problem. Conditions governing the formation and descent of avalanches in the Tien-Shan Mountains are similar to those in the Caucasus and the Alps. The work conducted in other countries on avalanche formation and the servicing of communications and industrial installations has not been studied yet. The avalanche forecasting system for the Khibiny Mountains now being used by the "Apatit" Combine Snow-Meteorological Service is based on calculation of the extent of snow drifting and cannot be applied in its entirety and without modification to other physico-geographical regions (for example, the Tien-Shan Mountains), since avalanche formation conditions in these regions are basically dissimilar.

The basic parameters of snow which determine the degree of avalanche hazard - shear strength, tensile strength, unit weight, coefficient of friction are, in the majority of cases, measured outside the area of avalanche formation, i.e. in safe areas, and therefore, are not always reliable.

The fact that the climatic peculiarities of the region have not been sufficiently well studied complicates the situation still further.

The physico-mechanical properties of snow are still being studied by inadequate means. The instruments used to determine the physico-mechanical parameters are not sufficiently accurate and need to be improved considerably.

Experiments in the artificial release of avalanches in the Tien-Shan Mountains were first carried out by specialists of the Directorate of Hydrometeorological Services of the Kirghiz SSR on southern spurs of the Kirghiz Range and in several other regions. Of particular interest were investigations conducted in the region of the Tyuya-Ashu Pass (Kirghiz Range). On the basis of this work it was established that avalanches occur during most of the winter and spring periods, and particularly in February, March and April. The most hazardous conditions were encountered on the south side of the pass where the entire left slope of the ravine of the South Dolen River is subject to avalanche activity. Here there are fourteen of the most dangerous avalanche accumulation areas, spawning avalanches with volumes of up to 1,000,000 m^3.

Measures specified by us for the defence of temporary structures and buildings were not carried through to completion, as a result of which we were forced to work out the necessary measures for releasing the snow by blasting and by cutting and sawing snow peaks. The need for such measures was dictated by the weather conditions. The winter of 1958-59 was characterized by copious snowfalls, sharp fluctuations in the air temperature, and snow storms, all of which created favourable conditions for the formation of avalanches.

The artificial release of avalanches was accomplished with the assistance of workers trained to carry out blasting work and who are responsible for enforcing the rules of safety during blasting operations.

The chief of the avalanche defence service at the avalanche station pin-points the blasting sites in the hazardous areas, takes the responsibility for selecting safe approaches to the avalanches, and decides on the need for and timing of successive blasts (if the avalanche is not released).

The release of snow was carried on throughout the entire winter in the upper and lower sectors of avalanche accumulation areas. The weight of the individual charges and also the distances between them depended on the depth and stability of the snow. Detonating fuses were used to explode the charges. Special attention was paid to the release of cornices which form on the crests of mountains and which, as a rule, act as avalanche triggers.

Six persons took part in the avalanche release expedition: a representative of the snow avalanche station, a blaster and four men to carry the explosives. Observing the rules of safety, it took the detachment 4 - 5 hours to reach the blasting site, first by way of the buttress and then along the water-divide. The representative of the avalanche station indicated the most suitable spot on the cornices for blasting. Three to five holes were dug to a depth of 1 m. Two men secured the safety line of those men digging the holes. The charge, weighing from 15 or 16 kg to 120 kg, was placed in the hole. The blasters detonated the charge from a distance of 250 - 300 m. Sometimes peaks were dislodged by cutting the cornices with a cable. A detachment of four men is needed for this operation. A section of a cornice on a steep slope is selected in such a way that when it is cut free it will displace the snow. The site from which the snow is to be moved is then probed and a crevice 30 - 40 cm wide and 0.6 - 0.7 m deep is carefully made with a spade. Then two men place a 3 - 5 mm cable under the cornice and saw it through. The cutting of a cornice of new snow is a relatively simple matter because of its low density. The principal disadvantage of this method of releasing avalanches are that it takes a considerable length of time to reach the crest and a degree of risk is involved.

A safe firing position is possible only at a considerable distance from the avalanche accumulation area. In this case the firing would have to be conducted from spurs of the main range at distances of 1 - 1.5 km, which not only would have reduced the firing accuracy, but would have increased the natural dispersion of the mortar fire. Apart from this, there was also the danger of mortar shells falling on the road owing to the complex nature of the topography of the valley.

Avalanche warnings were based on the following information:

a) the weather forecast for the next 24 hours from data provided by the Frunze Weather Bureau;

b) the actual depth of the snow cover in the avalanche accumulation areas observed through binoculars on permanent snow gauges located in the avalanche sites;

c) the physico-mechanical characteristics of the snow, which are determined daily at the station and at the avalanche sites. Snow structure, density, temperature, cohesion at the contacts of the layers, and tensile strength are ascertained.

The results of the observations are set out in the form of a composite graph of wind velocity, humidity, amount of precipitation, air temperature and temperature distribution in the snow mass.

The complex graph made it possible to determine the trend of the avalanche hazard, to keep track of variations in the condition of the snow and to establish when the snow on the slope will be in a critical condition.

First, the weather forecast was analyzed and, if necessary, amended.

Particular attention was paid to the critical values of elements characterizing avalanche danger. Thus, for example, in one of the regions we based our determination of the extent of the danger on the following considerations:

1) when the air temperature rises to -5°C and the relative humidity increases, a reduction in the internal cohesion of the snow is assumed;

2) when the cohesion between layers falls to 5.0 g/cm^2 it is assumed that a dangerous situation exists;

3) where the snow depth is not more than 20 - 25 cm (according to the estimated data of the critical values) avalanches are not expected to occur.

The possibility of avalanches arises when the depth of the snow exceeds 30 cm.

If a reduction of cohesion has occurred in the upper layers only and there is a fairly substantial degree of cohesion (10 g/cm^2 and above) in the lower layers, the depth of the layer with weak bonds is taken into consideration in calculating the critical depth.

A fall of 10 mm of precipitation is considered to have created a hazardous situation which might become threatening in the event of further precipitation on the hard surface of the underlying snow. Especially dangerous is the presence of firn crust at the contact of new and old snow, which results in a weak bonding of old and fresh snow.

On the northern slopes of the Kirghiz Range, the following factors were taken as a basis for determining the degree of avalanche hazard:

1) strong winds of 10 - 20 m/sec with a snowdrift rate of 12 g/cm^2 (after snowfalls);

2) freshly fallen snow to a depth of 25 cm on a slippery surface of wind crust or wind slabs;

3) the formation of snow cornices in the upper parts of avalanche accumulation areas;

4) the formation of crevices in the snow mass;

5) a sharp drop in the air temperature and the relative humidity. In this case there was a decrease in the cohesion (to zero) and ultimate tensile strength and formation of a layer of loose snow.

However, the above factors cannot always serve as criteria for evaluating the degree of avalanche hazard, since many other factors are involved the study of which requires considerable time.

The cutting of cornices involves considerable effort and an element of risk. Apart from this, the summits of some avalanche sites are completely inaccessible.

It should be noted that the volume of most avalanches which are dislodged by cutting and sawing cornices is small - from 2,500 to 7,000 m^3, whereas avalanches caused by blasting reach a colossal size.

Thus, our initial tests on the artificial release of avalanches permit us to draw the following conclusions:

a) the preventive release of avalanche by blasting appears to be the most efficient and economical method of combatting avalanche danger in Khirghizstan;

b) a decision concerning the need to dislodge avalanches should be based on consideration of the physico-mechanical parameters of the snow, since the resistivity of the snow to slipping varies in relationship to them;

c) in order to obtain effective explosions which will ensure the initiation of an avalanche, it is necessary to calculate accurately the size of the charge, the force of the shock wave in all directions, and to select the right location for the charge;

d) it is necessary to analyze carefully the depth and density of the snow to calculate the critical depth of the snow which determines the expediency of blasting;

e) the efficiency of the blasts depends on their seismic and acoustic effects and on the forces retaining the snow on the slope;

f) blasting is most effective when carried out 1 - 3 days after a snowfall, or when layers of loose snow form in the snow mass.

