Mechanics of snow avalanches

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Abstract. The main problems of mechanics of snow avalanches are those of: (1) predicting avalanches, (2) avalanche motion, (3) the action of an avalanche upon obstacles, (4) the air wave, (5) the slow moving snow cover and its interaction with protective constructions and (6) the problem of artificial release of avalanches. This paper surveys the modern state of scientific knowledge about the nature of physical and mechanical processes connected with these problems, the level of progress in solving them and the foreseeable prospects. The survey is based mainly on the results of scientists (mechanicians, mathematicians and geographers) of Moscow University.

INTRODUCTION

Snow avalanches, being a characteristic and sometimes frightful natural phenomenon, have drawn much attention in recent years. The reason for this is that during the extensive and many-sided exploitation of mountainous regions a number of practical problems have arisen. To solve these a deeper knowledge of the nature of snow avalanches is needed. Besides purely descriptive data about character, peculiarities and geographical distribution of snow avalanches there arose the necessity for quantitative data and numerical techniques to evaluate the dynamic characteristics of force interactions between an avalanche and different protective constructions and obstacles. Such formulation transmits the problem into the sphere of technology so it was quite natural that specialists in fields far from geography — mechanics and physics — were invited to take part in the work.

This paper deals with the modern state of scientific knowledge about snow avalanches and directions of further research mainly based upon investigations carried out during the last 8 years by scientists of the Institute of Mechanics, Mechanico-Mathematical and Geographic Faculties of Moscow University. These investigations were initiated and actively supported by M. Ya. Plam, Problem Laboratory for Snow Avalanche Research of the Geographic Faculty, who has timely understood the necessity for cooperation between geographers, mechanicians and mathematicians for such research.

THE MAIN PROBLEMS OF MECHANICS OF SNOW AVALANCHES

Below a short list of problems is presented, solution of which must, in our opinion, be the contents of modern scientific investigations in the field of mechanics and physics of snow avalanches:

(1) predicting avalanches,
(2) avalanche motion,
(3) the action of an avalanche upon protective constructions and other obstacles,
(4) air waves,
(5) the slow movement of snow cover and its interaction with protective constructions,
(6) artificial release of avalanches.

All these problems are associated with purely practical aspects.

The problem of predicting avalanches

This problem quite naturally is one of the most important and at the same time one of the most difficult to solve. The extent of its solution stays limited. The main result here is our present general understanding of the nature of interrelation of the relevant phenomena and of the character of investigations which are to be carried out in order to solve the problem.

The main question is — why is a rather thick snow cover quite stable under one set of conditions while under other conditions even a thinner snow cover turns into a frightful avalanche due to an infinitesimal outer influence?

Considering the problem from the viewpoint of continuum mechanics (for a snow cover under the conditions we consider certainly can be studied in the framework of this model) we must first of all state that a snow cover is a solid deformable body, possessing limited strength, and under certain critical stresses it must break, forming cracks of normal rupture or shear. Thus, critical unstable states of a snow cover are associated with such threshold stress states in some locations of a snow cover. In this respect two characteristics may be proposed as main indicators of snow strength — rupture strength \( \sigma^* \) and shear strength \( \tau^* \).

If mechanical properties of snow, in particular \( \sigma^*, \tau^* \) were constant, then the problem of prediction would be simple — with a given relief, everything would be defined by snow cover thickness. But unfortunately the situation is much more complicated. Mechanical properties of snow inside a snow cover alter continuously starting from the moment of its formation and these alterations are defined by complex physico-mechanical phenomena. Therefore, a precise description of all alterations within a snow cover, under changing weather and meteorological conditions, represents a problem which practically has no solution. But it is important to have a general idea of the character and reasons of these alterations in order to connect them, at least roughly, with characteristics of physicomechanical and meteorological processes and to use this connection later as a basis for prediction methods.

The simplest situation when such a connection is obvious is the case during continuous snowfall when a snow cover approaches a critical state. Shear stresses at the contact surface of a snow cover and the underlying rock, all other conditions being equal, are proportional to the snow cover thickness. Thus, if in the process of continuous snowfall the shear stress reached \( \tau^* \), then the snow cover will slide down, forming an avalanche. But even in this case the process is not so simple.

In reality snow continuously settles and its density increases, which increases its strength characteristics: the rate of this strengthening depending upon a number of factors (temperature, humidity, wind and gravitational compression etc.). Thus, the question of release of avalanches in the case of continuous snowfall depends on two processes — the increase in density and strengthening of snow and of the increase of snow cover thickness which results in growing stress. If the second one takes the upper hand, then an avalanche is formed. Thus, all other conditions being equal, formation of an avalanche during a snowfall will be defined by intensity of the latter — if the rate of growth of snow cover thickness is great enough and the snowfall continues long enough, then avalanches will release during the snowfall itself.
Atwater (1968) was the first to derive and to successfully use a criterion of an avalanche release associated with snowfall intensity. Study of snow strengthening at different temperatures, mechanical loads etc. should provide quantitative data about kinetics of the process which being compared with meteorological data may help to predict avalanche release during snowfalls.