These problems were resolved most successfully in the Kokomeren River basin in the winters of 1959, 1960 and 1961.

The experimentts on the preventive release of avalanches represent the initial attempts to resolve the question of economical and efficient anti-avalanche measures in regions where it is impossible to construct engineering avalanche defence structures.

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AUTOMATIC DEVICE FOR ESTIMATING THE DEPTH OF SNOW FROM A REMOTE POSITION

by

V.A. Korobkov

This article contains a description of an automatic snow gauge devised by the snow avalanche laboratory of the Dukant Avalanche Station. A similar gauge is at present undergoing field tests in the region of the avalanche station.

As a result of the intensive industrial development of mountainous regions, we are faced with the problem of investigating the processes of avalanche formation and descent. Such investigations have been going on for a long time at snow avalanche stations and laboratories in the U.S.S.R.

Similar investigations are still being conducted in the old way, without utilizing the latest developments in electronics and automation.

In 1963 a snow and avalanche laboratory was set up at the Dukant Avalanche Station (on a spur of the Western Tien-Shan Mountains). The reason for setting up this laboratory was to facilitate the adoption by the snow avalanche service of instruments and equipment based on the latest advances in the fields of radiotechnology, electronics, automation and telemechanics.

One of the problems undertaken by the laboratory was the design and construction of a snow gauge which can be used from a remote position. There is a manifest need for such a gauge in many scientific and practical fields.

The only existing method of measuring the depth of snow cover employs wood or metal rods from which readings are taken from a remote position with the aid of binoculars or telescopes. The drawbacks of this method are obvious: the rods must be located so that they fall within the field of vision, and visibility must be good; it is absolutely impossible to keep track of variations in snow depth which occur during short intervals of time, i.e. to keep track of intensive snow accumulation, a factor which is especially important in forecasting avalanches of new snow; it is impossible to take readings from great distances, i.e. from greater distances than the optical instrument allows.

Before attempting to design an instrument which would permit the depth of snow cover to be recorded with sufficient accuracy, a survey was made of the existing methods of measuring level of surfaces in general. The measurements of levels occupies a fairly important place in modern measuring techniques.

At present the location method is the most efficient for measuring the depth of snow cover. It permits simultaneous coverage of large areas and determination of the accumulated depth of snow cover in a certain specific area. A low degree of accuracy (up to 40% error) and the impossibility of determining the depth of snow cover at a specified point within a small area are among its chief defects.

A device proposed by the snow and ice laboratory at Moscow State University, consisting of light-sensitive transmitters (photoresistors) mounted at specified intervals on a rod, offers another method of determining snow cover depth. As these photoresistors are covered by snow, they are partially blacked out and this is recorded on a metering device. The method is fairly simple, but suffers from one serious disadvantage: the photoelectric cells have to be illuminated, and, moreover, it is desirable to use modulated light, i.e. light which is interrupted at a specific frequency. This creates a number of problems in connection with the need for complex equipment and large power supplies (depending on the local conditions, the apparatus must operate independently from four to nine months). Moreover, the accuracy of such a device would be limited by the number of photocells per unit length of rod.

A second method, also proposed by the laboratory at Moscow University, employs an altitude gauge-penetrometer. This functions as follows. A measuring rod, mounted below the surface of the ground, is pushed up through the layer of snow to its upper limit by a special electric motor. Thus, as well as measuring the snow cover depth, the device also registers the resistance of the snow to penetration by an external solid body, i.e. snow hardness. The advantages of such a method are indisputable: a high degree of accuracy in the measurement of snow cover depth coupled with a capability of recording additional information about the strength characteristics of the snow cover. However, the gauge has a number of disadvantages, the most important of which are: installation difficulty (it is necessary to embed the rod in the earth to a depth equal to that of the maximum snow cover in the given region), and the high cost of electric power consumption per measurement.

Following this brief and far from complete survey of the different methods of measuring snow cover depth (only those which we consider the most realistic have been mentioned), we shall consider the operational specifications of an instrument for measuring snow cover depth. These specifications have been worked out in the design department of a hydrometeorological instrument research institute. The main requirements are: 1) the instrument must be capable of measuring a snow cover depth of up to 300 cm to within ±1 - 2 cm; 2) the effective range of the device should be 1.5 km if the information is transmitted by line, and 20 km if radio transmission is used; 3) the power supply for the apparatus must come from primary sources (dry batteries); 4) the time required for one measurement should not exceed 2 - 3 minutes; 5) the weight of the equipment should not exceed 10 - 20 kg in the case of line transmission, and 30 - 40 kg in the case of radio transmission; 6) the equipment should be compact and easily transportable; 7) the device should be simple to operate and maintain.

It is evident that none of the above-mentioned pieces of equipment meets these specifications.

A device which does meet these requirements has been produced at the Dukant Avalanche Station. The mode of operation of this "automatic snow gauge": (ASG) is examined below.

A load in the form of a flat ring, which hangs from a flexible arm and slides lengthwise along the gauge, is let down from a fixed height onto the surface of the snow. The instant the load touches the surface of the snow, the tension on the arm is reduced. The slackening is registered at the metering point. At the same instant the load begins to rise to its original position. The rate of descent of the load is known, the height H (the height from which the load begins its descent) is also known. It is a simple matter to calculate the time t (with a stop watch) it takes the load to reach the surface of the snow. Ascertaining the depth of snow cover is then a matter of simple arithmetic:

$$h_{sn} = H - vt.$$

The degree of accuracy is proportional to the accuracy with which the quantities in the given formula were measured, and since the two quantities H and v in the formula are constant, the accuracy depends mainly on the time measuring device.

The automatic snow guage consists of two units. The "gauge-data" unit (Fig. 1) is the device in which the process described above takes place, i.e. the lowering and raising of the load between its original position and the surface of the snow. The "metering" unit (Fig. 2) is linked to the "gauge-data" unit by a communication channel (line or radio). This unit actuates the "gauge" and meters the depth of snow cover.

The main considerations in designing the automatic snow gauge were structural and operational simplicity.

The gauge-data unit consists of two assemblies joined by a light Dural tube. Assembly a is a device consisting of a base on which the unit systems* are mounted. Its function is to change the direction of movement of the cable on which the ring-load is suspended. The cover protects the

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* Translator's note: Sistemy blokov; literally systems of the units (assemblies or sets).

unit system and the ring-load from ice, hoar frost, snow and other types of precipitation.

Assembly b contains the device for lowering the ring-load to the surface of the snow and returning it to its initial position. It consists of a miniature electric motor with a reducing gear, at the output of which a sheave is fitted, a cable tension relay, and a commutating relay. All this is mounted on the upper panel of the set and enclosed in a moisture-proof case.

A pictorial diagram of the instrument is shown at Figure 3.

When the electric motor 1 is switched on, the sheave 2 begins to rotate and the cable unwinds from it. This sheave also functions as a counter. For every centimetre of cable travel, it short circuits contacts 4, which feed the resulting pulses to the "metering" unit. The weight of ring-load 5 stretches the cable to the point at which an arm with sliding pulley 6 fully extends spring 7 and pushes against fixed bar 8 with its free end. When the ring-load is lowered to the surface of the snow, the tension of the cable on which it hangs is reduced and the free end of the arm is pressed against miniature contact breaker 9, this is quite sufficient, with the help of the commutating relay, to reverse the electric motor, i.e. to change its direction of rotation. The ring-load is raised to its original position. On reaching a given position under the cover by means of reducing gear 10, the miniature contact breaker 11 is actuated and the electric motor is switched off. The gauge is then ready for the next metering operation.

The "metering" unit contains a pulse counter which registers the pulses sent by the "gauge-data" unit. For greater reliability and range the counter is switched in through a sensitive relay.

The depth of the snow cover is read as follows. As soon as the "start" knob on the panel is depressed, the unit starts to record the pulses representing centimetres travelled by the ring-load on its way to the surface of the snow. When the counter stops, a reading is taken. In order to obtain data on the depth of snow cover, the readings are subtracted from the overall length of the gauge.

The gauge is not difficult to install and it can be transported by any available means. The weight of the gauge and the power supply unit does not exceed 10 - 12 kg, of which 8.5 kg are accounted for by the power pack. The gauge is connected to the "metering" unit by a single wire; the ground serves as the second wire. The total resistance of the line may exceed 10,000 ohms, which permits it to be set up at considerable distances from the metering unit (theoretically 400 km and more, where the diameter of the connecting line is 1.0 mm).

The laboratory is now conducting work on an improved version of the automatic snow gauge which permits the water equivalent of the snow to be measured, as well as its depth. The water equivalent will be measured by the gamma method. Radio will be used instead of line communication. Such a gauge will make it possible to eliminate the wearisome process of carrying out observations along snow-observation routes and replace it by an automatic method of collecting information on snow cover.

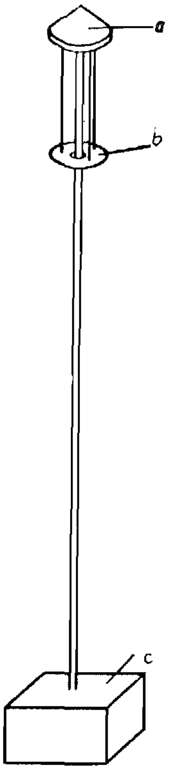


Fig. 1
"Gauge-data" unit

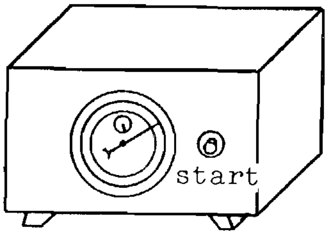


Fig. 2
"Metering" unit

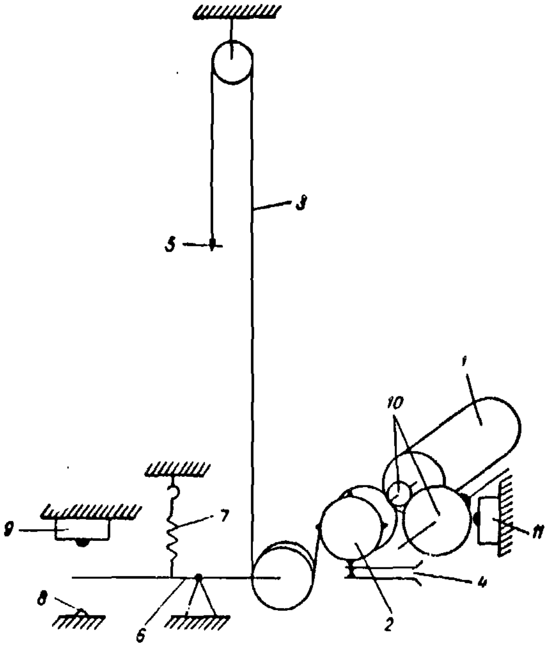


Fig. 3
Pictorial diagram of the instrument

OBSERVATIONS OF DRIFTING SNOW

The transport of snow during snowstorms and surface winds occurs mostly (up to 95%) on the surface of the snow cover up to a height of approximately 25 cm. Snowdrift observations are conducted in the layer of air above the snow with a "Cyclone" or a VO-2 snowstorm gauge. Snowstorm gauges based on the principle of measuring the absorption of light or γ-rays by the snow and wind flux may also be used.

The advantage of the "Cyclone" over the VO-2 gauge now in use is its large snow collection capacity (up to 99%); however, it is more sensitive to variations in wind velocity (and here the efficiency of the instrument drops to 95%). To obtain comparative data, parallel observations should be carried out with the new types of snowstorm gauges and the ones previously in use.

The dimensions of the "Cyclone" must correspond to the limits of wind velocity fluctuations. The layout and dimensions of snowstorm gauges for wind velocities of 4 - 20, 20 - 40 and 40 - 60 m/sec are shown in Figure 6a. It is also possible to make do with two gauges designed for velocities of 4 - 30 and 30 - 60 m/sec.

The main component of the "Cyclone" snowstorm gauge is a housing 1 with a tangential inlet pipe 2. The cylindrical casing becomes cone-shaped at its lower end; at the top it is cut in a spiral and closed with a ring cap 4; the outlet pipe 3 passes through this cap and into the cylindrical part of the housing to a precisely determined depth. A detachable hopper 5, in which the trapped snow accumulates is attached to the lower part of the housing. Air ducts 6 with an ejector and regulating device (butterfly valve) are an extension of the outlet pipe 3. The inlet pipe has a special intake head 7 mounted in a horizontal position. A liquid zero manometer acts as a control in the equalization (by means of the butterfly valve) of the air flow and wind velocities, which is necessary for the proper functioning of the snowstorm gauge.

The nozzle used for low wind velocities has a restricting conical section at the intake.

The VO-2 surface snowstorm gauge (Fig. 6b) is made in the form of a container 23 cm high, the upper part of which has a streamlined oval shape, 25 and 35 cm in diameter in the horizontal section, and the lower part is cylindrical and has a diameter of 25 cm. The container is covered with a detachable lid locked in place by two hooks. A pyramid-shaped nozzle 1 is fitted to the front of the device. The under side of the nozzle is horizontal, and the top face is inclined at an angle of 7^{0} to it, the lateral faces are parallel. The rectangular inlet aperture at the end of the nozzle measures 12.5 x 2 cm, i.e. its area is 25 cm^{2}. The under side of the nozzle is on the same level as the step of the rear side of the container, which is a transition from a cylindrical to a streamlined shape. The inlet aperture is covered by a special cap. The outlet pipe 2, which is mounted on the rear part of the lid of the device, has an aperture 10 x 3.5 cm, i.e. an area of 35 cm^2. Such a ratio of inlet and outlet aperture sizes ensures that the air flowing into the apparatus maintains its velocity, even at the outlet aperture, which is one of the principal requirements for the proper functioning of a snowstorm gauge.

There are horizontal baffle plates 3, 4, 5 inside the reservoir to trap all the snow which passes through the inlet aperture. These plates rest on special brackets and are taken out when clearing the reservoir of snow.

On the lid of the apparatus there is a carrying handle 6 and a vertical rod on which a small ribbon pennant 20 - 30 cm long is attached for determining the correct orientation of the apparatus in relation to the wind.

Snowdrift observations should be conducted in places where snowdrifting and precipitation correspond to those in the upper parts of avalanche accumulation areas.

In order to make systematic snowdrift measurements it is necessary to select open sites, where possible with fairly extensive, smooth stretches free of any obstacles which might hinder snow transportation. If such a site cannot be found, several sites facing in different directions should be selected and the extent of drifting in each direction determined separately. If the wind blows from the direction of structures, the snowstorm gauge should be located a distance of at least 30 times the height of these structures away from them, otherwise a separation distance of 50 - 60 m will suffice. The snow cover at the site where the gauge is set up should be typical for the area in terms of density and surface characteristics. The gauge should not be set up in isolated mounds of loose snow.

The observations consist of periodical measurements of snowdrift intensity for periods of 5 - 10 minutes (exposure time). The first measurement is taken as soon as drifting is noticed, at the onset of a snowstorm or blowing snow subsequent measurements are taken every 3 hours in storms of medium and high intensity and every 6 hours in storms of low intensity until the end of the storm. For each significant change in the force and direction of the wind, when there is a transition from blowing snow to a snowfall or vice versa, additional measurements are recorded. When the storm settles down on a steady course, the time to the next measurement (3 or 6 hours) is reckoned from this additional measurement and subsequent observations are made at the prescribed intervals until another change occurs in the intensity or character of the phenomenon (or until it ends).

Particular attention should be paid to the capacity of the instrument to cope with the intensity of the drifting snow. Prolonged exposure and intensive drifting result in the instrument becoming clogged with snow, thus reducing its capacity for accurate measurement. Brief exposures result in error due to inaccurate weighing. For each snowstorm intensity there is an optimum observation period which will yield the most reliable results. For low and medium intensities the recommended exposure time is approximately 10 minutes, for high intensity, approximately 5 minutes. Selection of the exposure time may be based on a visual estimate of the intensity.