The case considered is the simplest one for understanding the mechanics of processes initiating avalanche release and for formulation of problems, solution of which may serve as a basis for quantitative prediction methods. However, avalanches release in many other situations for which the problem of prediction becomes more difficult both for theoretical description and for carrying out field measurements.

One more factor which is clearly associated with the initiation of avalanches during continuous snowfall is wind causing the surface transfer of snow. Due to interaction of wind generated snow—air flow with relief, deposits of snow upon mountain slopes are nonuniform and the nonuniformity can be quite significant in the case of very uneven relief and unfavourable direction of wind. Thus, snow cover will grow more rapidly on some parts of the terrain and consequently avalanches will release according to the mechanism discussed above. However, wind influences preparation of a dangerous situation not only during snowfall itself. Prolonged observations of avalanche releases during snowfalls made near Mount Elbrus by Urumbaev (1967—1969) showed that a considerable number of avalanches of newly fallen snow release soon after snowfall ceases but with the wind continuing to blow.

As a rule snowfall cessation is accompanied with a temperature drop. The reason for release of such avalanches, as we see it, is as follows. If during snowfall the snow cover did not attain its critical state but is close to it, then its additional growth resulting in instability can occur after snowfall cessation due to transfer and redistribution of previously fallen snow upon slopes under the action of continuing wind. If the latter did not take place, then the process of compression going on inside the snow cover and assisted by wind, results in a growth of rigidity and strength of the snow cover and the critical state, as it may seem, is postponed. But here the temperature factor is important. The sharp temperature drop accompanying snowfall cessation makes a denser, and hence less deformable, snow cover (the so called mild snow slab), tending to shorten with temperature drop, and in certain locations states with threshold tensile stresses are reached resulting in a rupture crack giving rise to an avalanche. This scheme is in a very good accordance with observation data — the surface of rupture of a snow slab, normal to the slope, is very clearly seen at the origin of an avalanche.

In avalanche prediction, consideration of the wind factor both during and after a snowfall is done by accumulating observational data of wind velocity and direction in conjunction with the degree of nonuniformity of growth of snow cover at the most dangerous locations, also taking into consideration temperature drop after snowfall cessation. This problem can also be solved by a theoretical approach with the help of methods of aerodynamics of loaded flows but this possibility is of small practical use due to insufficient development of this theory and inescapable mathematical complexity of realistic problems which require complex and expensive numerical techniques for computer calculation. Some effect can be attained by means of simulating corresponding aerodynamic problems but this is also poorly developed.

All this means that snowfall intensity, its duration, direction, duration and intensity of wind and air (snow) temperature are the most important factors for prediction and must be measured (if possible continuously) during and after snowfalls. The above analysis points to a causal connection between the mentioned parameters and a possibility of development of an avalanche-dangerous situation. This connection would be established by systematization of observation data and field measurements. It is clear that this connection will be, generally speaking, different for different places.
Thus, a prediction technique will be associated with certain regions and even certain avalanche-dangerous locations.

The theory of image identification is one way of deriving a prediction technique based upon the described scheme. An avalanche-dangerous situation is reached, not by the influence of any single factor, but by a parallel development of a number of processes helping to create a dangerous situation. This is typical for the image identification problem. The formulation of the problem is as follows. Every situation (image) is presented with a number of characteristic parameters (snowfall intensity, its duration, wind velocity and direction, temperature, etc.). The situations are subdivided into two classes (dangerous and safe) in such a way that the space of these parameters is divided into two corresponding domains. The preliminary boundaries of these domains are established with the help of observations carried out and having registered avalanche releases or their absence. A measurement method introduced into the space which can be used to measure proximity of a considered situation to the boundary dividing the two domains and this, in its turn, defines degree of validity with which a considered ('tested') situation can be referred to one of the two classes, that is to decide what is the degree of validity of the prediction. This method, naturally, can give good results only due to accumulation of data about real situations, that is if the aforementioned domains are filled densely enough with elements which definitely belong to them. The prediction procedure can be formalized and programmed for a computer; hence, it can in principle be made continuous and automated.

Khomenyuk et al. (1973) have developed a corresponding technique and a program for numerical prediction of avalanche release. In 1970 this program was tested with the observation data obtained by ‘Apatit’ industrial complex (Khibiny) and proved to be highly efficient.