Identical rules apply to the measurement of snow transport at heights of 2 - 3, 5 - 6, 10 - 12 and 25 cm above the surface, but the gauge is set up so that the lower edge of the nozzle is at the required height. This is accomplished by digging a hole the same size as the lower, cylindrical portion of the gauge in a place where the snow is evenly deposited. The instrument is placed in the hole so that the inlet aperture is directed towards the snow and wind flux. First the outlet valve, then the cap of the nozzle inlet is opened, the time is noted and the stop-watch started. Observations are timed from the beginning of the snowstorm by a clock, the length of the exposures by a stop-watch.

Standing to one side, the observer measures the wind velocity with a manual anemometer set up an a portable stand or held as high as possible above the head. For a short exposure (up to 5 minutes) the average wind velocity is calculated from measurements taken over a period of approximately 1 - 3 minutes. For longer exposures the average of two sets of measurements (one at the beginning and the other at the end of the test) is taken. A wind vane or pennant is used to determine the wind direction. For exposures longer than 5 minutes the wind direction is noted twice (once at the beginning and once at the end of the exposure). If the wind direction changes, the gauge is oriented accordingly.

While the gauge is in use the nozzle should be checked to ensure that the inlet aperture does not become clogged with snow. If this does happen, the snow should be pushed inside the container with a small rod which passes freely through the nozzle inlet aperture. If, after cleaning, the nozzle becomes blocked up again, the test is discontinued. If a snow ridge or a hole forms in front of the nozzle, the inlet aperture should be covered and the surface of the snow levelled out. The time taken for this is not included in the exposure time. All these deviations from the normal course of the test should be recorded.

On expiry of the exposure time, the inlet and outlet apertures, in that order, are closed and the moment of closing the inlet aperture is entered on a special form (Table IV), on which other noteworthy data are entered. The remaining entries are made on the station premises in the log book of meteorological observations (Table V), which includes the processed data taken from the form.

The type of snow transport (general snowstorm, surface snowstorm, blowing snow) is determined by the wind direction and velocity, and the wind force is estimated in terms of the three-point system (light, moderate, strong), simultaneously with the operation and observation of the snowstorm gauge. At night and when there is insufficient light during the daytime, the form of moving snow crystals is determined by catching them on a dark fabric (clothing) and examining them to establish their predominant shape and size. The approximate height to which the snow is driven by the wind is gauged visually.

On completion of the measurements and supplementary observations, the snowstorm gauge is taken inside. If scales are available, the instrument or its detachable part is weighed to an accuracy of 1 g (surplus snow should be wiped off before weighing and the inlet aperture of the VO-2 gauge should be closed during weighing). If scales are not available, the snow collected in the gauge is melted and the quantity of water measured in a measuring glass. If a large amount of snow has been collected it is tipped into a suitable vessel (e.g. a basin) for melting. In this case the baffle plates of the VO-2 are carefully removed and stood vertically in the same basin in order to collect the water from the snow adhering to them. The reservoir is left open, with the nozzle tilted slightly upwards, and when all the snow adhering to the sides has melted, it is carefully emptied into the basin. A spare basin should be kept at the station. It is possible to leave all the snow to melt in the reservoir of a snowstorm gauge only when small quantities are involved, since the instrument may be needed in a hurry for further measurements in the event of a change in the drifting conditions.

The gauge is prepared for subsequent observations immediately after the collected snow has been measured. If this is done by weighing the gauge (VO-2), then, when the results have been recorded, the snow is emptied out of the apparatus, and the reservoir with its lid and plates removed is left upside down in a warm room to allow the snow adhering to the sides to melt and run off and the parts of the apparatus to dry out. If the snow is liquified, the same procedure is followed after the snow in the reservoir and on its parts has melted and the resulting water has run into the basin with the snow poured from the reservoir. As soon as the instrument is dry it is reassembled and made ready for the next observation.

When the snowstorm ends the measurements are processed; mass flux and wind speed are calculated and an analytical report on the storm is prepared (Table VI).

The following formula is used to calculate the mass flux

$$q = \frac{G - g}{Ft_e} \text{ g/cm}^2 \text{ min},$$

where G and g are the weight of the snowstorm gauge with and without snow, respectively; F is the area of the inlet aperture of the gauge in cm^2; and t_e is the gauge exposure time in minutes.

The average amount of drifting during the entire snowstorm is found as a weighted average using the formula

$$q_{av} = \frac{q_1 t_1 + (q_1 + q_2)(t_2 - t_1) + (q_2 + q_3)(t_3 - t_2) + \ldots + q_n (t_k - t_n)}{2t_k},$$

where q_1, q_2, q_3 ..., q_n are the mass flux for the 1st, 2nd, 3rd, ... and final measurements; respectively t_1, t_2, t_3 ..., t_n are the times from the beginning of the snowstorm to the half-way point of the exposure periods of the 1st, 2nd, 3rd and final measurements, respectively; t_k is the time from the beginning to the end of the snowstorm.

The following formula is used to calculate the total amount of transported snow:

$$Q = \frac{1}{2}[q_1 t_1 + (q_1 + q_2)(t_2 - t_1) + (q_2 + q_3)(t_3 - t_2) + \\ + \ldots + q_n(t_k - t_n)]$$

or

$$Q = q_{av} t_k.$$

If the wind direction changed by N compass bearings between two observations, the total amount of transport by the wind with respect to compass bearings is calculated from the formula:

$$Q_r = \frac{q_i - q_{i-1}}{t_i - t_{i-1}} \frac{b_i^2 - a_i^2}{2} + \left(q_i - \frac{q_i - q_{i-1}}{t_i - t_{i-1}} t_i\right)(b_i - a_i),$$

where $a_i = b_{i-1}$; $b_i = t_{i-1} + \frac{2N_i}{2(N-1)}(t_i - t_{i-1})$; q_{i-1} and q_i are drift intensities during the first and second observations, respectively; t_{i-1} and t_i are times at which these observations were carried out, N_i is the ordinal number of the cardinal point in the period between two observations.

In order to facilitate processing of snowstorm observations it is desirable to construct a graph (Fig. 7a) on which time is plotted along the abscissae and flux of snow along the ordinates. The times at which the wind changes direction through intermediate points for an interval of time between observations are found by dividing the latter into equal parts, corresponding to the number of compass bearings in a uniform change of wind direction.

Snowdrifting with respect to compass bearings (or the total for any length of time) is calculated in terms of the area corresponding to that part of the figure bounded above by the broken line of the diagram, below by the axis of abscissae and at the sides by the vertical demarcation lines. If, for example, 1 cm on the diagram corresponds to 1 g/cm^2 min on the vertical axis and 20 min on the horizontal axis, then the corresponding figure for 1 cm^2 will be 20 g/cm^2 of drifted snow. Vertical demarcation lines are drawn equidistant between consecutive moments of change of wind direction through the corresponding compass bearings, so that the bearings at the beginning and the end of a given interval of time have a 1/2 weight, while the intermediate points have a weight equal to unity.

Example (see Fig. 7a). Between 2,020 and 2,305 the wind direction changed four times; the given interval of time is divided into four parts. In this case the wind changed from west to northwest at $2{,}020 + 1/2 \cdot \frac{2{,}305 - 2{,}020}{4} \approx 2{,}041$ and the remaining wind direction changes occurred at intervals of 41 min 15 sec. Similarly, the time interval from 0,100 to 0,400 is divided evenly between the wind from the north and the north-northeast. The entire area of the diagram is divided into parts by corresponding verticals; it is measured in sections and as a whole (for control), after which the amount of snowdrifting is calculated from it. The results of these calculations are entered on a form similar to Table VI, which is an example of snowstorm analysis by means of the diagram.

The snowstorm observation data are generalized for the requisite period (month, season, year, number of years). The data are then used to construct snowstorm roses (Fig. 7b), which show, in the form of three combined roses: wind velocity during the snowstorm, mass flux and the number of occurrences of snowstorms associated with a wind from a given direction. To construct a directional rose, segments representing the number of instants for each direction are plotted from the zero point of the chart along the appropriate compass bearings; the ends of the segments are joined by a closed broken line. Wind velocity and mass flux roses differ in that the lengths of the segments represent, on the selected scale, the average wind velocity or flux for a given length of time. A snowstorm rose can be constructed from data for the total amount of transported snow associated with winds from given directions and also for the number of snowstorms associated with a given wind direction.