Above we described processes which define an avalanche release during snowfall or soon after it and the principal possibilities of organizing its numerical prediction. However, avalanches release not only in this way. If a snow cover is preserved after the snowfall is over, the processes inside it continue which result in a substantial alteration of physicomechanical and especially strength properties of snow pack. These alterations can result in a critical state of snow cover, and some insignificant outer influences (a sharp temperature change, fallout of new, even small, snow masses, vibrations etc.) can initiate an avalanche. The most important of these slowly developing processes are the processes of heat and mass transfer inside a snow pack resulting in a sharp redistribution of snow mass, its crystalline structure and strength characteristics in the vertical direction. These processes are especially intense in case of thin snow covers, low air temperatures and wind compression of the surface snow layer. Temperature gradient inside a snow pack results in evaporation of snow near the underlying surface, transfer of water vapour to the upper layers where condensation occurs. Thus, the density of the lower layers of a snow pack lessens, their mechanical strength diminishes while near the upper surface a hard crust is formed and the snow cover becomes vertically nonuniform. If a snow cover is intact after a number of separate snowfalls then a number of layers are formed inside it which have different mechanical strengths.

The described process of depth evaporation (so called depth hoar formation) is the main reason for development of avalanches in old snow. The actual reason of a release in this case can be a new snowfall resulting in adding load upon the old snow close to a critical state. This shows that even the problem of predicting avalanches during snowfall is much more complicated than it was considered above. The set of factors defining possibility of an avalanche release during a snowfall or soon after it must include factors characterizing conditions of development of depth hoar and of a multilayer structure inside the snow cover which existed before the snowfall. These factors must include both numerical parameters (thickness of the old snow
cover, the number of layers etc.) and functional parameters, that is the magnitudes defining the time history of development and transformation of the whole old snow pack and its separate layers effected by changes in temperature, humidity, wind etc. All this is evidently necessary for predicting avalanches of old snow triggered not by additional snowfall but by other reasons. The latter include temperature change (which can result in origination of a rupture crack, in mechanical destruction of depth hoar layer and hence in setting down and cracking of the upper pack of compressed snow — snow slab), outer mechanical reasons (overload of unstable snow slab which lies upon a weak deeper layer, under the weight of a skier, a running animal, a piece of fallen hard snow, a seismic shock, a wind blast etc.), meteorological reasons (rain, melting due to radiative heating etc.).

All this means that purely empirical prediction of releases of avalanches of old snow presents a very complicated problem. Thus, the problem of quantitative study of processes of snow cover metamorphism resulting in generation of depth hoar and an unstable state, acquires a special significance. Such an investigation would try to define the temporal relationship between the processes and their dependence upon relevant outside factors which can be observed and measured. Unfortunately, all this work is still far not only from completion but even from a rational formulation and analysis of the main problems.

The problem of avalanche motion

In principle, this problem is less complicated than the problem of prediction, because motion of an avalanche can be predetermined to a greater degree and depends on a smaller number of factors. Avalanches usually slide down along fixed elements of a mountainous relief. Snow distribution upon this surface at the moment of avalanche release is principally known though it cannot be easily measured.

Thus, to solve the problem of avalanche motion one needs only a mathematical model of the process of motion and means for measuring the initial parameters used in the model.

The publications on avalanches contain a number of mathematical schemes of this process, a critical review of which can be found in the paper by Eglit (1968). These schemes are based upon the assumption according to which a moving avalanche may be treated as a material particle possessing certain mechanical properties. However, this assumption is a very rough one. More realistic quantitative results may be derived if avalanche motion is considered in the framework of fluid mechanics. This approach was evidently at first proposed in the USSR by Grigorian et al. (1967) (see also Briuchanov et al., 1967) referring to the initial studies by scientists of Moscow University. This paper describes the movement of an avalanche by an approximate formulation, similar to the so-called 'shallow water' theory in hydrodynamics. In this case motion parameters in the dense part of an avalanche are averaged over its thickness and determination of average values (of velocity and thickness) is reduced to a mathematical problem for a system of partial differential equations taking into account the moving force (gravity) and drag forces generated by friction of an avalanche upon the underlying surface, engulfing of stationary snow ahead of it and turbulent pulsations and mixing of snow masses inside an avalanche. This scheme was used in a number of papers (Bakhvalov and Eglit, 1970, 1973; Kulikovsky and Eglit, 1973; Grigorian and Ostroumov, 1972) where qualitative and quantitative results were compared with observation data. The possibility of organizing numerical solution of realistic problems of avalanche motion with the use of computers was considered. Formulae obtained by Eglit, Bakhvalov and Kulikovsky for simplified situations and using the analysis of asymptotic properties of solutions in more complicated cases may be used for evaluating the main elements of the motion in connection with applied problems. The method and numerical technique developed (Grigorian and Ostroumov, 1972) for
calculation of the so-called ‘bed avalanches’ takes into account the geometrical details of a real surface along which an avalanche slides and distribution of snow cover thickness along the route of the avalanche. The complete movement from the release of the avalanche to its stopping can be calculated by this method. The practical application can be recommended as calculations using this technique for particular avalanches in the region of Elbrus and in the Khibiny mountains agree well with the field measurements. Continuation of the work in this field must be directed to obtaining a better knowledge of drag forces and finding out what must be the scope and precision of the initial data given by observations and field measurements so that quantitative data good enough for practical needs could be obtained.

The schemes and numerical techniques described above are suitable only for calculating the motion of avalanches having sufficiently compact structure (avalanches of compressed, sometimes wet, heavy snow). However, an avalanche may represent a moving cloud of snow—air mixture or a combination of such a cloud and a dense near-surface part. Such avalanches fall when a snow cover consists of recently fallen dry snow or of a combination of older unstable snow with developed depth hoar and fresh dry snow. Motion of such purely ‘dust’ avalanches or combined avalanches differs significantly from that of dense heavy avalanches and no appropriate mathematical theory has been constructed. For light dust avalanches a more important mechanism defining their motion is turbulent mixing of a snow—air mixture and entrainment of air by this mixture in the process of motion and, to a lesser degree, friction upon the underlying surface (or upon the compact part in case of combined avalanches). In this case the ‘shallow water’ approximation evidently cannot be considered an appropriate mathematical scheme. A description based upon semiempirical methods of two-phase turbulent flows and jets may be more useful in this case and a corresponding theoretical scheme is now being developed.

A mathematical theory of motion of dust and combined avalanches is needed also for a theoretical description of the process of formation and propagation of the so-called air wave (see the section on the problem of air wave).

The problem of action of an avalanche upon constructions and obstacles

Formulation and solution of this problem become possible only after the problem of avalanche motion in absence of any obstacles is solved. So, let a compact avalanche approach an obstacle of given dimensions and configuration. The character of loads and their temporal relationship in this case will be similar to those which develop when a shock wave impacts upon a construction. The process of action of an avalanche upon a construction will consist, generally speaking, of two essentially different stages, just as in the case of a shock wave impact. The first stage corresponds to the impact of the frontal part of an avalanche. In this stage the time of growth of loads acting upon the obstacle will be quite small and of the order of \( l/v_* \), where \( l \) is a characteristic length of the obstacle in avalanche motion direction and \( v_* \) is the velocity of avalanche front, while the magnitude of pressures developed upon elements of a construction may be defined by compressibility of the snow—air mass and reach \( \Delta p \sim p\rho c \), where \( \rho, v, c \) are density, velocity and sound speed for the avalanche material.

The duration of the period of high pressures may be evaluated as a magnitude of the order of \( kH/c \), where \( k \sim 3-5 \), if \( H \gg l \), where \( H \) is the thickness of the avalanche in its frontal part, or \( kH/c \), if \( H \ll l \). Thus, the magnitude of loads acting upon a construction and their duration at the first short stage of interaction of an avalanche with an obstacle depends essentially on compressibility of avalanche material while it was ignored in the mathematical scheme for computing the process of avalanche motion described earlier. In order to consider compressibility of a snow—air mass it is necessary to have an appropriate equation of state for the mass. This question was considered by Yakimov and Shurova (1968) (see Briuchanov et al., 1967), who derived a theoretical
state equation confirmed with specially designed tests. This investigation among other things showed that sound speed in an avalanche mass may be relatively low (30—60 m/s).

The second — longer — stage of action of an avalanche starts at the moment of cessation of nonstationary phenomena of the first stage and is characterized by the flow of an avalanche mass past an obstacle with relatively slow rate of change of parameters of the flow. If avalanche motion in the absence of obstacles is found, then the time history of these parameters is known in every point of the avalanche route and, in particular, in the location of the obstacle, thus the problem of calculating forces acting upon an obstacle at the second stage is defined. It is similar to a hydrodynamic problem of flow of a nonstationary liquid jet past an obstacle. This is a rather simple problem which may be solved with the help of the known hydrodynamic approaches.

The order of pressure acting upon an obstacle at this stage is estimated by $\Delta p \sim \frac{1}{2} \rho v^2$ where $\rho$ and $v$ are density and velocity of an avalanche flow. This problem differs from the hydrodynamic one in that the obstacle's surface will be acted upon not only by the normal pressure forces but by friction forces too, the latter being close to dry (Coulomb) friction. These forces may be evaluated to an order of magnitude by relation $\tau \sim f \Delta p \sim \frac{1}{2} f \rho v^2$ where $f$ is the friction factor.

These particularities of appearance and change in time of forces acting upon an obstacle interacting with an avalanche were experimentally confirmed in the Institute of Mechanics of Moscow University (Shurova, 1967).