A chart showing the relationship between flux and wind speed is also constructed from wind speed measurements made during the snowstorm: wind speed values are plotted along the axis of abscissae, and flux values along the axis of ordinates (Fig. 45).

Table IV

KS-6

Specimen page of notebook for recording snowstorm observations

Date $\frac{14/3/56}{15/3/56}$. Site No. 2. Snowstorm gauge No. 4

Exposure of snowstorm gauge	Anemometer readings	Exposure of anemometer	Wind direction	Snow crystals (type and size)	Other information
Light drifting of snow began on 14/3 at 8:05 p.m.; wind W, 4 m/sec					
20 hr 15 min - 20 hr 25 min	3,840 - 4,251	100 sec	W-WNW	Stars 3 mm	Drifting snow up to 5 - 10 cm
23 hr 00 min - 23 hr 10 min	4,251 - 5,053	100 sec	N	Needles 1 - 1.5 mm and broken crystals 1 - 2 mm	Heavy drifting up to 50 cm
00 hr 05 min - 00 hr 10 min	5,053 - 6,200	100 sec	N	Broken crystals 1 - 2 mm	Heavy drifting up to 70 cm
00 hr 55 min - 01 hr 05 min	6,200 - 6,823	100 sec	N	Broken crystals and stars 2 - 3 mm	Surface snowstorm

Light surface snowstorm* finished on 15/3 at 4:00 a.m.; wind NNE, 6 m/sec

Observer's signature: Ivanov, N.F.

Table V

Page of snowstorm log

Snowstorm No. 97. Began 14/3/56, ended 15/3/56. Site No. 2.
Snowstorm gauge No. 4 (weight 3,689 g)

Drifting snow				Wind		Type of phenomenon	Snow crystals		Remarks	Intensity of drifting g/cm² min	Interval of time between meas., min	Magnitude of drifting g/cm²
Time of meas. hr min	Expos. min	Wt. of instr. with snow, g	Wt. of snow, g	Direction	Speed, m/sec		Type, size	Elevation, cm				
20 05	Beginning of phenomenon			W	4	Light drifting					15	0.45
20 20	10	3,705	16	W-WNW	4.7	Drifting snow	Stars 3 mm	5-10	Instr. orientation corrected	0.06	165	305
23 05	10	4,600	911	N (veered from NW)	8.6	Heavy drifting	Needles 1 - 1.5 mm and broken crystals 1 - 2 mm	50		3.64	63	325.5
00 08	5	5,400	839	N	11.5	Heavy drifting	Broken crystals 1 - 2 mm	70	Meas. made with snowstorm gauge No. 6 (wt. 4,561 g)	6.71	52	227.5
01 00	10	4,200	511	N	6.8	Surface snowstorm	Broken crystals 1 mm and stars 2 - 3 mm		Nozzle cleared once	2.04	180	184
04 00	End of phenomenon			NNE	6	Light surface snowstorm			Total		475	1,042
									Average	2.2		

Observer's signature: Ivanov, N.F.

Table VI

Analytical report of snowstorm No. 97 (model)

Date: 14th - 15th, Month: March, Year: 1956

1 2 3 4 5

Время измерения, час. мин.	Величина метелевого переноса, г/см² мин	Момент измерения относительно начала метели, мин.	Порядковый номер периода	Румбы в периодах	b	a	$K = \frac{q_i - q_{i-1}}{t_i - t_{i-1}}$	$c = q_i - Kt_i$	$K \frac{b_i^2 - a_i^2}{2}$	$c(b_i - a_i)$
20 05	0	0	1	W	15,0	0	0,0040	0	0,4	0
20 20	0.06	15	2	W	35,6	15.0	0,0217	—0,2660	11,3	—5,5
—	—	—	2	WNW	76,9	35,6	0,0217	—0,2660	50,4	—11,0
—	—	—	2	NW	118,1	76,9	0,0217	—0,2660	87,2	—11,0
—	—	—	2	NNW	159,4	118,1	0,0217	—0,2660	124,3	—11,0
—	—	—	2	N	180,0	159,4	0,0217	—0,2660	75,9	—5,5
23 05	3,64	180	3	N	243,0	180,0	0,0487	—5,1241	648,9	—322,8
00 08	6,71	243	4	N	295,0	243.0	—0,0898	28,5310	—1256,3	1483,6
01 00	2,04	295	5	N	385,0	295,0	—0,0113	5,3675	—345,8	483,1
—	—	—	5	NNE	475,0	385,0	—0,0113	5,3675	—437,3	483,1
04 00	0	475								

Total during snowstorm

Q_r

$Q = 1,042.0$ g/см²
$q_{av} = 2.2$ g/см² min.

Q_r as % of Q

1 Time of measurement, hr min
2 Mass flux, g/cm² min
3 Time of measurement relative to beginning of snowstorm, min
4 Serial number of period
5 Bearings during periods

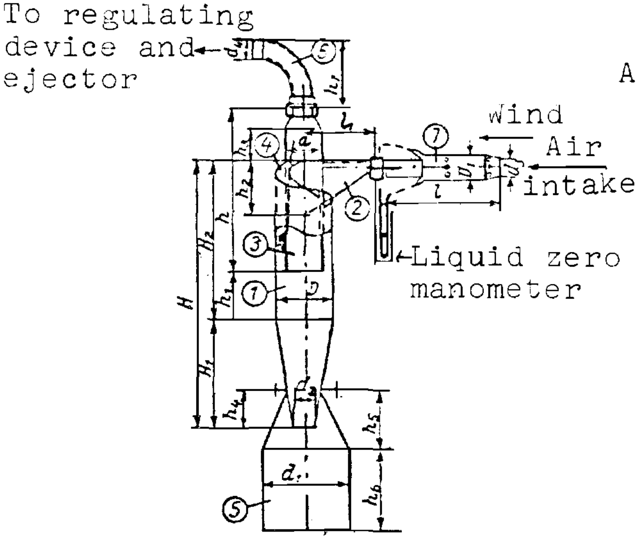
Snow drifting with respect to compass bearings, g/cm²

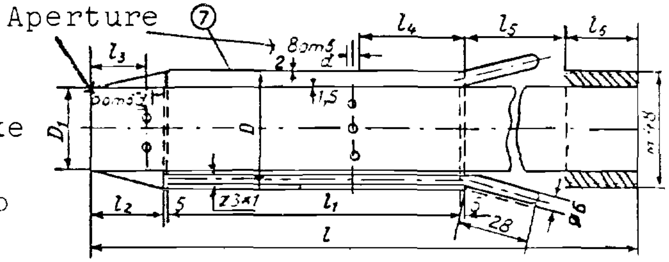
$$Q_r = K \frac{b_i^2 - a_i^2}{2} + c\,(b_i - a_i)$$

N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
—	—	—	—	—	—	—	—	—	—	—	—	0.4	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	5.8	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	39.4	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	76.2	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	113.3
70.4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
326.1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
227.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
137.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	45.8	—	—	—	—	—	—	—	—	—	—	—	—	—	—
761.1	45.8	—	—	—	—	—	—	—	—	—	—	6.2	39.4	76.2	113.3
73.0	4.4											0.6	3.8	7.3	10.3

Processed by: Chernov, A.I.

Checked by: Obraztsov, V.S.