The study of an avalanche impact upon obstacles can be done also by means of physical simulation defined as follows. Analysis of the above mathematical problem of motion of compact avalanches shows that the main defining parameters are gravity acceleration $g$, snow density upon the slope $\rho_0$ and avalanche density $\rho$, geometrical characteristics of an avalanche route $L_i$, friction factor $f$ and hydrodynamic resistance coefficient $k$. The analysis of dynamics of impact of an avalanche upon a construction shows that compressibility and strength properties of an avalanche mass may be important. Thus, sound speed $c$, a number of parameters $A_i$ characterizing strength of an avalanche mass, friction factor $f$ and geometry of an obstacle $l_i$ must be added to the list of the defining parameters. Thus, the similarity theory (Sedov) shows that for two avalanche phenomena to be similar the following conditions must be satisfied

\begin{equation}
\frac{L_{im}}{L_{if}} = \frac{\rho_{im}}{\rho_{if}} = \frac{c_{im}}{c_{if}} = \frac{f_{im}}{f_{if}} = \frac{\left(\frac{\rho_0}{\rho}\right)_m}{\left(\frac{\rho_0}{\rho}\right)_f} = \frac{\left(\frac{\rho_0}{\rho}\right)_m}{\left(\frac{\rho_0}{\rho}\right)_f},
\end{equation}

\begin{equation}
\frac{A_{im}}{A_{if}} = \frac{\rho_{im}}{\rho_{if}} \frac{c_{im}}{c_{if}} = \frac{1}{\lambda}.
\end{equation}

where subscripts $m$ and $f$ mean that the corresponding value belongs to 'the model' or 'the full-size object'; $\lambda = L_i/L_m$ is the geometric scale. Then the model and full-size values will be connected by the following expressions

\begin{equation}
\frac{v_m}{v_f} = \sqrt{\frac{g_m L_m}{g_l L_f}} = \frac{1}{\sqrt{\lambda}}, \quad \frac{t_m}{t_f} = \sqrt{\frac{L_m g_l}{g_m L_f}} = \frac{1}{\sqrt{\lambda}},
\end{equation}

\begin{equation}
\frac{\rho_m}{\rho_f} = \frac{\rho_m v_m^2}{\rho_f v_f^2} = \frac{\rho_m}{\lambda \rho_f} \text{ etc.}
\end{equation}

where $v$, $t$, $p$ are respectively characteristic velocity of the avalanche material, time and pressure.
Thus, the main defining factor is gravity and simulation must be done according to Froude's number.

Considering conditions in equation (1), we see that not all of them may be satisfied easily in model tests. While using snow and natural underlying rock in model tests $f_m = f_f, k_m = k_f, (\rho_0/\rho)_m = (\rho_0/\rho)_f$ and $f_m = f_f$ conditions can be satisfied, the last two conditions in equation (1) cannot be satisfied because if snow in model tests is the same as in a natural environment, then conditions $A_{im}/A_{if} = \rho_m/\rho_f = 1$ and $C_m/C_f = 1$ will be satisfied which contradict the two mentioned conditions in equation (1). However, this circumstance is not actually significant for quite often the short duration initial stage of an avalanche impact upon an obstacle is either weakly expressed or altogether absent. Thus, a sufficiently good simulation may be done without consideration of strength properties and compressibility of an avalanche flow.

A simulating facility based upon the aforementioned simulation rules was constructed by the Institute of Mechanics of Moscow University near Mount Elbrus (at the Glaciological Station of Moscow University). This facility was used for experiments with varying geometrical scale $\lambda$ which have well confirmed the possibility of simulation according to Froude's number. The tests showed that the strength properties of snow mass cease influencing characteristics of interaction when a model's dimensions exceed $\sim 10$ cm (Yakimov and Shurova, 1968).

The above methods of theoretical and experimental studies of the processes of motion and impact of avalanches upon constructions and obstacles seem to be a reliable basis for development of techniques necessary for practical purposes.

The problem of air wave

We call 'air wave' the disturbance propagating ahead of the compact part of an avalanche which came to a standstill. The air wave can exert a considerable force upon obstacles and destroy them. Among many different effects accompanying an avalanche fall the air wave is the only phenomenon for which a large number of hypotheses were proposed. However, it is still mysterious and far from being explained. We shall only point out that the most valid one seems to be the hypothesis by Yakimov (Briuchanov et al., 1967; Yakimov and Shurova, 1968) which considers the air wave to be a macroscopic vortex formation created at the moment when an avalanche loses its speed rapidly and is capable of propagating for considerable distances due to the hydrodynamic particularities of such a formation. The hypothesis is based upon the known hydrodynamic fact that a closed vortex or a semivortex with its ends upon a solid surface propagates in the surrounding fluid with small dissipation and thus has a considerable 'range'.