D	D_1	d	d_1	d_2	d_3	d_4	H	H_1	H_2	h	h_1	h_2	h_3	h_4	h_5	h_5	h_7	l	l_1
120	50	75	180	40	35	42	580	240	340	354	100	85	70	80	120	180	140	289	160
85	45	50	130	35	28	,,	350	150	200	179	80	59	-	30	50	200	,,	230	140
50	32	29	100	20	16	,,	255	115	140	159	50	35	-	35	29	150	,,	210	95

D	D_1	d	d_1	l	l_1	l_2	l_3	l_4	l_5	l_5
50	35	5	5	278	125	43	30	45	60	30
45	28	4	4	233	110	34	25	25	40	30
32	16	3	3	197	105	27	20	15	35	30

Fig. 6a

Diagram of "Cyclone" snowstorm gauge

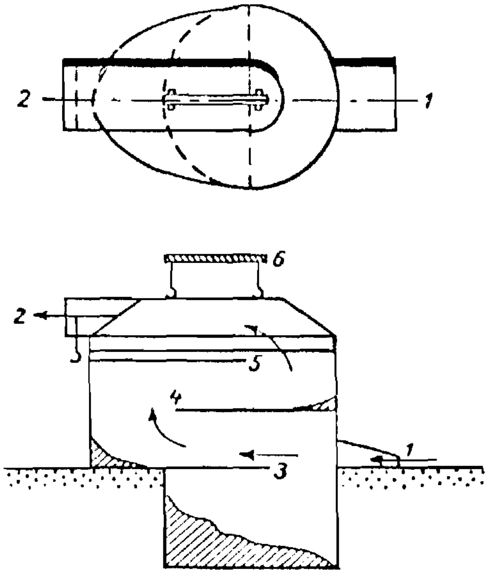


Fig. 6b

Diagram of VO-2 snowstorm gauge

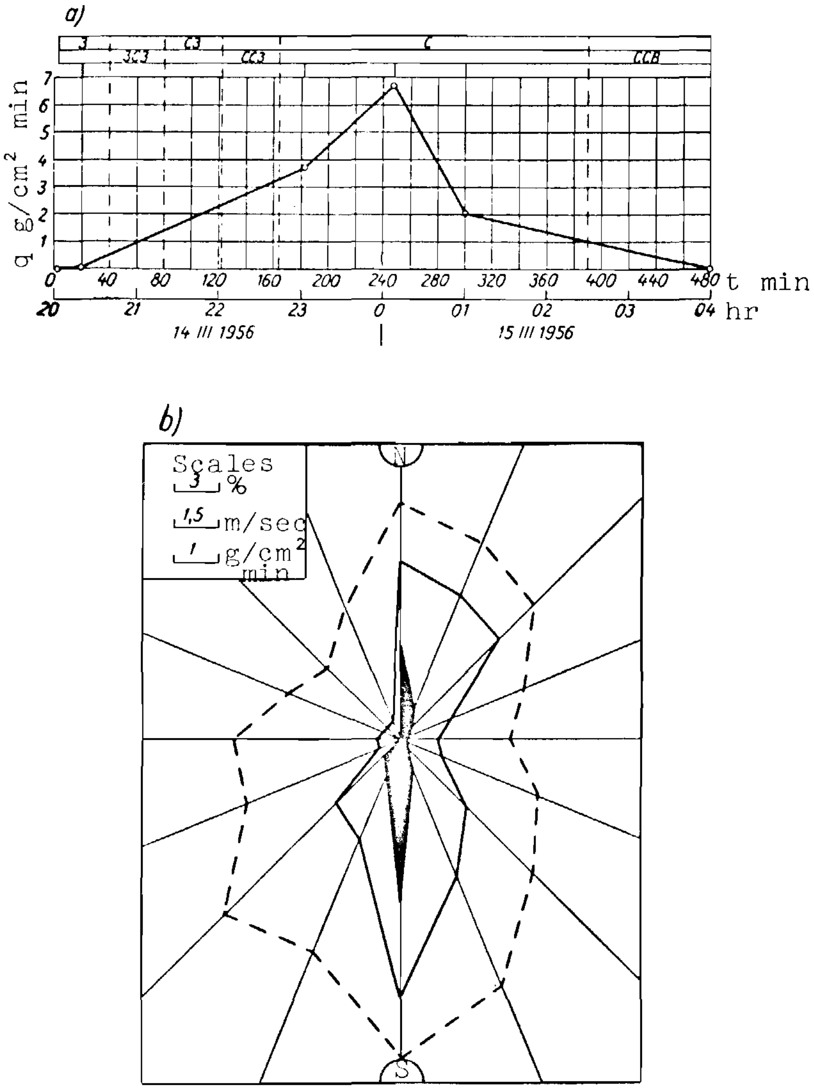


Fig. 7

Graph analysis of snowstorm observations
a - auxiliary diagram; b - snowstorm rose
(n - number of instances of given direction,
v - wind speed in m/sec; q - flux in g/cm^2 min)

RULES AND METHODS OF FORECASTING AVALANCHE HAZARD

An analysis of data obtained from avalanche observations in a specific mountain region reveals the principal meteorological conditions which cause avalanches. A first approximation of the degree of avalanche hazard (greater or lesser probability of avalanche occurrences) may be made purely quantitatively on the basis of an examination of the factors enumerated in para. 94*: the greater the number of them favouring avalanche formation, the greater the likelihood of avalanche occurrences.

Avalanches do not begin to form immediately after a break in the weather, but after a certain interval of time during which the stability of the snow mass is disturbed. However, for avalanches directly associated with changes in meteorological conditions, this interval is usually small. Therefore, it is important to foresee changes in the weather. The analysis of synpotic situations preceding and accompanying avalanche formation makes it possible to forecast avalanche danger for a mountain range and individual large sectors of it at a much earlier date than for other phenomena, for example, the onset of a heavy snowfall.

In well-defined physico-geographical regions it is possible to work out specific rules for recognizing the onset of avalanche danger periods.

The following is an example of the climatic-meteorological method of forecasting avalanche periods in one of the Greater Caucasus regions (V.S. Chitadze).

Dry avalanches of compacted snow occur:

a) following snowfalls resulting in 40 - 50 cm of new snow. The weight of the new snow causes deformation of the surface of the old snow, fissures and depressions appear, or the new snow breaks away and, having acquired a certain speed, causes the old, dry snow to slide as well;

b) during a sudden cold spell, when fissures appear as a result of temperature contraction, and the surface layer is disturbed by the warming effect of the latent heat from condensation of water vapour migrating through the snow mass;

c) during a warm spell, when the crusty surface has melted;

d) in clear weather, when, as a result of the absorption of solar radiation, the temperature of the surface layer rises and the layer becomes unstable (snow has the capacity of absorbing radiant energy with wavelengths of 600 - 1200 millimicrons, which creates the greatest heat effect);

e) when snow cornices collapse, and during high winds;

f) during föhns when the humidity exceeds 80% and the temperature of

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* Translator's note: Information given in para. 94 repeated on next page in paragraph on forecasting avalanche hazards.

the snow surface is lower than that of the air.

Wet snow avalanches occur:

a) during falls of wet snow and when the snow is thawing;

b) when cohesion and internal friction are simultaneously reduced to a minimum in all the layers;

c) at any time during a period of intensive thaw;

d) during spring rains;

e) when snow cornices collapse, and during high winds.

For forecasting avalanche hazards due to snowfalls and snowstorms, we can examine the effect of the ten principal avalanche formation factors (para. 94) on the probability of avalanche occurrences (under specific meteorological conditions): 1) depth of old snow, 2) condition of underlying surface, 3) depth of new snow, 4) type of new snow, 5) its density, 6) intensity of snowfall, 7) intensity of precipitation, 8) settlement of snow, 9) wind, and 10) temperature. This analysis is carried out by one of the following methods, depending on accumulated experience.

a) Each factor is marked with a plus or a minus sign depending on whether or not it is conducive to the initiation of avalanches, and zero if it has no influence on avalanche formation at the given time. A preponderance of negative signs permits the assumption that the danger of avalanches occurring is negligible or does not exist at all; a preponderance of positive signs indicates that danger does exist, the greater the danger, the greater the number of plus signs in excess of minus signs. This method of estimating the probability of avalanche formation is the least accurate since it does not take into account the relative significance of each factor in the formation of avalanches, and it can be used only during the initial period when insufficient observations have been made.

b) Each factor is allocated a number of points between 0 and 10, depending on how much it conduces to avalanche formation. These points are added together; the greater the total number of points, the greater the danger of avalanche occurrences. The minimum and maximum number of points obtainable will be 0 and 100, 0 denoting the lowest degree and 100 the highest degree of probability of avalanche occurrences. A total of 40 to 60 points is an indication of a condition bordering on the dangerous, when minor snow slides may occur. If the total number of points is 75 or over avalanche warnings should be issued. This method takes into consideration the relative significance of individual factors in relation to the physico-geographical peculiarities of a given region.