Near Mount Elbrus observations of avalanche-generated air waves and instrumental measurements of their parameters were organized. Urumbaev (1967—1969) observed for many years various aspects of general avalanche regime of the region and in particular the origin and action of air waves (Grigorian et al., 1971). This work showed that powerful air waves are associated with falls of avalanches of dry fresh snow with obligatory presence of a well developed 'dust' component. Urumbaev studied and systemized results of the destructiveness of some powerful air waves and the material obtained permitted evaluating pressures exerted by an air wave upon trees, using for the purpose data for timber strength and actual data about dimensions and distribution of broken and fallen trees (Grigorian et al., 1971). The calculations showed that in order to produce the observed destruction by a flow of pure air the flow must possess unrealistic (large) velocities, far exceeding the maximum velocities of an avalanche itself. At the same time with realistic velocities the necessary destructive force is obtained if one supposes that the flow's density is larger by an order of magnitude. Thus it was concluded that the destructive 'air wave' is actually a flow of air—snow dust mixture. This conclusion is confirmed by other indirect evidence associated
with the observation data (formation of hard snow crusts upon the windward side of
trees and other obstacles, having experienced the action of an air wave, the actual
movement of a dense snow—air cloud ahead of a stopped avalanche etc.). Besides
evaluation of pressures (the dynamic pressure) acting upon obstacles facing an air
wave, Urumbaev performed instrumental measurements of the pressures, using
measuring devices designed and made in the Institute of Mechanics of Moscow Uni-
versity. The results of these measurements (not many yet) well agree with estimations
received earlier, thus giving the final confirmation of the above conclusion about air
wave structure.

At present we see the structure of 'air wave' as follows (Grigorian and Urumbaev,
1974). In the process of an avalanche of dry, low density snow the upper part is a
snow—air flow propagating through the surrounding air together with the compact
part of the avalanche under it. After the avalanche acquires a large speed, the further
conduct of its light and heavy parts may be different. The compact part follows along
the avalanche ‘bed’, i.e. its route is being defined by relief elements of the underlying
surface. Due to large friction upon this surface the heavy part slows down and stops
at the avalanche cone. The light part, being weakly connected with the heavy one,
separates from it and continues to move independently and ‘straightly’. Due to a con-
siderable difference of densities of the light part of an avalanche and the surrounding
pure air (by an order of magnitude or more) and to the stabilizing action of gravity
holding down intense upward development of the snow—air cloud and its rarefaction,
the latter is able to pass over considerable distances, preserving sufficient density,
compactness and velocity which assure its long ‘range’ and destructiveness. The frontal
part of the cloud and the surrounding air has vortex structure in accordance with
Yakimov’s hypothesis.

The following evaluation demonstrates validity of these speculations. Considering
a snow—air cloud as a solid body moving in air, one can write its equation of motion
in the form
\[
\frac{dv}{dt} = -\frac{1}{2} C_X \rho v^2 S, \quad m = \rho_1 l S
\]
where \( m, \rho_1, S, l, C_X \) are the cloud’s mass, its average density, cross-section area, length
and drag coefficient. This equation does not account for friction over the underlying
surface and gravity (the horizontal part of the cloud’s trajectory is considered).

The assumption of solidity of the cloud is justified, for inner circulatory motions
due to external air flow are \( \sqrt{\rho_1/\rho} \) times smaller than the velocity of translational
cloud motion and, since \( \rho_1 \sim 10 \rho \) (see above), this velocity difference will be large,
and additional motions inside a cloud may be neglected for the purpose of estimation.

Integrating the above equation, one receives
\[
v = v_0 \exp \left( -\frac{1}{2} C_X \frac{\rho}{\rho_1} \frac{x}{l} \right)
\]
where \( x \) is the distance covered by the cloud from the initial point where it had velo-
city, \( v_0 \). Assuming \( C_X \sim 1, \rho/\rho_1 \sim 0.1, l \sim 100 \text{ m} \) we see from the formula that a con-
siderable slowing of the cloud takes place at distances of the order of \( 10^3 \text{ m} \), which is
dozens of times larger than its dimension \( l \). These estimations show that the observed
long range of snow—air clouds may be explained sufficiently well by their high average
density and low friction over the underlying surface.

To construct a sufficiently precise and applicable quantitative theory of motion of
a snow—air cloud of an avalanche (of the ‘air wave’) useable also for calculation of
motion of light parts of combined and purely 'dust' avalanches, additional investigations are needed (see previous section). Such a theory will allow simple calculation of the force action of avalanches of this kind upon constructions and obstacles. In fact with the known velocity and density fields of such avalanches and their 'air waves', the problem of defining loads upon obstacles is reduced to a purely aerodynamic problem which in its turn may be solved by a numerical or experimental approach with the help of aerodynamic simulation.