In addition to all this, it is necessary to bear in mind the possibility that a dangerous horizon of loose snow could form. The presence of deep hoar frost should always be interpreted as a sign of probable avalanche formation, regardless of the weather (see also para. 98)*. The analysis of meteorological conditions should complement, not replace, the study of the growth of the snow mass, since, by itself, it cannot yet provide a positive answer to the question of the possibility of avalanche occurrences.

The forecasting of avalanche hazards during periods of thaw, spring snow-melting and rain is based on the fact that a direct relationship exists between the initiation of wet avalanches and the presence of liquid water in the snow. It has been established by observations that the critical value is a moisture content of 0.10 - 0.15, which corresponds to the maximum water-retaining capacity of old snow. In some cases the time and place of wet avalanche occurrences can be forecast with a fair degree of accuracy, providing that the temperature and moisture content are measured in the starting zone. At the same time it should be remembered that it is possible for the melting process to produce a change in the stability of the snow and thus start an avalanche within a very short time - as little as one hour. In addition to this, the heat balance of the snow mass and the melting process depend on the location of the site (the bottom of a valley or the crest of a range, a slope with a southern or northern exposure).

Rain is the most obvious cause of water entering into the snow cover. Downpours of rain in the winter or spring should always be regarded as a source of avalanche danger, since, as a result of them, the snow either becomes very stable or slides down the slope and causes a wet avalanche. Dry powdery snow, which often falls after such rain, slides off the ice-covered surface very readily. Intensive thawing also produces large quantities of water which may lead to avalanche formation. Warm winds are a major source of heat in this case. It should be remembered that the rate of melting may be higher on foggy days than on clear days, particularly with a warm wind. A combination of these conditions is an indication of danger, and in this case avalanches associated with warm winds and rain showers may occur on slopes facing in any direction, if there is sufficient snow. Wet avalanches usually occur on southern slopes warmed directly by the sun's rays, which can penetrate 10 - 20 cm below the surface of the snow and cause melting inside the snow cover, even when the air and snow surface temperatures are below the freezing point.

The danger of wet avalanches arises most frequently when a cold snow cover which has not had time to settle is exposed to a sudden downpour or thaw. The melt water in the dry loose snow rapidly gives rise to a state of dangerous instability resulting in the formation of large avalanches, whereas old, settled snow, warmed to melting temperature during previous thaw periods is not nearly as dangerous. The first pronounced thaw at the end of winter or the beginning of spring marks a very dangerous period;

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* Page of 189 of original text. Not translated.

similar conditions may recur several times during the season as a result of fresh snowfalls. A snowstorm following a clear, sunny period at the end of spring may cause wet snow to break away, even in those cases where the snow drifts onto snow which has subsided and lies firmly on the slope.

Landslides, which may be of very large proportions, are caused by prolonged thawing or rain. They usually occur on even, grass covered, or smooth, rocky, slopes. In some cases avalanches occur even on a thick ice layer deep inside the snow cover.

If any of the avalanche formation factors in a given locality for a given type of avalanche are decisive, it is permissible to use empirical and semi-empirical calculation methods of forecasting, the essence of which is clear from concrete examples.

a) In the Khibiny Mountains empirical formulae and a graph of the avalanche hazard period (V.N. Akkuratov) are used to predict the onset times of periods of avalanche hazard due to snow storms. Time from the beginning of the snow storm is plotted along the axis of abscissae of this graph (Fig. 43), and rate of drift along the axis of ordinates; the lower curve on the graph denotes the beginning of the avalanche danger period, the upper curve, the end of the period. The drift intensity is measured at the beginning of the snow storm and from the chart we determine the interval of time at the given drift rate before the onset of avalanche danger. The drift rate is measured periodically and after each measurement the avalanche hazard forecast is made more precise with respect to the graph.

The times of onset t_{on} and termination t_{term} of the danger period in hours from the beginning of the snow storm can also be calculated from the formulae

$$t_{on} = \frac{q + 38}{q + 2} \text{ and } t_{term} = \frac{6.8q + 95.0}{q - 1.86}$$

where q is the flux of drifting snow in g/cm^2 min.

These formulae and the graph are suitable only for a clearly specified area and climatic conditions.

The flux of snow may be determined indirectly from the measured wind velocity and snow density by means of graphs (Fig. 44 and 45) or the following empirical equations:

flux of snow

$$q = 0.051\ v^2 - 0.233\ v + 0.140,$$

maximum flux

$$q_{max} = 0.13\ v^2,$$

flux during snow storm and surface drifting in a 2 m layer above the surface

$$q = 0.0129\ v^3,$$

where v is the wind velocity in m/sec.

These relationships should be established more precisely by means of observations.

b) For the southern slopes of the main Caucasus Range a relationship has been noted between avalanches of new snow and variation of average daily relative humidity, the depth of the snow cover the day before this change and the increase in depth or the amount of precipitation after the change (V. Sh. Tsomaya, K.L. Abdushelishvili), which is illustrated graphically in Figure 37. The date of steady transition of the average daily relative humidity through 75% and the depth of the snow cover h_{75} on the eve of this transition are determined from meteorological observations. The amount of precipitation x_n and the minimum depth of snow cover h_n which will cause avalanches of new snow are calculated from the equations

$$x_n = 55 - 2.8\sqrt{h_{75}},$$
$$h_n = 55 + 0.9h_{75},$$

where the number 55 is parameter corresponding to the minimum critical amount of precipitation (in millimetres) or the depth of snow cover (in centimetres), at which avalanches occur; 2.8 and 0.9 are the coefficients depending on the angle of slope and its degree of roughness (in the present case the angles of slope vary between 40 and 50 - 55°). More accurate values should be determined for a given region by analyzing graphs showing the relationship between the minimal depth of snow cover or amount of precipitation which will cause avalanches and the initial depth of the snow cover (Fig. 46a and b).

The day after the date on which the necessary quantity of snow has accumulated, which is determined from weather forecasts, is the probable date of avalanche occurrences. Alternatively, the following formula may be used:

$$t = \frac{55 - 2.8\sqrt{h_{old}}}{i},$$

where t is the time of onset of the avalanche danger period, i is the rate of precipitation, h is the depth of the old snow cover.

c) Forecasts of avalanches associated with rain falling on the snow cover and with snow melting are based on the equation (K.S. Losev)

$$c_0 w - a\left(\Sigma T + \sum_{1}^{n} T_i\right) = 0 \text{ and } t = \frac{c_0 w - e}{i},$$

where t is the time of onset of the avalanche danger period, e_o the critical value of the free water content in the snow cover (e_o = 10 - 15% of the water reserve of the snow cover), w the water reserve in the snow cover (its water equivalent or water content), e the free water content in the snow cover at the time of issue of the forecast, σ the amount of melting per degree of air temperature above $0^{0}C$, ΣT the sum of the average daily positive temperatures up to the time of issue of the forecast; $\sum_{1}^{n} T_i$ the sum of the average daily positive temperatures according to the meteorological forecast for several days ahead.