The problem of slow motions of snow cover and its interaction with protective constructions

One could have noted that depending on the problem to be solved the snow mass was considered to be a solid deformable body (in the problem of evaluation of critical unstable states of a snow cover), an incompressible fluid (in the problem of motion of compact snow avalanches) and a compressible fluid (in the problem of impact of a dense avalanche upon an obstacle). To solve the problem of this section we shall need one more mechanical model of a snow cover. In fact, since in the case of prolonged stay of a snow cover upon a slope, not only its physicomechanical properties change but a slow flow of snow masses also occurs, then to consider the question of force interaction of a snow cover with the snow-holding constructions, it is necessary to establish rheological laws governing such slow flows. It is natural to suggest that snow under continuous action of loads will creep as all real materials do. Thus, the problem we consider now leads us to the necessity to use methods of the creep theory. This theory contains a lot of models designed to account for particularities of mechanical behaviour of materials belonging to different classes and the corresponding methods of solution of the problem in the framework of these models. However, experiments indicate that under a load condition resulting in sufficiently slow and prolonged motions it is possible to simplify such models considerably and reduce them to the model of a nonlinear viscous fluid with rather simple dependence of stresses upon deformation rates. Thus, creep properties of most different materials (metals, ice, rocks, soils etc.) under such conditions (of the so-called steady creep) merge to a significant extent, that is the structure of the rheological law for them proves to be qualitatively the same (with different numerical characteristics, naturally). This allows supposition that in this respect snow cannot be an exception and using the model of a nonlinear viscous fluid is a valid solution of the problem of slow motion under steady creep conditions. The validity of this assumption is emphasized by the fact that in the case of ice the possibility of such an approach was demonstrated with direct tests (see, for example Shumski, 1969) and, since snow consists of ice crystals, a completely different creep law would not be expected. Of course, due to its porous structure snow differs from solid ice and this difference influences rheological laws for snow. However, since physical nature of development of creep deformations in solid ice and in elements of ice structure of snow is the same, it is to be expected that the form of the rheological law for snow will coincide with that for ice with the only exclusion that in ice, creep influences only shear deformations while in a snow mass it must influence both shear and volume deformations. The latter, being defined by porosity, unlike shear deformations, cannot grow without limit and must slow down with diminishing porosity in the process of snow compression or to terminate in rupture in the case of expansion. One more particularity differing snow rheology from that of ice or other materials is a strong dependence of the rheological law on snow temperature and especially on its free water content, which diminishes viscosity considerably.

The aforementioned leads to general rheological relations for snow while numerical characteristics may be established experimentally. These may not necessarily be laboratory experiments with snow samples but field observations of the slow movements of snow cover (Grigorian and Berman, 1971; Ioselevich et al., 1972).
It should be mentioned that due to the mentioned ability of snow cover to metamorphose the problem of definition of the dependence of characteristics of the creep law on the age of snow acquires a special importance. Of great practical importance here is the definition of the rheological law for the depth hoar layer.

Considering mathematical problems about slow motion of snow cover upon mountain slopes equipped with snowholding constructions or without it various simplifications are possible (linear approximation in rheological law etc.).

Bozhinsky (1967, 1968, 1970), Geographic Faculty of Moscow University, considered model problems about stability of slow motions of a snow cover of constant thickness upon a slope of constant inclination and found out that in the case of snow slip along the underlying surface nonstability can develop. Although practical applicability of this result to the problem of formation of an avalanche is not still studied, the effect itself is interesting. There have also been obtained some results on the problem of slow snow flow upon a slope with regularly distributed obstacles based on the model of viscous fluid (Bozhinsky, 1969). They can be used to evaluate force interaction of snow with elements of constructions necessary for a rational design of the latter.

While evaluating maximum possible forces one can use the assumption that they develop when snow cover of maximum possible thickness approaches unstable conditions which means complete absence of connection of snow mass between two sequential rows of constructions with the underlying surface and the whole mass tears from the upper row of constructions. This means that the weight component of this snow mass, parallel to the slope, acts upon the lower row of constructions and this is just the situation when the force acting upon the row is maximum. Evidently while designing a snow holding construction for a 100 per cent prevention of avalanches, the elements of the construction must be able to resist such maximum loads.

Besides the above problems, rheology of snow mass must be considered also when the influence of curvature of the relief upon slow snow flows is considered and, in particular, possibility of attaining threshold tension states in such flows, which result in appearance of rupture cracks and formation of avalanches, and in some other problems. Attempts at a theoretical solution of such problems have not been done yet. Note that analysis of these problems can be essentially simplified if one uses the fact that the snow cover thickness is usually small compared to characteristic curvature radii of the underlying surface and it allows use of the boundary layer theory methods which simplify the mathematical problem considerably. Such studies are still to be done.