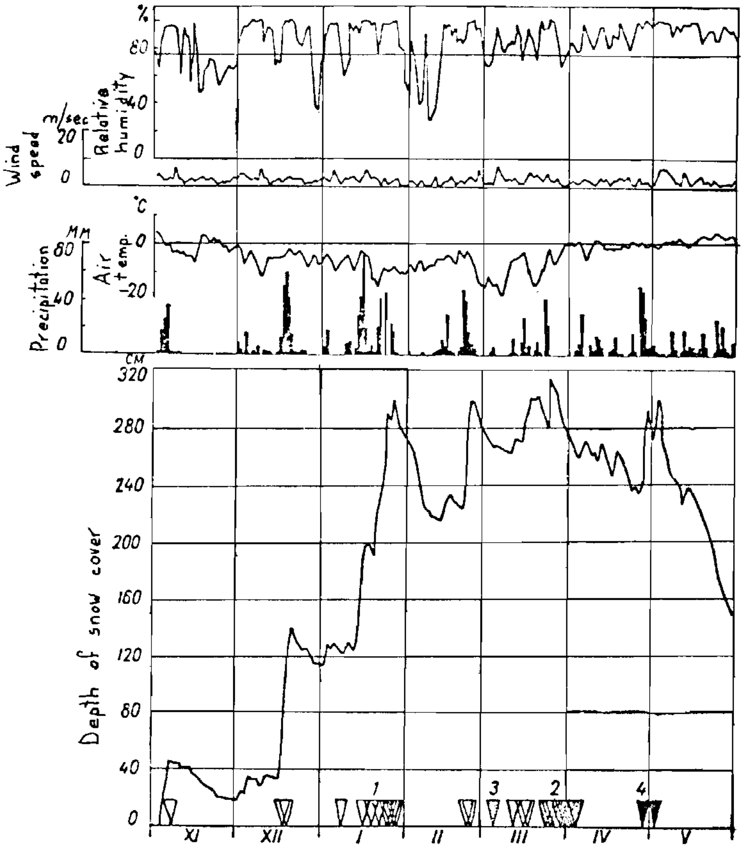

Fig. 37
Comparison of principal meteorlogical elements with dates of avalanche occurrences

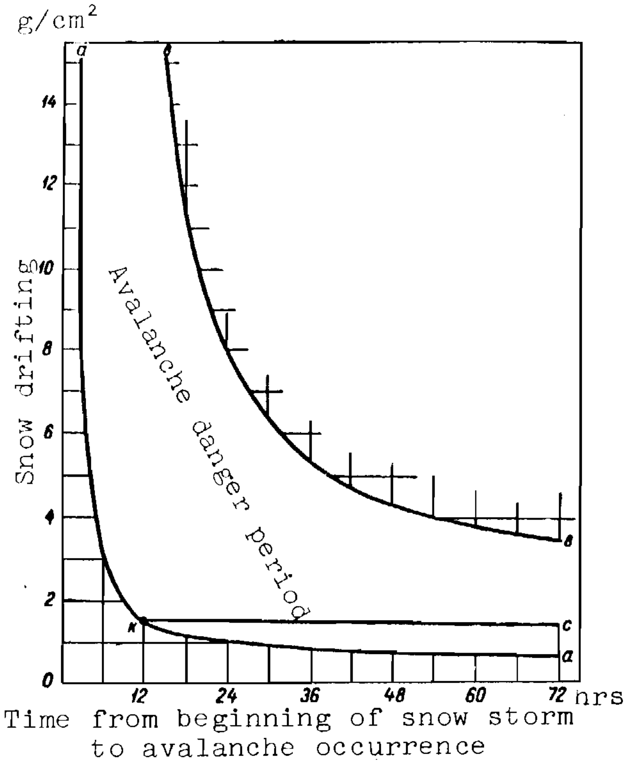

Fig. 43

Graph showing period of avalanche danger

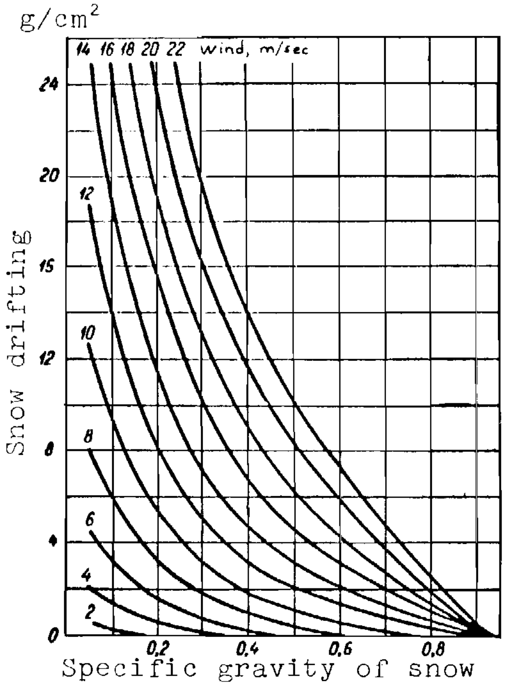

Fig. 44

Dependence of flux of snow on specific gravity of snow and wind velocity

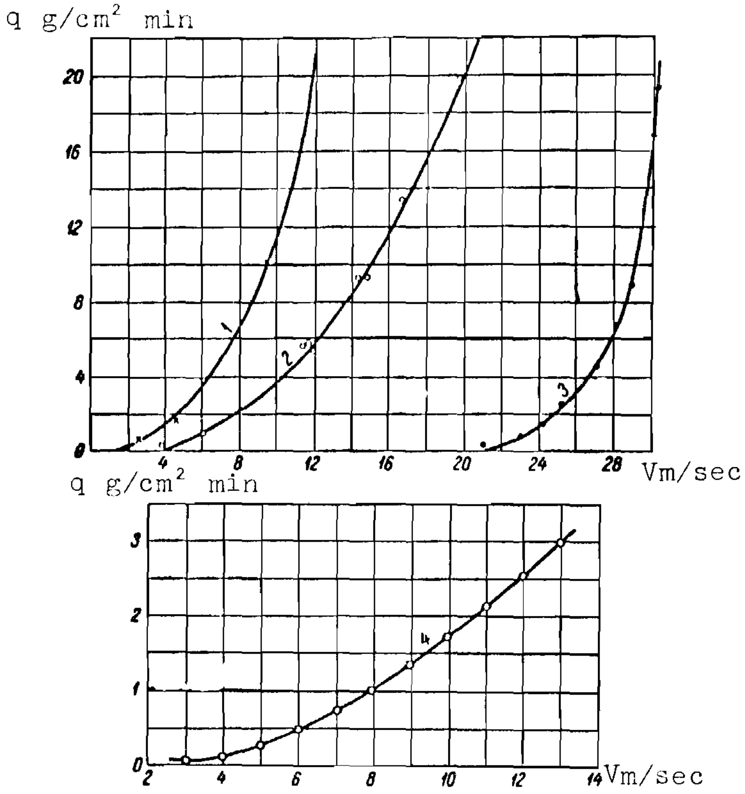

Fig. 45

Relationship of flux of snow q and wind velocity v

1 - maximum, 2 - average, 3 - minimum drifting during snow storm, 4 - average snow transportation during surface drifting

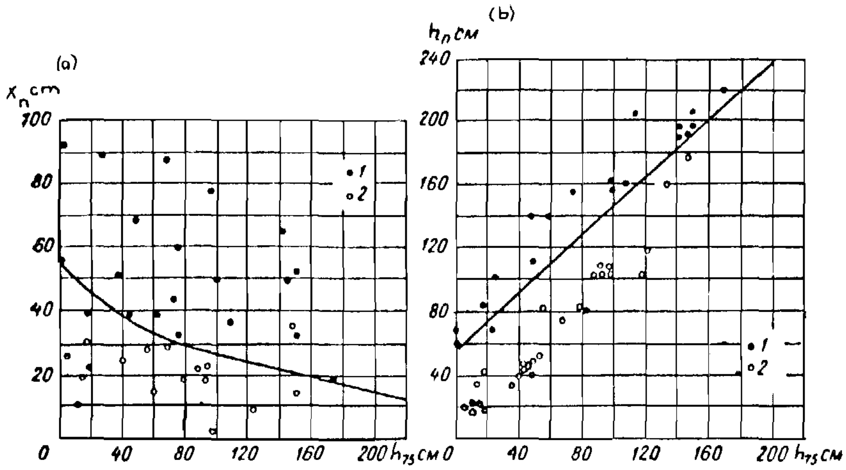

Fig. 46

Relationship of initial depth of snow cover h_{75} to minimal amount of precipitation x_n (a) and to minimal depth of snow cover h_n (b) necessary for initiation of avalanche

1 - avalanche occurrence observed;
2 - avalanche occurrence not observed