The problem of artificial release of avalanches
The most widely used means for artificial avalanche release is the use of an explosion acting upon the snow cover. However, as far as we know, until recently there were done no systematic studies of the mechanics of this process. At the Glaciological Station of Moscow University, near Mount Elbrus, the author organized experimental studies of this kind in the springs of 1969 and 1970. The studies were made as follows. Explosions of varying power were produced inside a thick snow cover while special gauges surrounding the charges registered the explosion wave parameters (stresses and mass rates). Dimensions of the explosion cavity and crack region concentric to the cavity were also measured. The results thus obtained allowed us to state that the character of development of an explosion wave in compressed avalanche snow is the same as in mild soils (Grigorian et al., 1969).

Our experiments with explosions inside compact snow have shown that decay of the explosion wave in this case is very strong. Therefore the region of compressed and cracked snow around the explosion cavity is relatively small. This means that if the snow cover state is far from critical (unstable), then the explosion will not launch
an avalanche. Therefore, efficient and economic use of explosions to launch avalanches must be well timed and made when snow cover state is sufficiently close to critical. Thus the problem of predicting critical states is most important for the problem we consider now. Such a situation was often encountered in practice when the use of explosions resulted in unpredictable consequences — sometimes an intense bombardment of dangerous slopes with projectiles and mines was quite ineffective while in other cases a single shot could start tremendous avalanches. This was well understood by American workers (Atwater, 1968). They have also stated that influence of an explosion upon a snow cover where formation of depth hoar layer is already under way but did not still result in a critical state, may prevent development of such a state over a large area due to local destruction of the latter layer. Such destructions create local strengthened zones and prevent avalanche release, just as anti-avalanche constructions do.

The use of explosions to launch avalanches could be made more effective and suitable if the energy of explosion were transformed into surface elastic waves propagating in the underlying rock. Actually these waves die out much slower than volume explosion waves in snow and the shock they produce can shake considerably larger parts of snow cover than in the case of an explosion inside the snow cover. This idea was put forward by Prof. Baranov and his colleagues, Institute of Physics and Mechanics of Rock, Academy of Sciences of Kirghiziya.

The aforementioned signifies that artificial initiation of snow avalanches must be done only at those moments when a snow cover is already close to a critical state. Then it can be done not only by means of an explosion but also by any other means. Kirghiz chabans (mountain herdsmen) can determine the time of approaching instability of snow cover by tokens known only to them and release avalanches by a most simple way — treading paths along the upper parts of mountain slopes. This proves to be a safe and effective procedure.* One cannot help admiring this simple and effective method developed, of course, without any help of science.

Despite the fact that the present paper cannot to any extent be considered a review of the modern state of the discussed subject, the author hopes that it will be useful for avalanche specialists and glaciologists.

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* Personal communication to the author by Prof. K. Yusupov, Frunze University.


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**DISCUSSION**

**J. F. Nye presented the paper on behalf of the author**

**W. H. Graf:**

I have several questions relating to the Froude number:

1. Is the avalanche dimension in the Froude number valid for all sizes of avalanche?
2. What velocity is used for the Froude number?
(3) How valid is the Froude number given that air compressibility and variable
density may play a role? Maybe a densitometric Froude number should be used, e.g.

\[ Fr = \frac{v^2 \rho_s - \rho}{\gamma l \frac{\rho}{\rho}} \]

A. N. Bozhinsky:
(1) The Froude number is valid for all avalanches. This is a requirement for the
model tested.
(2) The velocity in the Froude number is the particle velocity in the front
because we must calculate the pressure which is derived from the mass of the avalanche.
(3) The density used is the average value in the front.

E. J. Hopfinger:
You give values for the sound velocity of 30—60 m/s. This is an extremely low value
and I would like to know how it is obtained. From what we know of multiphase
systems the sound velocity should only be 20—30 per cent lower than the value for
free air.

A. N. Bozhinsky:
We have a very complicated disperse medium and the sound velocity in this medium
is not necessarily within the limiting values of pure air and undisturbed snow cover.
The value used is a calculated value.

R. L. Brown and W. H. Graf:
Could the viscosity be ignored if the Reynolds number became large in slab avalanches?

R. I. Perla:
In similar studies we have found that the Reynolds number does not become large
enough for turbulence to develop.

J. F. Nye:
Grigorian's theory is not for turbulent flow even though Reynolds number is quite
high. The equations are therefore valid.

M. de Quervain:
Density of powder avalanche was said to be about 10 times that of the air. We believe
that the density may vary from that of air to that of the lightest deposited snow which
is about 20—30 kg/m³.

For a powder avalanche we use a figure of 5 kg/m³ for practical purposes. Does Dr
Grigorian find a range of values and does the figure of 10 times the air density cor-
respond to that required for destruction by the air wave?

A. N. Bozhinsky:
The value of 10 is an order of magnitude.